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An improved interferometer for ultrasonic attenuation or velocity measurements

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Résumé. — Dans cet article, nous décrivons une méthode pour améliorer la sensibilité d'un interféromètre à ultrasons. Nous réalisons, pour cela, une modulation de phase (ou d'amplitude) du signal hyperfréquence. Celle-ci est détectée grâce à un amplificateur à détection de phase. Nous expliquons la manière de construire un tel interféromètre et discutons les différents facteurs qui affectent ses performances. Nous donnons enfin des résultats expérimentaux qui démontrent la capacité de ce système à détecter de très faibles variations de la vitesse de phase d'un signal ultrasonore.

Abstract. — A method for increasing the sensitivity of ultrasonic interferometers through the use of phase (or amplitude) modulation and lock-in detection of the signal is described. The operation of such a modulated interferometer is analyzed and factors affecting performance are discussed. Experimental results are given which show that the system has good sensitivity for the detection of small ultrasonic velocity changes.

Ultrasonic velocity measurements are useful for investigating a wide range of physical phenomena and, as a result, many different experimental techniques have been developed which are capable of detecting small velocity changes. These techniques have been described in various review articles [1, 2]. Particular experimental requirements and the availability of apparatus usually determine the method to be used in any specific case. We describe in this article a method which differs in several respects from previous approaches. Two important characteristics of the present method are : (1) it has good sensitivity ; and (2) it is easily incorporated into existing ultrasonic pulse-echo interferometers.

In the usual interferometers [3] an electromagnetic signal due to an ultrasonic echo from a sample is overlapped in time with a corresponding signal from a reference arm in order to create the interference. We represent the signal from the sample by

$$V_s = A_s \sin(\omega t + \varphi_s) \quad (1)$$

and that from the reference arm by

$$V_r = A_r \sin(\omega t + \varphi_r) \quad (2)$$

where A_s and A_r represent the envelopes of the echoes. These two signals are added together, amplified, and then detected.

If we assume that the output of the detector is proportional to the square of the amplitude of the input (experimentally verified for our case) then the detected signal is given by

$$S_D = G[A_s^2 + A_r^2 + 2 A_s A_r \cos(\varphi_r - \varphi_s)] \quad (3)$$

where G includes amplifier gains and the conversion efficiency of the detector.

We now define new variables $a = (A_r - A_s)/A_r$ and $\delta = (\varphi_r - \varphi_s) - \pi$ and assume that the interferometer is near balance so that $a, \delta \ll 1$. In this case the signal becomes

$$S_D \simeq G A_r^2 (a^2 + \delta^2). \quad (4)$$

Variations in the ultrasonic velocity result in variations in φ_s and hence in δ . These changes are measured by noting the value of φ_r which gives a minimum in S_D . The ultrasonic attenuation is, of course, related to a .

Boxcar detection of the output of the interferometer

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is usually used to provide a DC signal and to enhance sensitivity. Even though sensitivity is improved in this way, the δ^2 dependence of S_D means that the minimum is not sharply defined. In order to more sharply define the minimum we have added phase modulation and lock-in detection to the above interferometer. The remainder of this article will describe how this modification is achieved and discuss the performance of the system.

The components enclosed by the dashed line in figure 1 produce the phase modulation. A part of the signal from the reference arm passes through a directional coupler (10 dB in our case), through a phase shifter, an *amplitude* modulator, and then through another directional coupler (10 dB) back into the reference arm. The phase shifter is adjusted so that the signal from the auxiliary arm is added back into the reference arm at a phase of $\pi/2$ with respect to the main reference signal. Under these conditions (small signal from the auxiliary arm, $\pi/2$ phase shift) the amplitude modulation in the auxiliary arm results in phase modulation of the main reference arm as is now shown. The reference signal is given by

$$S_R = A_R \sin(\omega t + \varphi_R) + M \sin(\omega t + \varphi_R + \pi/2) \quad (5)$$

where M represents the amplitude modulation at frequency Ω and will be specified later. Eq. (5) may be written as

$$S_R = A_R [1 + (M/A_R)^2] \sin(\omega t + \gamma) \quad (6)$$

where $\gamma = \varphi_R + \tan^{-1}(M/A_R)$. Because $(M/A_R) \ll 1$ the effect on the amplitude of S_R is negligible and the result of M is a phase modulation of S_R by

$$\Delta\varphi = \tan^{-1}(M/A_R) \simeq (M/A_R).$$

The analysis proceeds as before, but it is now convenient to specify M . The modulation is supplied by a diode-switch which is biased in such a way that the transmission factor is given approximately by

$$M = \varepsilon A_R (\cos \Omega t + 1) \quad (7)$$

where $\varepsilon \ll 1$ and is determined by the directional couplers. Neglecting terms in ε^2 the detected signal is found to be

$$S_D = G A_R^2 [a^2 + \beta^2 + 2 \varepsilon \beta \cos \Omega t] \quad (8)$$

where $\beta = (\varphi_R + \varepsilon - \varphi_S) - \pi$. The reference phase is now effectively $\varphi_R + \varepsilon$ which, of course, is just as valid a reference as φ . β is a direct measure of velocity changes. We use a lock-in detector to detect the signal at the frequency Ω . The lock-in signal is simply

$$S(\pi/2)_{LI} = 2 G' A_R \varepsilon \beta \quad (9)$$

where G' includes the gain of the lock-in amplifier.

It should be pointed out that the system can be used to detect small changes in attenuation. In this case the signal from the auxiliary arm is added back into the main reference arm with zero phase shift. An analysis similar to that above show that

$$S(0)_{LI} = 2 G' A_R^2 \varepsilon a \quad (10)$$

and the output is proportional to a , the amplitude unbalance.

Figure 1 shows a diagram of the modulated interferometer. A few words about the operation may be useful at this point. (i) The $\pi/2$ phase shift condition for the auxiliary arm is easily achieved by disconnecting the signal arm and observing the lock-in signal as the phase is changed in the auxiliary arm. The lock-in amplifier is sensitive to the amplitude modulation at frequency Ω of the detected signal. With the signal arm disconnected such an amplitude modulation results only from an amplitude modulation of the reference arm signal, and not from phase modulation. The amplitude modulation at frequency Ω is zero for a phase shift of $\pi/2$ in the auxiliary arm and hence the proper setting of the auxiliary arm phase shifter corresponds to zero signal from the lock-in amplifier. (ii) The derivation of eq. (9) was based on the assumption that the system is near balance, thus both amplitude and phase are balanced by observing the output of the boxcar integrator before the lock-in is used.

In order to measure very small velocity changes, it is necessary to have good frequency stability of the oscillator because a variation in frequency will result in an output signal which appears as noise or drift. The stability requirement is relaxed if the signal travel time is approximately the same for the two arms of the interferometer. The reference arm usually contains an acoustic delay line. We assume for simplicity (although it is not necessary) that the acoustic velocity is the same in the two arms of the interferometer.

Fig. 1. — Diagram of the modulated interferometer. The phase modulation is produced by means of the components enclosed with the dashed line. These components plus the modulation supply and lock-in amplifier convert an ordinary interferometer into a modulated interferometer. The modulation supply consists of a DC bias for the diode-switch plus a sinusoidal modulation.

If it is desired to measure the phase shift with a resolution Δl (phase shift of the electromagnetic wave expressed in length) then it is easily shown that the frequency stability which is required is

$$\frac{\Delta f}{f} = \frac{\Delta v}{Lc} \quad (11)$$

where v is the acoustic velocity, c is the electromagnetic wave velocity, and L is the difference in acoustic path lengths of the two arms. If the difference in the electromagnetic parts of the two paths is large, then L should be interpreted as the difference in equivalent acoustic path lengths.

The apparatus can be used in two ways. In the first way, the phase modulation and lock-in detection are used simply to detect the minimum in the interference pattern. Eq. (9) shows that this minimum corresponds to zero output from the lock-in detector. Thus, the phase in the reference arm is adjusted and the value which causes the lock-in signal to pass through zero is recorded. This procedure results in a significant ($\sim 10 \times$) increase in sensitivity as compared to the determination of the minimum by observing the direct output of the boxcar integrator. In practice, the main limitation with this method is the resolution of the phase shifter.

The second way in which to use the apparatus is to record the lock-in output as the velocity, and hence β , changes. Eq. (9) shows that the output is expected to be linear in β . Of course this is true only for a narrow range around zero because, (i) higher order terms have been neglected, and (ii) no allowance has been made for the fact that, as balance is destroyed, the rf amplifiers approach saturation and have less gain than at low level. In practice, it is best to take a calibration curve just prior to, or just after, taking the data. The output of the lock-in is recorded for various reference arm phase settings around zero. A typical calibration curve is shown in figure 2. The range of linearity and the slope of the curve depend on the level of the rf signal and the particular amplifiers used. This method overcomes, to a limited extent, the problem of resolution of the phase shifter as it is possible to interpolate between calibration points. In using this method it is necessary to exercise some caution with regard to the attenuation, because a change in attenuation will unbalance the system and may change the calibration curve. This problem does not arise when the system is used for zero detection.

As eq. (9) shows, sensitivity is increased by operating with a high value for A_R (and hence A_S). This increased sensitivity occurs at the expense of a reduced range, however, and in practice it is necessary to use a signal level which gives a reasonable compromise between high sensitivity and wide range. Figure 2 gives an idea of the sensitivity and range for our system.

As indicated above, the measurements are made in terms of the phase shift l of the electromagnetic wave.

Fig. 2. — Output of the lock-in amplifier vs. phase shift of the reference signal. The dots represent the measurements and the solid line drawn through the dots is used as a calibration curve.

A relative variation of the acoustic velocity ($\Delta v/v$) results in a phase shift given by

$$l = \frac{c}{v} d \frac{\Delta v}{v} \quad (12)$$

where d is the sample thickness. A thin sample, a small velocity shift or a combination of the two may result in l being small.

We have used this system [4] to measure the temperature dependent velocity of 1 GHz acoustic waves which were propagated through a sample of β -alumina perpendicularly to the c -axis. The objective of the experiments was to study the logarithmic variation of the velocity in the 0.1-5 K temperature range. The total expected variation of ($\Delta v/v$) was less than 2×10^{-4} . In addition, the samples available to us had a thickness of only 1 mm (compared to 1 cm for usual ultrasonic measurements). As a result the total expected phase variation was 6 mm. In order to test the logarithmic temperature law we needed a sensitivity of approximately one twentieth of the full variation (i.e. 0.3 mm). Commercial delay lines do not have this sensitivity (we used a Wiltron 3114 delay line with a 1 mm resolution). With our new system we had a sensitivity of 0.2 mm with a reasonable range as shown in figure 2.

The stability requirements for the reference arm give another indication of the sensitivity of the system.

The acoustic delay line was a 12 mm quartz rod used in reflection. The relative velocity variation for quartz near room temperature is about $10^{-5}/^{\circ}\text{C}$ leading, using eq. (12), to a phase shift of $2.6 \text{ cm}/^{\circ}\text{C}$. In order to obtain the sensitivity indicated by figure 2 it would be necessary to control the temperature of the quartz rod to better than $10^{-2} ^{\circ}\text{C}$. Rather than control the temperature to this accuracy we immersed the quartz rod in liquid helium where : (i) the temperature was

very stable, and (ii) the temperature dependence of the velocity is very weak. With this precaution the calibration curve of figure 2 was stable over a period of one hour as we checked by recording it before and after taking data.

As shown here and in ref. [4] the system has good sensitivity. The technique is easily added to existing interferometers to improve the sensitivity of those systems.

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