ACCURACY EVALUATION IN ULTRASONIC-DOPPLER-BASED MEASUREMENT OF SMALL VIBRATIONS FOR ACOUSTICAL DIAGNOSIS OF THE AORTIC WALL

K. Kawabe, H. Kanai and N. Chubachi

Indexing terms: Biomedical ultrasonics, Measurement

To diagnose atherosclerosis based on the acoustic characteristics of the aortic wall, it is necessary to detect vibration signals from various parts of the aortic wall near the heart. It is, however, difficult to obtain such small vibrations using previously proposed ultrasonic diagnostic methods or systems because the small vibrations are superimposed on the motion with large amplitude due to the heartbeat. The authors developed a new method for overcoming this problem and accurately measuring small vibrations of the aortic wall using ultrasound. The Letter describes the accuracy of evaluation using this new method by simulation experiments using a system which simulates small vibrations of the aortic wall near the heart.

Introduction: The need for a method to quantitatively measure heart sounds and vibrations on the aortic wall is becoming increasingly important [1]. However, the *vibrations* of the aortic walls with small amplitude (about ±100 μm, up to at least several hundred Hertz) are superimposed on the *motion* with large amplitude (about ±10 mm, several Hertz) due to the heartbeat. Thus, there are large fluctuations (about ±10 μs) in the transit period for the round trip travel of an ultrasonic wave travelling between a transducer on the chest wall and the aorta near the heart during one cardiac cycle. It is difficult to obtain the small local vibrations on the large motion described above. To overcome the problem, we have already proposed a new method [2]. This Letter describes a measurement system which we have constructed to detect small vibration signals over a wide frequency range based on the principle of the method. From simulation experiments in a water tank, the accuracy and effectiveness of the proposed method are evaluated.

Principle: In the standard ultrasonic Doppler system [3], the velocity of an object is measured from the phase shift of the reflected ultrasonic wave. In the measurement of small vibrations on the heart motion, however, phase shifts due to the instantaneous change of the object position cannot be neglected. Thus, we have proposed an alternative new method to estimate the vibration velocity $v(t)$ of an object moving with a large amplitude [2]. In this method, the velocity $v(t)$ of the object is estimated by

$$\bar{v}\left(t+\frac{\Delta t}{2}\right) = -c\cdot\frac{\theta_{t+\Delta t}-\theta_t}{4\omega_0\,\Delta t} \tag{1}$$

where c, θ_t, ω_0, and Δt denote sound velocity in water, the phase of the reflective ultrasonic wave at a time t, the angular frequency of the incident ultrasonic wave, and the time interval between a pulse received at time t and the successive received pulses, respectively. That is, the vibration velocity $v(t)$ superimposed on a large amplitude motion is estimated from the phase change $\theta_{t+\Delta t}-\theta_t$ and the time interval Δt between the successively received pulses as shown in Fig. 1.

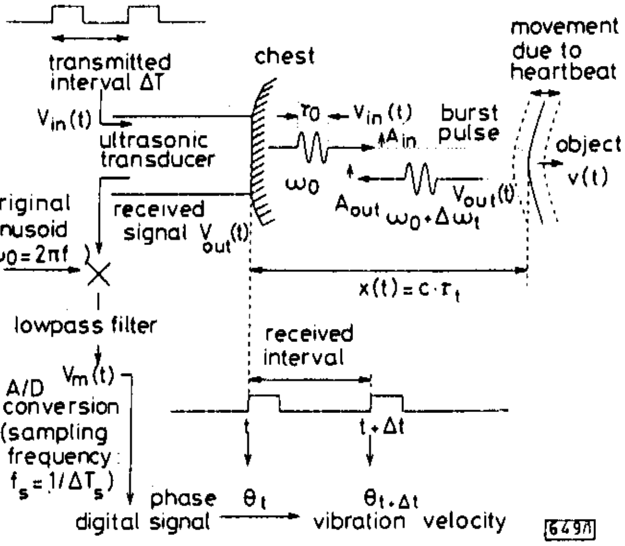

Fig. 1 *Description of the transmitted wave $V_{in}(t)$ from an ultrasonic transducer, the wave $V_{out}(t)$ reflected at an object, and an outline of the measurement procedure in the proposed method*

Experimental apparatus: Fig. 2 shows the experimental apparatus. The motor and the rotating eccentric cam are employed to generate motion with a large amplitude (±8 mm, 1 Hz), which simulates the heartbeat. The vibrator is employed to apply the vibration with small amplitude (10 μm–1 mm) to a rubber plate of size 30 × 30 mm² in a water tank. This small vibration simulates a small vibration of the wall of the aorta near the heart. The centre frequency of the ultrasonic wave is 3·5 MHz, the pulse width is 1 μs, and the pulse repetition frequency is 5 kHz.

The received output signal of the ultrasonic transducer is amplified and demodulated by multiplying the resultant pulse wave by cosine and sine signals at 3·5 MHz. The resultant real and imaginary signals are simultaneously A/D converted with a 12 bit A/D convertor at a sampling rate of 1 MHz. The length of each signal is ~512 × 10³ points.

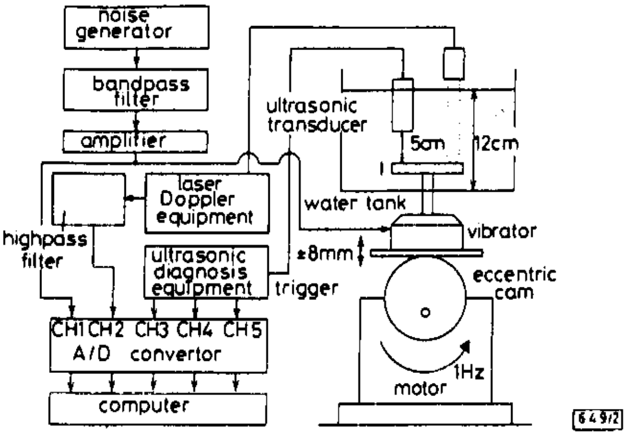

Fig. 2 *Experimental system which simulates the vibration of the aortic wall with heartbeat of large amplitude using a vibrator and a motor with an eccentric cam*

Experimental results: To evaluate the correlation at each frequency between the velocity signal $v_1(t)$ and the velocity signal $v_2(t)$, the following coherence function $\gamma^2(f)$ is calculated:

$$\gamma^2(f)=\frac{|E[V_1(f)^*V_2(f)]|^2}{E[|V_1(f)|^2]E[|V_2(f)|^2]} \tag{2}$$

where $V_1(f)$ and $V_2(f)$ are the spectra of $v_1(t)$ and $v_2(t)$, respectively. The term $E[.]$ and $*$ denote the average operation and the complex conjugate, respectively. The average is made from 16 sets of signals in these experiments. Before superimposing the motion with large amplitude, only the small vibration is applied to the rubber plate in the water tank, which corresponds to white noise in the frequency band ranging from 5 Hz to 1·5 kHz and the peak vibration amplitude is equal to 10 μm–1 mm. Fig. 3*a* shows the experimental results for this condition. The coherence function $\gamma^2(f)$ is calculated between the velocity signal $v_0(t)$ obtained from the laser Doppler equipment (Ono Sokki LV-1500) and the velocity signal $v_a(t)$ obtained from the standard ultrasonic diagnosis equipment (Yokogawa Medical RT-3600). From these experimental results, the vibration signal is successfully estimated by the ultrasonic diagnostic equipment. For experiments of the small vibration superimposed on the large amplitude motion, however, there is no correlation between $v_0(t)$ and $v_a(t)$ as

Reprinted from ELECTRONICS LETTERS 13th May 1993 Vol. 29 No. 10 pp. 915-916

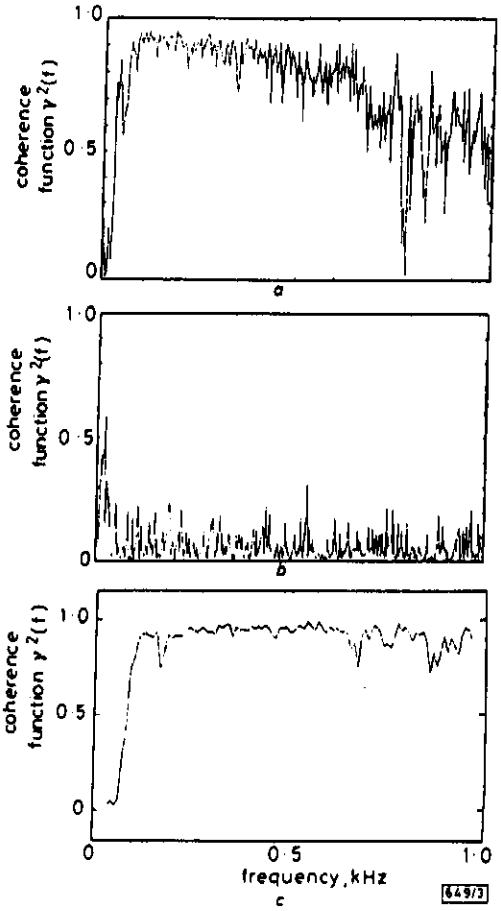

Fig. 3 *Coherence function $\gamma^2(f)$ between the vibration velocity $v_0(t)$ and $v_e(t)$ using analogue signals from ultrasonic diagnosis equipment, and coherence function $\gamma^2(f)$ between the vibration velocity $v_0(t)$ and $\tilde{v}(t)$*

a Experimental result without rotating eccentric cam: coherence function between $v_0(t)$ and $v_e(t)$
b Experimental result with rotating eccentric cam: coherence function between $v_0(t)$ and $v_e(t)$
c Experimental result with rotating eccentric cam: coherence function between $v_0(t)$ and $\tilde{v}(t)$
$v_0(t)$: output from laser Doppler equipment, $v_e(t)$: output from ultrasonic diagnosis equipment, $\tilde{v}(t)$: vibration velocity estimated by proposed method

shown in Fig. 3*b*. Because the laser Doppler equipment is sufficiently reliable for this measurement condition, the small vibration on the aortic wall near the heart cannot be measured by the standard ultrasonic Doppler system. To confirm the principle of the method proposed to solve the above problem, the small vibration signal $v(t)$ of a rubber plate in a water tank is estimated from the signal received by an ultrasonic transducer as shown in Fig. 2.

Fig. 3*c* shows the experimental results obtained by the proposed method for the same experimental conditions as Fig. 3*b*. The output signal of the laser Doppler equipment is passed through a highpass filter (cutoff frequency $f_c = 10$ Hz) before A/D conversion to remove the components of large amplitude due to the motion of the eccentric cam. The resultant signal $v_0(t)$ is obtained by the laser Doppler equipment. The vibration velocity signal $\tilde{v}(t)$ is estimated by the proposed method using the signals of the demodulated output of the ultrasonic transducer. Fig. 3*c* shows the coherence function $\gamma^2(f)$ between $\tilde{v}(t)$ and $v_0(t)$. From these experimental results, the small vibration velocity on the large motion is successfully detected in the frequency range up to 1 kHz.

Conclusions: This Letter experimentally evaluates the accuracy of the new method proposed for measuring small vibrations of the aortic wall on a large motion due to a heartbeat using ultrasonic techniques. These experimental results lead to the conclusion that evaluation of small vibrations of the aortic wall in the frequency range up to 1 kHz to diagnose its acoustic characteristics is achievable.

6th April 1993

K. Kawabe, H. Kanai and N. Chubachi (*Department of Electrical Engineering, Faculty of Engineering, Tohoku University Aramaki-aza-Aoba, Sendai 980, Japan*)

References

1 KANAI, H., CHUBACHI, N., KIDO, K., KOIWA, Y., TAKAGI, T., KIKUCHI, J., and TAKISHIMA, T.: 'New approach to time dependent AR modeling of signals and its application to analysis of the fourth heart sound', *IEEE Trans.*, 1992, **SP-40**, (5)

2 KANAI, H., HIROSE, K., SATO, H., and CHUBACHI, N.: 'A new method to measure local vibrations in a heart using ultrasonic', *IEEE Engineering in Medicine and Biology Society*, 1991, **13**, (1), pp. 131–132

3 BARBER, W. D., EBERHARD, J. W., and KARR, S. G.: 'A new time domain technique for velocity measurements using Doppler ultrasound', *IEEE Trans.*, 1985, **BME-32**, (3), pp. 213–229