INVESTIGATIONS OF EXTENSIONAL AND TORSIONAL ACOUSTIC WAVE THIN ROD SENSORS

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INTRODUCTION

Modern instrumentation systems require a transducer to convert the physical property of interest into a form which is ultimately usable to the scientist. In that sense, an increasing interest in the development of integrated acoustic sensors has been demonstrated in recent decades. Most of them use either bulk (BAW) [1], surface (SAW) [2], plate (or Lamb) [3], or thin rod [4] acoustic waves.

It has been shown recently that the thin rod is a good gravimetric sensor candidate [5,6]. In addition, this type of technology can also be applied to sense a large number of physical measurands such as temperature, strain, acceleration, etc.

In a thin rod there exist longitudinal, torsional, and flexural acoustic modes. Since an acoustic sensing device normally operates in a single mode regime, we are only interested in the lowest branch order of these modes namely L_{01}, T_{00}, and F_{11} [6]. Since the flexural (F_{11}) mode has already been extensively reported [4,5], this paper will focus on longitudinal (extensional) and torsional modes.

The T_{00} mode has the advantage of being non-dispersive (fig.1). This particularity permits an easier device design since phase and group velocities do not change with frequency. Furthermore, in that mode, particle motion is always parallel to the fiber surface. This means that such a sensor can be immersed in any ideal inviscid liquid without any loss of energy. However, in a rod as thin as 20 μm, a torsional wave cannot be generated easily.

The L_{01} mode has similar characteristics in the low frequency part of its dispersion curve (fig.2). In that range, the phase velocity of an extensional wave is effectively almost constant and the particle motion is almost exclusively axial (parallel to the fiber surface).
Fig. 1 Torsional wave phase velocity as a function of frequency-radius product (Vs: Shear Wave velocity of the fiber material).

Fig. 2 Longitudinal wave phase velocity as a function of frequency-radius product (Vext: Extensional Wave velocity, Vs: Shear Wave velocity, Poisson's Ratio: 0.3).

In this paper, we describe several methods to excite these modes in thin rods and we present preliminary temperature sensing measurements on such devices. We also report fabrication of a miniature thin rod delay line and an oscillator based on it whose stability is as high as 1 part in 10 million.

MAGNETOSTRIVE EXCITATION OF ACOUSTIC WAVES

A thin magnetostrictive rod passing through coaxial RF coils have been used to excite and receive acoustic waves. Figure 3 shows a schematic diagram of the set-up used.

The transmission medium is a 127 μm diameter nickel fiber immersed in a temperature controllable (± 0.5°C) water bath with effective length of 179 mm. Two coils are used to excite and receive acoustic waves along the fiber. A NEWPORT M-420-1 precision translation stage (± 0.5 μm) is used to move the receiver along the fiber. The tone-burst source is a MATEC 755 and the monitor is a TEKTRONIX 7603 with a 7D20 digitizer plug-in.

Under suitable conditions, either torsional or extensional waves can be generated in this system according to the so called Joule and Wiedemann effects [7].
Extensional waves were successfully excited and received in the previously described set-up. Maximum transduction efficiency was obtained around a center frequency of about 2.8 MHz. An input 20 ampere pulse generated a 20 millivolt pulse at the receiver coil (1 MΩ load impedance) corresponding to an insertion loss of -180 dB. It is not practical to make a real device with such a high insertion loss transducer, but it is a convenient system to use for laboratory measurements.

By moving the receiver along the axis of the thin rod while continuously monitoring the received signal, we measured a phase velocity of 4920 m/s. This agrees well with the theoretical value of 4850 m/s found for a Ni fiber in vacuum.

The same set-up has been used to generate torsional waves of group velocity around 2900 m/s. The pulse transmission of this torsional wave is shown in figure 4 where we observe a maximum transduction efficiency around a center frequency of 2.7 MHz. An input 1.5 ampere pulse result in a 24 millivolt pulse at the receiver coil corresponding to an insertion loss of -156 dB.

TEMPERATURE SENSITIVITY

The temperature dependence of the phase velocity of both extensional and torsional waves has been measured using the temperature controlled water bath. In both cases, water loading reduced the output pulse amplitude by 3 to 6 dB.

Figure 5 shows the shift in the extensional wave phase delay recorded when the water temperature was raised from 26 to 61°C. The variation is linear with a slope of 5.68 ns/°C.

In order to evaluate this sensing performance and to compare it to other types of acoustical sensors, we define the relative temperature sensitivity of the phase as:

\[
S_T = \frac{1}{t_d} \cdot \frac{\Delta t_d}{\Delta T} = \frac{V_p}{l_{eff}} \cdot \frac{\Delta t_d}{\Delta T}
\]

in which \(t_d\) is the phase delay, \(T\) is the temperature, \(V_p\) is the wave phase velocity, and \(l_{eff}\) is the effective length of the fiber's active area (length of the water bath). By this definition, \(S_T\) represents the fractional change in the phase delay time due to unit change in temperature. Hence, the experimental results obtained for an extensional wave in the Ni fiber correspond to a relative sensitivity of 156 ppm/°C.

![Fig.4 Pulse transmission of a torsional wave in a Ni fiber (Horz. scale: 20 μs/div., CH1 scale: 0.5 A/div, CH2 scale: 5 mV/div).](image)
In the same way we found an even larger temperature dependence for torsional waves (fig.5). In fact, a fairly linear variation with a slope of 11 ns/°C has been observed in the 26 to 80°C range. Using the theoretical value of \( V_p = 3000 \text{ m/s} \) for the \( T_{00} \) mode, this leads to a relative sensitivity of 184 ppm/°C.

**MINIATURE DEVICE**

A more practical approach has been investigated to fabricate a miniature, low insertion loss thin rod device. Two 5 MHz compressional mode LiNbO\(_3\) transducers were used to generate and receive extensional waves in a thin gold fiber as shown in figure 6. Different coupling mechanisms have been tried to improve the transmission of energy between the LiNbO\(_3\) transducers and the gold fiber. One of the best results obtained with such a structure exhibits an insertion loss lower than 36 dB. In that device, the coupling mechanism was a sort of celluloid cone sticking the gold fiber to the lithium niobate transducers.

Figure 7 shows the frequency response of the above device. According to the graph, it can be seen that the lowest insertion loss occurs at a frequency of 5.05 MHz and that the 3 dB bandwidth of that response peak is less than 8 kHz.
Pulse transmission measurements gave a pulse delay of about 16 μsec corresponding to a group velocity around 2000 m/sec. This agrees well with the value of an extensional wave in bulk gold and also confirms the extensional nature of the mode.

This delay line has been used as the phase control element in the feedback loop of an amplifier (fig.8). The resulting oscillator frequency is determined by the minimum insertion loss in the frequency response and the phase shift introduced by the delay line which permits a total loop phase shift of 2π.

The dimensionless stability of this oscillator can be described using the definition given by J.A. Barnes et al [8].

\[
\sigma = \frac{\langle (\xi_{k+1} - \xi_{k})^2 \rangle^{1/2}}{\sqrt{2} \langle \xi_{k} \rangle}
\]

in which \( f \) is the average frequency during one measurement cycle of the frequency counter and \( \langle \xi \rangle \) denotes average over a large number of cycles (ideally, an infinite number of cycles).

For over 2000 cycles of 1 second duration, we obtained a stability of \( \sigma_{1 \text{ sec}} = 8.6 \times 10^{-8} \). This corresponds closely to an observed 0.55 Hz/sec long term drift of unknown origin.

Temperature tests have also been done on a similar device where the coupling mechanism was an aluminium cone stuck to the transducer surface using celluloid. The gold fiber was then bonded to the tips of the cones with ordinary glue. The temperature test was done with the aid of an Associated SW-5101 oven-refrigerator. It reveals a relative sensitivity of 201 ppm/°C.

CONCLUSION

We have proved that the acoustic fiber, as a sensing element, is a good candidate to be incorporated in some miniature physical sensors. Effectively, acoustic fiber oscillators can provide good stability at relatively low operating frequencies. Furthermore, almost
any material can be used to make a fiber. In that sense, the highest achievable sensitivity can be reached with an appropriate choice of the fiber material.

This work has demonstrated that basic technological problems related to the realization of an acoustic fiber sensor have been solved. Of course, the technology involved here is not yet mature, but it is promising. Already, the temperature behaviour of acoustic fibers has been investigated. This lays the groundwork for future work on chemical sensors which will use chemically selective layers deposited on the fiber surface or even fibers directly made from this chemically selective material. In fact, acoustical fibers should lead to a low cost, high performance family of acoustical sensors.

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REFERENCES


