# Detection of fluid velocity and hydroacoustic particle velocity using a temperature autostabilized nonlinear dielectric element (TANDEL)

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A ferroelectric sensor operated in the temperature autostabilized mode was developed for the measurement of the particle motion in hydroacoustic fields. The sensor is a capacitorlike element constructed from antimony sulfur iodide (SbSI) single crystals and SbSI-polymer composites. The device is operated slightly above the Curie point of SbSI, which is approximately 20 °C. Using a Schering bridge, the element is heated by driving it through the hysteresis cycle. The heat transferred to the surrounding fluid is related to the motion of the fluid. The technique was applied to the measurement of a constant velocity flow field and to a low-frequency acoustic field. In the case of the constant velocity flow field, an exponential relationship between fluid velocity and sensor voltage was observed. For acoustic fields, the response of the sensor decreased sharply with frequency above 100 Hz. The acoustic particle velocity could be measured to a frequency around 1 kHz.

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## INTRODUCTION

Techniques for measuring fluid motion differ according to whether the acoustic field is hydrodynamic, a steady-state hydroacoustic field, or a turbulent field. Most hydroacoustic detectors measure variations in acoustic pressure. The acoustic particle velocity may be calculated from pressure measurements by spatial differentiation; in more complicated fields, measurements of both magnitude and phase of the pressure fluctuations at many points in the acoustic field are necessary. Direct measurement of acoustic particle velocity has been accomplished by hot-film anemometry (HFA)[1,2] and pressure-gradient measurement.[3] Hot-film anemometry[4] was originally developed for measuring steady or turbulent flow in fluids, but has recently been adapted for hydroacoustic measurements. The hot-film or hot-wire anemometer detects fluid velocity by determining the amount of heat transferred by a resistance-heated wire or film to the ambient medium. This quantity is related in a rather complicated fashion to the physical properties of the fluid, the type of fluid motion present, and the temperature difference between the wire and ambient fluid.

A device capable of measuring fluid motion using the same principle as HFA may also be constructed from a temperature autostabilized nonlinear dielectric element (TANDEL) constructed from a ferroelectric material.[5] This device can stabilize its own temperature within a narrow range slightly below the Curie temperature. The TANDEL has numerous electronic applications, as outlined by Glanc and others.[5–9] In most of the early articles, single crystals of triglycine sulfate (TGS) were used to construct the nonlinear device. Other ferroelectric materials, including $BaTiO_3$, potassium dihydrogen phosphate (KDP), and SbSI, have also been used.[10] The principle of automatically stabilizing the temperature of the ferroelectric crystal is discussed by Dvořák *et al.*[7] Essentially, ferroelectrics show sharp peaks in both the real and imaginary parts of the dielectric permittivity near the Curie temperature. Heat produced by the dielectric loss maintains the temperature of the crystal slightly above the transition temperature, provided the crystal temperature is kept somewhat above the ambient temperature. Simultaneously, the strongly varying real part of the dielectric permittivity may be used to detect small changes in the temperature of the TANDEL. The amount of heat transferred from the crystal to the fluid is sensitive to the motion of the fluid, and may be quantitatively measured by the change it produces in the capacitance of the TANDEL. This device has been previously adapted to measure gas flow, and was shown to have several times the sensitivity of an anemometer based on a bead thermistor.[5] Theoretically, the relative change in dielectric constant of a ferroelectric material near its Curie temperature is much larger than the relative change in resistance of a thin metallic wire when both are produced by the same small temperature fluctuation. The dielectric constant often varies several orders of magnitude within a few degrees of the ferroelectric phase transition. In this article, a nonlinear element constructed from SbSI is used to demonstrate measurements of both fluid flow and acoustic particle velocity in a liquid.

## I. EXPERIMENTAL PROCEDURE

### A. Characterization of SbSI as a hydroacoustic velocity sensor using the TANDEL effect

The TANDEL effect was demonstrated in SbSI by Mali and Levstik.[11] This material seems to be an appropriate choice for designing a fluid velocity sensor since its Curie temperature is approximately 20 °C, which is near room

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temperature. The greatest sensitivity of the dielectric constant to temperature changes occurs at this point, and the automatic stabilization should be fairly easy to achieve. Furthermore, this material is readily available.

The temperature dependence of the dielectric constant of this starting material was measured in order to establish the ferroelectric transition temperature precisely and to determine the temperature coefficient of capacitance, which is directly related to the sensitivity of the device, for any given temperature within the transition region. Bhalla *et al.*[12] had previously measured the dielectric and piezoelectric properties of similar SbSI single crystals as a function of temperature. Figure 1 shows the dielectric constant for one of the SbSI samples used in this study as a function of temperature. The curve has a fairly broad maximum centered at approximately 20 °C. The autostabilization region is located on the high side of the transition. The temperature at which the crystal will stabilize depends on a number of factors, including the level of current being driven through the crystal, the frequency of the drive signal, the ambient temperature, and the real and imaginary parts of the dielectric permittivity.

### B. Construction and operation of a flow sensor

Several velocity sensors were constructed from SbSI crystals embedded in epoxy encapsulant. The composite was approximately $3\times1\times0.5\ mm^3$ in dimension. The SbSI crystals have a fibrous morphology. Electrical leads were attached with a conductive epoxy and mounted into a hot-film probe. The capacitance of the probes was typically 8 pF with a dissipation factor of approximately 0.1 at 1 kHz. The probe was used in one arm of a bridge circuit as shown in Fig. 2. The variable capacitor and resistor are adjusted to balance the bridge at the operating frequency between 5 and 15 kHz. The voltage applied to the bridge was varied between 10 and 50 V, according to the crystal thickness. This corresponded to an applied electric field of approximately 1000 V/m. The bridge was then balanced using the variable capacitance and decade resistor. When the sensor was placed in a moving fluid, the bridge became unbalanced and current would flow

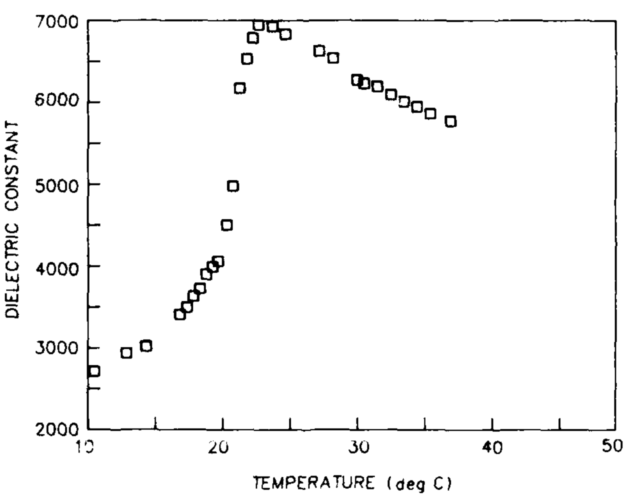


FIG. 1. Temperature dependence of the dielectric constant of composite of SbSI and epoxy.

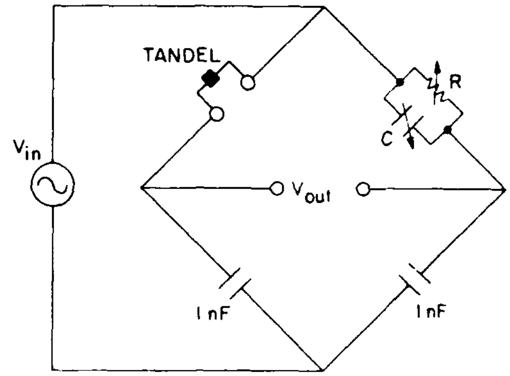


FIG. 2. Schematic of bridge circuit used in flow velocity and acoustic particle velocity sensors.

through the measuring resistor, thus producing a constant ac voltage that was related to the fluid velocity. Since SbSI was fairly conductive at low frequency, the voltage at which the polarization saturates was difficult to discern on the observed hysteresis loop. However, the heat produced was calculated to be approximately 50 mW for the known magnitude of the electric field.

In order to test the flow sensor, a constant-speed, liquid-filled rotating cylinder was constructed to provide a known flow with constant angular velocity. The sensitivity of the sensor can be calibrated at different fluid velocities by varying its distance from the center of the drum. Since the surfaces of the crystal and lead wires were exposed, a dielectric fluid had to be used to avoid shortcircuiting the crystal. Fluorinert FC-43 (manufactured by the 3M Corporation) was chosen as the fluid because its acoustic properties are not radically different from those of water. When the sensor was placed in the fluid, some time was allowed for equilibration. The output of the bridge circuit was amplified using a Princeton Applied Research model 113 preamplifier and measured by a digital voltmeter (Hewlett–Packard model 3438A) as a function of the fluid velocity (Fig. 3). The lines drawn through the data points were fitted by eye and serve to separate the two sets of measurements. The curves have exponential shapes reaching fairly constant values at high ve-

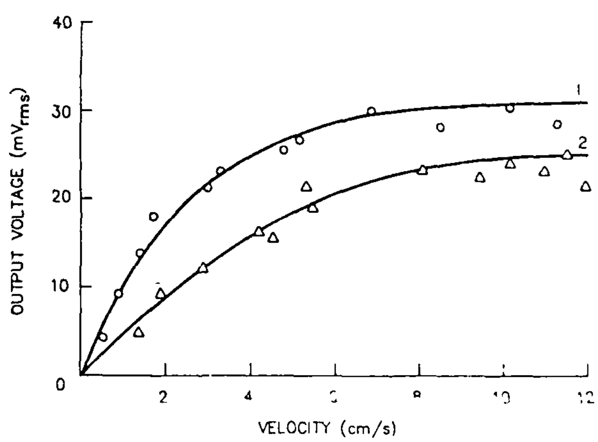


FIG. 3. Voltage output of sensor circuit as a function of fluid velocity for steady flow conditions. (Curve 1: sensor axis perpendicular to flow direction; curve 2: sensor axis parallel to flow direction.)

locities. The upper curve (labeled 1) represents the output of the bridge circuit when the long axis of the sensor is placed perpendicular to the fluid velocity. The lower curve (labeled 2) represents the output of the bridge circuit when the fluid velocity is parallel to the long axis of the sensor. At low velocity, the sensor is very sensitive, as indicated by the steep slope. The curve is similar in form to that measured by Glanc[5] for an airflow sensor using TGS and to hydrodynamic measurements reported by Blackwelder using hot-wire anemometry.[4] The sensitivity of the device is directional and is higher when the flow is perpendicular to the major sensor axis. This demonstrates the potential of the device for making measurements of the flow velocity.

### C. Application of the TANDEL as an acoustic particle velocity detector

In detection of acoustic particle velocities, the time required for a sensor to respond to acoustic signals is generally short. The large crystal used in the measurement of steady flow was found to be insensitive to time-varying fields. A smaller sensor made from several thin filaments of SbSI was constructed. The elements were on the order of 100 $\mu$m thick, 1–2 mm long, and 0.5 mm wide. They were mounted to wire leads as before. The capacitance of the sensor was about 3–5 pF.

A Naval Research Laboratory-Underwater Sound Reference Detachment (NRL-USRD)-type G19 calibrator, which consists of a small projector mounted in the bottom of an aluminum tube, was filled with Fluorinert FC-43 and used to test the TANDEL detector. The G19 calibrator is useful over the frequency range 50–2000 Hz, but the transmitting voltage response varies considerably over this range. The pressure at various depths within the calibrator was measured using an NRL-USRD-type F61 standard hydrophone. The particle velocity at each depth was then calculated by using Euler's equation

$$\frac{\partial u(z)}{\partial t} = \frac{-\partial p(z)}{\rho_0 \partial z}, \qquad (1)$$

where $p(z)$ is the pressure at depth $z$ and $\rho_0$ is the density of the fluid. The pressure gradient with respect to $z$ is practically constant in the G19 calibrator at low frequency. Consequently, the acoustic particle velocity should be independent of the depth of the sensor if it is far enough from the piston driving the fluid. The block diagram of the system used to measure the acoustic particle velocity is shown in Fig. 4. For a steady-state signal of angular frequency $\omega$, Eq. (1) may be written as

$$u(z) = \frac{\partial p}{\partial z} \Big/ \rho_0 \omega. \qquad (2)$$

The transducer in the G19 calibrator was driven by an Optimation model PA250M amplifier with a sinusoidal signal produced by a Hewlett–Packard model 3300A function generator. The output of the TANDEL, which is at the frequency of the bridge oscillator, is modulated by the acoustic signal. A Brookdeal model 9412A phase sensitive detector was used to demodulate the amplified signal, and the magnitude of the demodulated signal was measured using a Princeton Applied Research model 5204 lock-in analyzer.

The response of the TANDEL sensor to acoustic signals was recorded as a function of frequency. The fluid was cooled to a temperature of 15 °C using copper tubing through which cold water was passed. This provides a larger difference between the temperature of the sensor and of the ambient fluid, thereby improving the heat transfer between them. Alternatively, this could be accomplished by using a ferroelectric material with a higher Curie temperature.

The nature of the sensor can be described by the ratio of its output voltage to the Reynolds number

$$r(f) = V_{out}/\text{Re}, \qquad (3)$$

where $V_{out}$ is the ac output voltage of the bridge circuit and the Reynolds number is the dimensionless quantity

$$\text{Re} = ud/\nu, \qquad (4)$$

where $u$ is particle velocity, $d$ is the thickness of the sensor, and $\nu$ is the kinematic viscosity of the fluid. A frequency-independent value of $r(f)$ indicates that the output voltage of the sensor is proportional to particle velocity rather than

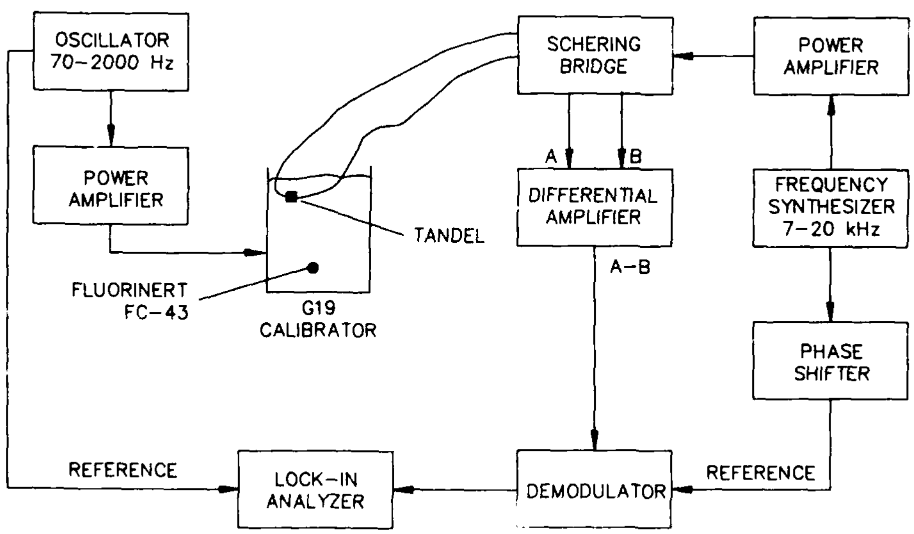


FIG. 4. Block diagram of system used to measure acoustic particle velocity.

to acceleration or particle displacement. The function described in Eq. (3) is constant with frequency up to approximately 200 Hz, but decreases as the frequency of the acoustic wave is increased further (Fig. 5). For fine hot-film anemometry sensors, Dubbelday[1,2] found that output voltage is proportional to acoustic particle displacement, rather than particle velocity, over the measurable range of frequency. Hot-film anemometry using larger sensing elements demonstrated a more complicated dependence of the sensor output voltage with respect to particle velocity, but the relationship between them appears to be linear for low frequencies.[13] To check for possible piezoelectric contributions to the output signal, the depth of the sensor was varied. For frequencies less than 500 Hz, the output from the TANDEL sensor did not vary with depth. This indicates that the output signal is indeed related to the particle velocity, rather than to the acoustic pressure. At frequencies above 2 kHz, the output of the TANDEL sensor was found to vary with depth, which might indicate that above 2 kHz the signal is generated by the direct piezoelectric effect and is, therefore, associated with the pressure variation rather than the particle velocity of the acoustic wave.

## II. DISCUSSION

The TANDEL sensor appears to be a possible alternative—both as a fluid velocity sensor and as an acoustic particle velocity detector—to other available methods. The design of the sensor is considerably more intricate when it is used as an acoustic particle velocity detector, because it is necessary to have a fast thermal response while maintaining adequate capacitance. The TANDEL sensor is quite sensitive to steady flows, particularly for low flow velocities. In this case, the size of the element is not so crucial, and a fairly large sensor with high capacitance may be used. For measuring acoustic particle velocity, the TANDEL sensor must be made rather small in volume for reasons mentioned previously. The large dielectric constant of SbSI is advantageous in maintaining a measurable capacitance and raising the signal-to-noise ratio of the device. However, the morphology of the crystal limits the available electrode area, thereby reducing the obtainable crystal capacitance. Use of a film capacitor would seem to be a logical alternative, but a sharp ferroelectric transition region is normally difficult to obtain in thin-film SbSI due to small compositional fluctuations in the material. Other ferroelectric materials have been fabricated into thin films, and may provide usable alternatives if their transition temperatures are in the desired range and the sharpness of their dielectric peak is maintained throughout the material. It is difficult to compare the performance of the TANDEL sensor to ordinary HFA sensors because of the complexity and variety of HFA sensors available. There is, of course, much room for improvement in the actual design of the TANDEL sensor and in the electronics and signal-processing instrumentation used in conjuction with it. At present, the inherent sensitivity of the TANDEL has not been fully utilized due to the design limitations. Characteristics of the sensor, such as the dielectric properties of the ferroelectric material, sample dimensions, and design of the electrodes and leads on the crystal, need to be optimized before the true capability of the TANDEL sensor can be fully evaluated. However, the possibility of using a TANDEL for measuring hydrodynamic and acoustic velocities has been demonstrated.

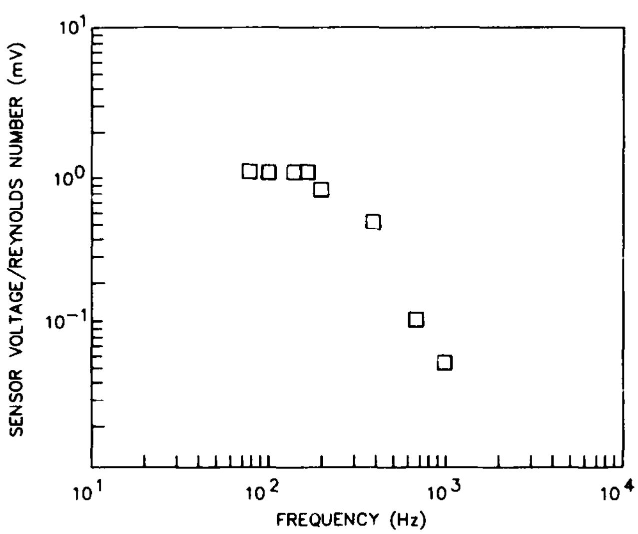


FIG. 5. Frequency dependence of the function $r(f)$, defined as the sensor output voltage divided by the acoustic Reynolds number, for the TANDEL sensor.


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