Noninvasive method for measuring velocity of leaky surface skimming compressional wave propagating on bone surface

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The authors propose a new method, based on the microdefocusing method [1], for transcutaneously measuring the velocity of leaky surface skimming compressional waves (LSSCWs) propagating on the surface of bone. The method is realised by an ultrasonic measurement system which is applicable to *in vivo* measurement using ultrasound of 1MHz. The velocity of the LSSCW propagating on the surface of a Bakelite sample is snccessfully determined in a preliminary experiment, and the principle of the proposed method is confirmed.

Introduction: Since ultrasound-based diagnosis of osteoporosis does not necessitate the use of x-rays, it is preferable to, and can be more frequently applied than other diagnosis methods. Acoustic and elastic properties of bone obtained by ultrasonic-based methods are highly useful in the direct evaluation of bone characteristics. Thus, many methods and systems have been developed such as the acoustic emission (AE) method [2], the apparent velocity of the ultrasound (AVU) method [3], and the speed of sound-broadband ultrasound attenuation (SOS-BUA) method [4, 5]. It is, however, well known that the propagation loss is large in bone even for ultrasound of 1MHz and that it is difficult to transcutaneously measure the bone thickness, which is essential to the evaluation of velocity and the attenuation per unit length. Thus, the ultrasonic reflection method is more effective than the pulse transmission method. In this Letter, we propose an ultrasonic reflection method, in which the velocity of the LSSCW propagating on the surface of bone is determined based on the $V(z)$ curve analysis used in acoustic microscopy. Since the propagation loss of the LSSCW is also large for bone, there are only a few periods of Δz due to interference between the LSSCW component $V_I(z)$ and a wave component $V_L(z)$ reflected perpendicularly from the sample surface in the measurement of the $V(z)$ curve of bovine bone [6, 7]. Thus, periodical analysis, such as the fast Fourier transform (FFT) is not adequate for accurate velocity determination. In this Letter, as an alternative, we propose a new method for the evaluation of the velocity of the LSSCW based on the microdefocusing method [1]. In the proposed method, only the $V_I(z)$ component is received by a pair of transducers. Phase $\theta(f_0, z)$ of the $V_I(z)$ component at the centre frequency, f_0, of the transducers is measured for several values of the sample position z. From the phase characteristics $\theta(f_0, z)$ of $V_I(z)$, the velocity of the LSSCW is determined. From a preliminary experiment using a measurement system constructed in our laboratory, the LSSCW velocity for a Bakelite sample, almost the same as that of human bone, is successfully determined and the principle of the proposed method is confirmed.

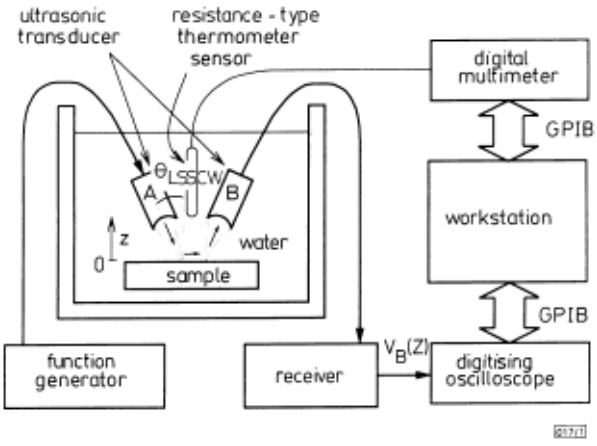

Fig. 1 *Block diagram of measurement system*

Principle: Fig. 1 shows a block diagram of a system for the measurement of the velocity of the LSSCW. There are two ultrasonic transducers, transducer (A) for transmitting and transducer (B) for receiving. Transducer (A) is positioned so as to transmit an ultrasonic pulse. Its centre axis is almost the same as the critical angle θ_{LSSCW} of the sample so that only the LSSCW component is excited on the sample surface. The centre frequency of the transducer f_0 is 1MHz, and the focal length is 95mm. Transducer (A) is driven by an RF burst pulse wave of 1MHz, 50μs in length. The ultrasonic wave is transmitted from the transducer (A), as shown in Fig. 1, to the sample surface with its critical angle with the LSSCW being set at θ_{LSSCW}. The LSSCW is excited and propagates on the sample surface. When the distance between the transducers and the sample is decreased by changing the sample position z toward to the transducers, the leaky wave $V_B(z)$ which is re-transmitted from the sample surface, is detected by transducer (B) for each sample position z, and is digitised by a digitising oscilloscope. The received signal is transferred to a workstation. The longitudinal velocity v_w in water is determined from the temperature T measured by a resistance-type thermometer sensor using the previously reported relation between T and v_w [8].

By calculating the phase spectrum $\theta(f, z)$ of the detected signal $V_B(z)$, the phase delay $\theta(f_0, z)$ at the centre frequency f_0 = 1MHz of the received signal is determined for each sample position z. When only one mode of the leaky waves (the LSSCW mode in this case) is excited on the sample surface, the velocity of the LSSCW is determined by the microdefocusing method [1]. Since the acoustic path in Fig. 1 is the same as that for the LSSCW component $V_I(z)$ of $V(z)$ which is measured in the acoustic microscope, the change $\delta\theta$ of the phase delay caused by moving the sample closer to the transducer by δz is given by

$$\delta\theta = 2k_w \frac{\delta z}{\cos\theta_{LSSCW}} - 2k_{LSSCW}\delta z \times \tan\theta_{LSSCW} \quad (1)$$

where k_w and k_{LSSCW} are the wave number of the longitudinal wave in water and the wave number of the LSSCW, respectively. Since the critical angle θ_{LSSCW} for LSSCW is given by

$$\sin\theta_{LSSCW} = \frac{v_w}{v_{LSSCW}} = \frac{k_{LSSCW}}{v_w} \quad (2)$$

and $v_{LSSCW} = 2\pi f/k_{LSSCW}$ is the phase velocity of LSSCW, eqn. 1 is simplified as

$$\delta\theta = 2k_w\delta z \times \cos\theta_{LSSCW} \quad (3)$$

The phase change $\delta\theta$ is measured for each sample position z while the distance between the sample and the transducers is decreased. The gradient ξ of the phase delay $\theta(f_0, z)$ is given by

$$\xi = \frac{\delta\theta}{\delta z} = 2k_w \cos\theta_{LSSCW} \quad (4)$$

Substituting eqn. 4 into eqn. 2, the velocity v_{LSSCW} of the LSSCW is determined by

$$v_{LSSCW} = \frac{v_w}{\sqrt{1-\left(\frac{\xi}{2k_w}\right)^2}} = \frac{v_w}{\sqrt{1-\left(\frac{\xi v_w}{4\pi f_0}\right)^2}} \quad (5)$$

Thus, the velocity v_{LSSCW} of the LSSCW propagating on the sample surface is determined by measuring the gradient ξ of phase change $\delta\theta$, due to the decrease of the distance δz between the sample and the transducers.

Experimental results: To confirm the principle of the proposed method, the velocity v_{LSSCW} of the LSSCW is measured for a sample of Bakelite. The critical angle θ_{LSSCW} for the Bakelite is ~24°, assuming that v_w is 1500m/s and the longitudinal velocity v_L of the Bakelite is 3718m/s which is measured in advance by the ultrasonic pulse transmission method [9].

Fig. 2 shows the relationship between the phase delay $\theta(f_0, z)$ of the received signal, which is measured by reducing the distance between the sample and the transducers. The temperature is 25.8°, and v_w is 1499m/s. The gradient ξ is determined as 7.583×10^3 by applying the least mean square method to Fig. 2. Substituting the resultant values of v_w and ξ into eqn. 5, the velocity v_{LSSCW} of LSSCW for the Bakelite sample is determined to be 3515m/s, which is different from the longitudinal velocity v_L = 3818m/s of Bakelite. Thus, the LSSCW mode is successfully excited and detected by the proposed method and system.

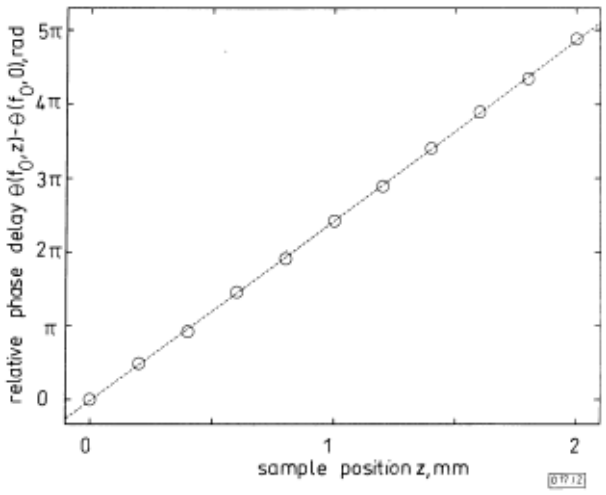

Fig. 2 *Phase change* θ *in received signal measured for Bakelite sample*
$\xi = d\theta/dz = 7.583$ rad/mm

Conclusions: In this Letter, we have proposed a new method for *in vivo* measurement of the velocity of the LSSCW for human bone. A system based on the microdefocusing method was constructed and from a preliminary experiment using a Bakelite sample, the principle of the proposed method was confirmed. By comparing the measured velocity v_{LSSCW} of the LSSCW with its longitudinal velocity v_L, the LSSCW was successfully excited and its velocity was measured by the microdefocusing method. To realise an *in vivo* system for human bone, soft tissues surrounding the bone must be taken into account in any analysis. Fortunately, since the velocity and acoustic impedance of soft tissues are close to those of water, the proposed system and method of analysis are also applicable to human bone.

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