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Electromagnetic Response Exited by Amplitude-Modulated Ultrasonic Waves in Bones

振幅変調された超音波によって誘起された骨の電磁応答

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1. Introduction

Bone is a connective tissue largely composed of collagen and inorganic mineral hydroxyapatite. Bone mineral density obtained by X-ray or ultrasonic techniques is normally used as an indicator of bone conditions [1], but the evaluation method of collagen quality is still in development., Recently, we found the acoustically stimulated electromagnetic (ASEM) response originated from piezoelectricity of bone [2,3]. Since the origin of piezoelectricity of bone is attributed to fibrous collagen crystals [4,5], the ASEM response may provide an indicator of collagen evaluation.

One of the important factors in the ASEM measurements is how to avoid strong noise signals generated by excitation of an transducer. In the pulsed ASEM method [2], the time delay of ASEM signals, caused by a huge velocity difference between ultrasonic and EM waves, has been utilized by maintaining a proper distance between the transducer and the target sample. In this method, however, the net integration time to avarage weak ASEM signals is much shorter, comparing with the actual measurement time. In order to significantly improve the effective sensitivity, we here report a continuous amlitude-modulation (AM) method.

2. Method

Figure 1 (a) shows the schematic representation of the AM method. When the sample is placed at a distance of $d=(2n+1)\lambda_m/4$, the ASEM signals have a quadrature phase relationship for the transducer signals ($n=0,1,2\ldots$, λ_m: the wavelength of ultrasonic modulation waves in an acoustic medium). Through the lock-in techniques, the ASEM signals will be extracted in the imaginary part of the demodulated input signals to the lock-in amplifier (Fig. 1(b)). For the ultrasonic delay time τ, the ASEM response is given by

$$V_{\mathrm{AM}}=B\sin\{2\pi f_c(t-\tau)\}$$
$$+\frac{B_m}{2}\sin\{2\pi(f_c+f_m)(t-\tau)\}$$
$$+\frac{B_m}{2}\sin\{2\pi(f_c-f_m)(t-\tau)\}, (1)$$

where the B and B_m are the amplitudes of the carrier and modulation waves of the ASEM response. The f_c and f_m are the frequencies of

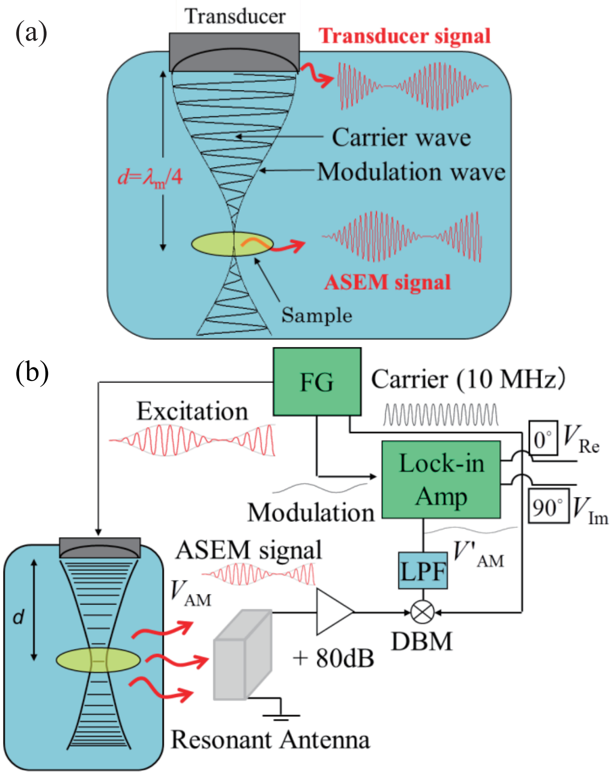

Fig.1: (a) Schematic of ASEM measurement using continuous AM waves. Longitudinal ultrasonic AM waves are schematically represented as a transversal form. (b) Block diagram of the measurement setup.

the carrier and modulation waves, respectively. We here note that the bandwidth of the resonant antenna is properly set so as to detect the sideband waves as well as the carrier waves. The ASEM response demodulated at the f_c can be written as

$$V'_{\mathrm{AM}}=\left\{\frac{DB}{2}+\frac{DB_m}{2}\cos 2\pi f_m(t-\tau)\right\}$$
$$\times\cos(2\pi f_c\tau), \quad (2)$$

where the D is the amplitude of the demodulation signals to a double balanced mixer (DBM) The transducer noise signals can be also expressed by the formula of eq.(2) at $\tau=0$ if the amplitudes are substituted by much larger values than B and B_m. Using $\tau=d/v$, the real part of output voltages from the lock-in amplifier is

$$V_{\mathrm{Re}}=G+\frac{B_mD}{2\sqrt{2}}\cos\left(2\pi f_c\frac{d}{v}\right)$$
$$\times\cos\left(2\pi f_m\frac{d}{v}\right), \quad (3)$$

and the imaginary part is

$$V_{\mathrm{Im}} = \frac{B_m D}{2\sqrt{2}} \cos\left(2\pi f_c \frac{d}{v}\right) \sin\left(2\pi f_m \frac{d}{v}\right), \quad (4)$$

where the v is the ultrasonic velocity in the acoustic medium. If the modulation frequency is

$$f_m^n = \frac{2n+1}{4d} v, \quad (5)$$

the real part shows a constant value for $\tau = d/v$, arising from transducer signals and background noises, and the imaginary part has a maximum value which corresponds to the target ASEM response. This frequency condition is equivalent to the above mentioned condition of $d = (2n+1)\lambda_m/4$. We can thus find the well extracted ASEM signals by sweeping the modulation frequency. Note that the signal intensity still depends on the distance d as a function of $\cos(2\pi f_c d/v)$. To find the maximum intensity of ASEM signals, we further need to finely tune the distance of an order of $|\Delta d| = v/2f_c$.

4. Results and discussion

The ASEM response from a bone specimen (rat femur) was first measured by the pulsed method and the distance is evaluated to be $d = 60$ mm from the time delay analysis (**Fig. 2**(a)). The signal-to-noise (SN) ratio normalized by the measurement time is estimated to be about $1.1\ \mathrm{Hz}^{-1/2}$ in the pulsed method. For the velocity in water $v = 1500$ m/s, the frequency conditions required in the AM method are $f_m^0 = 6.25$ kHz, $f_m^1 = 18.75$ kHz and $f_m^2 = 31.25$ kHz. As shown in Fig. 2(b), the obtained maximum peaks of the imaginary part are well agreement with the expected frequencies. Here, we also perform the fine tuning of the distance to check the maximum condition for the carrier waves (Fig. 2(c)). The $|\Delta d|$ is evaluated to be about 80 μm at an antenna resonate frequency of $f_c = 9.26$ MHz. The results shown in Fig. 2(c) provide the experimental evidence that phase information is maintained through the conversion process from ultrasonic to EM waves in the bone specimen. The SN ratio in the AM method is estimated to be $179\ \mathrm{Hz}^{-1/2}$, yielding an improvement factor of about 170 in effective sensitivity.

5. Conclusion

We present a continuous ASEM method for sensitively detecting weak signals. The improvement factor of about 170 is achieved for sensitivity in a bone specimen, reducing the measurement time by a factor of 170^2.

Acknowledgement

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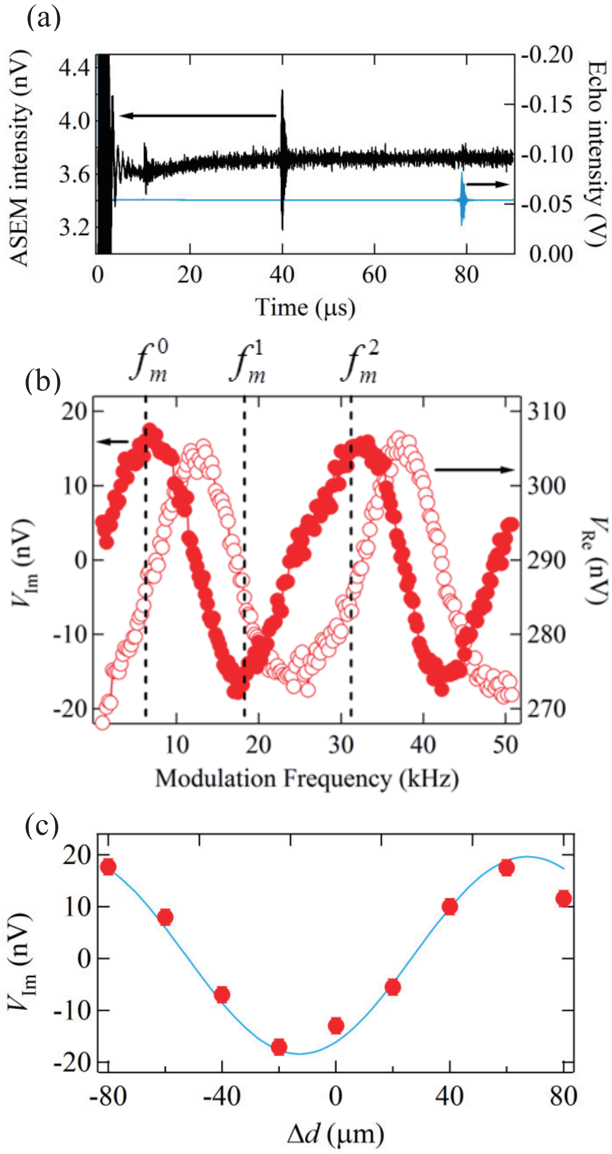

Fig.2: (a) Pulsed ASEM response from a bone specimen (rat femur). (b) Modulation frequency dependence of ASEM response in the AM method. (c) Fine tuning of the distance. The closed circles indicate the experimental data at $f_m = 6.25$ kHz and $f_c = 9.26$ MHz and the solid line shows the curve fit of the data based on eq. (4).

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