Ultrasonic Measurements

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Semi-Automatic Determination of Ultrasonic Velocity and Absorption in Liquids*

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Summary

A reliable semi-automatic pulse technique for rapidly determining the velocity and absorption of ultrasound in liquids over the frequency range from 1 MHz to 200 MHz is described. The acoustic path length is changed at a known constant rate and the velocity of sound is determined from the length of time for the path length to change by an integral number of wavelengths. The absorption is determined from the slope of the line which results from recording logarithmically the received pulse amplitude as a function of the instantaneous path length.

Détermination semi-automatique de la vitesse et de l'absorption des ultrasons dans les liquides

Sommaire

On décrit une technique semi-automatique d'impulsion, valable pour déterminer rapidement la vitesse et l'absorption d'ultrasons dans des liquides pour une gamme de fréquences de 1 MHz à 200 MHz. On modifie la longueur du parcours acoustique à une vitesse constante connue, et on détermine la vitesse du son d'après le temps nécessaire pour que la longueur du parcours soit modifiée par un nombre entier de longueurs d'onde. On détermine l'absorption d'après la pente de la ligne qui résulte de l'amplitude de pulsation reçue, enregistrée logarithmiquement en tant que fonction de la longueur instantanée de parcours.

Halbautomatische Bestimmung der Ultraschallgeschwindigkeit und Absorption in Flüssigkeiten

Summary

Es wird eine zuverlässige, halbautomatische Pulstechnik beschrieben zur schnellen Bestimmung der Geschwindigkeit und Absorption von Ultraschall in Flüssigkeiten über einen Frequenzbereich von 1 MHz bis 200 MHz. Die akustische Weglänge wird um einen bestimmten, konstanten Betrag geändert und aus der Zeitdauer für die Änderung der Weglänge um ganzzahlige Vielfache der Wellenlänge wird die Schallgeschwindigkeit bestimmt. Die Absorption wird aus der Neigung der Geraden bestimmt, die sich ergibt, wenn man die erhaltene Pulsamplitude logarithmisch als Funktion der augenblicklichen Weglänge aufträgt.

1. Introduction

The pulse technique first described by PELLAM and GALT [1] is commonly employed today to measure the acoustic properties of liquids. The velocity of sound, V, is determined by measuring the transit time of an acoustic pulse over a known path length or by measuring the change in transit time which arises from a change in the acoustic path length. Furthermore, the ultrasonic absorption coefficient, α, is determined from the acoustic path length increment necessary to produce an insertion loss equivalent to the attenuation provided by an electrical standard. In a series of investigations by the authors, the ultrasonic properties of aqueous solutions of biological macromolecules were measured as a function of pH, temperature, concentration, molecular weight and frequency [2], [3], [4]. Because of the limited stability of relatively large quantities of these materials over the long periods of time required for acquisition of data with this basic pulse technique, several innovations were introduced in order to allow rapid determination of the ultrasonic absorption coefficient to $\pm 3\%$ and of the ultrasonic velocity to $\pm 0.03\%$ over the approximate frequency range 1 MHz to

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200 MHz. The apparatus described in this report operates as an acoustic pulsed interferometer for velocity measurements, wherein the path length is changed at a constant rate and the length of time for it to change by an integral number of wavelengths is measured. For absorption measurements, a servo recorder plots the logarithm of the received acoustic pulse amplitude as a function of the path length, and the absorption coefficient is determined from the slope of the resulting straight line.

2. Mechanical apparatus

The sample chamber in which the acoustic measurements are performed employs the conventional sliding piston and cylinder arrangement surrounded by a temperature control jacket. Two air-backed piezoelectric transducers are employed for transmitting and receiving pulses of longitudinal acoustic waves, respectively. One transducer is mounted on the moveable piston which is mechanically driven at a constant velocity via a synchronous motor, worm gear and lead screw arrangement. The other transducer is mounted in a ball socket at the end of the cylinder and both are coaxial and parallel to each other. Over the frequency range 1 MHz to 75 MHz odd harmonics of 1 MHz or 3 MHz fundamental frequency transducers are employed. For use above 75 MHz, 15 MHz fundamental transducers, bonded to fused quartz delay rods are employed. The minimum pulse duration used is fifteen periods at the ultrasonic frequency and the acoustic measurements are carried out entirely in the near field of the sound source.

3. Electronics system

The block diagram of the electronics system is shown in Fig. 1 [1]. An acoustic pulse is formed by gating and amplifying a c. w. electrical signal of the appropriate frequency, and applying it to the transmitting transducer through an electrical matching network. The acoustic pulse travels through the sample liquid, where it undergoes attenuation due to the losses in the sample, to the receiving transducer where it is partially reflected. The reflected acoustic pulse undergoes subsequent attenuation as it continues to travel between the two transducers. The pulse length is short compared with the travel time of the acoustic pulse in order to prevent standing waves and the pulse repetition rate is low so that an acoustic pulse is not produced until the preceding acoustic pulse has virtually dissipated. For velocity of sound measurements the received electrical signal is combined with a reference signal from the c. w. oscillator and the sum signal is amplified and video detected. A coincidence gate with a variable delay gating pulse is used to isolate the video signal, which arises from the first received acoustic pulse, and to track it as the acoustic path length changes. Also, the gate width can be made narrower than the acoustic pulse in order to eliminate transients which appear at the leading and trailing edges of the received pulse. In the absence of acoustic absorption, the fundamental frequency component of the first received acoustic pulse varies according to the following equation, as the path length is changed at a constant rate V_p,

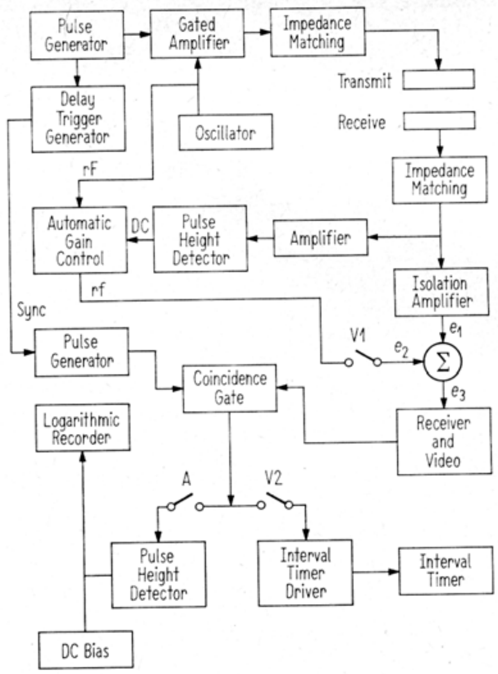

Fig. 1. Functional block diagram of semi-automatic system for measuring the acoustic properties of liquids. Switches V1 and V2 are closed for velocity measurements while switch A is closed for absorption measurements.

$$e_1 = A_0 \sin[(\omega_0 + \omega_p)\, t + \Phi] \qquad (1)$$

where ω_0 is the angular acoustic frequency, $\omega_p = 2\pi V_p/\lambda_s$, λ_s is the wavelength of sound and Φ is a constant which accounts for all other phase shifts which do not depend upon the acoustic path length. If e_1 is added with the reference signal, $e_2 = A_0 \sin \omega_0 t$, the resultant signal e_3 can be written as

$$e_3 = \left[2 A_0 \cos \frac{\omega_p}{2} t\right] \left[\sin\left(\omega_0 + \frac{\omega_p}{2}\right) t\right]. \qquad (2)$$

[1] It is realized that there may be better ways to implement electronically the functional block diagram of Fig. 1 than was done when the authors' instrument was designed. Therefore, it was decided not to include the electronic circuitry in this paper. However, the authors are willing to supply this information upon request.

Signal e_3 is passed through a peak detector and the amplitude of the video pulse train at the coincidence gate output, E_3, goes through zero whenever the piston has travelled the distance of one wavelength. Since $\omega_p/\omega_0 < 10^{-6}$ for the piston velocities employed, the error due to DOPPLER shift is negligible. The output of the coincidence gate is fed to a pulse height detector and the slowly varying D.C. level output of this device is represented by E_3.

Two methods are employed for obtaining velocity of sound data with this apparatus. The first method consists of recording the pulse amplitude as the acoustic path length is changed. With knowledge of V_p and the recorder chart paper speed, V can be determined directly from the measured value of λ_s. A typical recording is shown in Fig. 2. Tracking

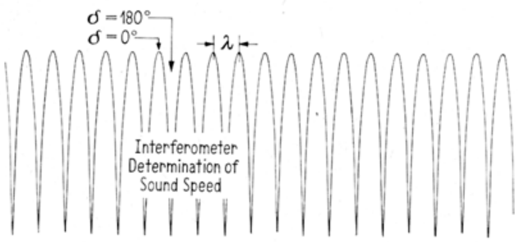

Fig. 2. Pulsed interferometer waveform (recorded with with switches V1 and A closed).

between the piston and the chart paper is maintained to within the linearity of the mechanical components since both mechanisms are driven by synchronous motors. The second and more rapid method of determining the ultrasonic velocity is to time electronically the interval between zeros of E_3. The "interval timer driver" forms the derivative of the waveform of Fig. 2 and a zero-crossing detector produces a pulse at each polarity change of $\mathrm{d}E_3/\mathrm{d}t$. Start-and-stop signals are derived from these pulses and are used to control the interval timer. The velocity of sound in the sample, V, is then determined by measuring the time, Δt, necessary for the acoustic path length to change by 100 wavelengths and using the formula

$$V = \frac{100\, V_p\, \omega_0}{2\pi\, \Delta t}. \qquad (3)$$

The line period can also be averaged over the duration of the experiment in order to determine the average motor speed accurately.

In the presence of absorption, the relative amplitudes of e_1 and e_2 do not remain constant as the acoustic path length changes and this can be compensated for by an automatic gain control circuit as illustrated in Fig. 1. For many liquids at low frequencies this will not be necessary since the start-and-stop signals arise from $dE_3/\mathrm{d}t$ instead of E_3 and, the absorption over a 100 wavelength path may be small, i. e., on the order of 10^{-3}. In order to measure the ultrasonic absorption coefficient, the reference signal e_2 is set to zero. In the absence of electronic nonlinearity, the amplitude of the pulse train E_3 is now given by eq. (4) for plane waves,

$$E_3 = A_0\, \mathrm{e}^{-\alpha x}, \qquad (4)$$

where α is the ultrasonic absorption coefficient and x is the instantaneous path length. Electronic nonlinearity is compensated for over a particular range of video pulse amplitudes by the zero offset which is injected into the logarithmic recorder. The amplitude of this DC which is necessary for accurate logarithmic recording of E_3 is determined by constructing a piecewise linear model of the overall transfer function of the receiving system up to the recorder input, selecting a suitable linear operating range, and introducing enough DC bias to shift the extrapolated operating curve to pass through the origin of the transfer function.

4. Discussion

Because of mechanical nonlinearities in the drive system, the piston velocity should be measured accurately before ultrasonic velocity measurements are be made. This is readily accomplished by measuring Δt for 100 wavelengths of sound in a liquid whose velocity is already determined; for example, water serves as a convenient reference liquid. The other factors which limit the precision and accuracy of velocity measurements are random electrical and acoustic noise, diffraction effects [5] and temperature gradients [6]. These, however, are not peculiar to this automatic technique.

The electronics system described above has also been employed with two other variations of the pulse technique, viz., the single transducer pulse-echo technique [1], and the double chamber comparison technique [7]. Also, this instrumentation can be easily adapted for use with an acoustical c. w. interferometer and with a DEBYE-SEARS light-sound interaction cell for the measurement of the acoustic properties of liquids.

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