Design of a Broadband Semi-Conical PVDF Ultrasonic Sensor For Obstacle Detection Applications

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Abstract

Most of the commercially available air ultrasonic transducers are ceramic based and operate at 40 kHz. This paper describes a method to design and build ultrasonic transducers using low-cost piezoelectric Polyvinylidene Fluoride (PVDF) film. The transducer has a semi-conical geometry, which provides a higher bandwidth, low ringing time compared to traditional ceramic ultrasonic transducers. We have built a prototype sensor and compared its typical characteristics with a commercially available ceramic transducer. In experiments, pulse compression technique used to detect reflected ultrasonic waves with a high SNR. We found it to be practical for applications requiring short-range obstacle detection and distance measurement.

1. Introduction

Low-cost, short-range distance measurement sensors have a variety of commercial applications including toys, liquid level and liquid-dispensing sensors, seat-occupancy detectors, human-body detectors for medical equipment, object-detection for automated mass production [1]. These sensors are used to reveal the presence of objects and to measure their distance from the end-effector. This is achieved by measurements of the time-of-flight (ToF), i.e., the time interval between the emission of an acoustic signal and the reception of its echo. In these applications, transducer efficiency, bandwidth, and the lateral resolution are the key parameters. A sensor is usually characterized by two major properties: sensitivity and resolution. The sensitivity is related to the electromechanical coupling coefficient whereas the resolution is related to the center frequency and bandwidth. At the beginning of the ultrasonic imaging industry lead zirconate titanate (PZT) was the common piezoelectric material. Most of commercially available air ultrasonic transducers are ceramic (i.e. PZT) based and operate at 40 kHz. Their electromechanical coupling coefficient is very high, resulting a sensor with high sensitivity. However, PZT has an high acoustic impedance, making it very difficult to be used to send ultrasonic energy into the air, which has very low acoustic impedance. In addition, the Q value of PZT is very high so that the bandwidth is narrow resulting in poor resolution due to ringing effects.

On the other hand, polyvinylidene fluoride (PVDF) is a ferroelectric polymer with unique properties making it suitable to be used in a wide range of medical and biological imaging applications. PVDF also has a very good acoustic impedance match with air and can be used in air ultrasound.

In the following sections, first, theoretical approach will be made and the design of a semi-conical ultrasonic transducer using piezoelectric PVDF film will be described. Then, with experimental results on an obstacle detection system, transducer's resonance frequency, bandwidth, pulse response, ringing time, sensitivity and axial-resolution will be compared with a commercially available high sensitive 40 kHz ultrasonic sensor.

2. PVDF Sensor Design

The principle is that piezoelectric displacement is in the direction of molecular orientation which is parallel to the film plane and the length mode displacement is converted to the film normal direction by the clamped curved structure because motion is only allowed in the direction normal to the plane (Fig. 1).

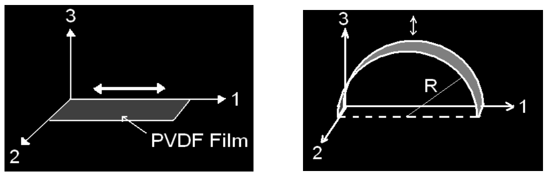

Fig. 1. Converting length mode displacement to normal direction of a PVDF Film

This principle was discovered by Japan scientists in early 1970s [1]. This structure was used for acoustic transducers such as speakers, headphones, microphones, hydrophones or ultrasound generators and receivers. Additinoal theoretical work was also done by several researchers [1-8]. M. Tamura et al. [1], dealt with static analysis. H. Naono [2] and A. S. Fiorillo [4] analyzed the resonance modes, assuming uniform vibration displacement and neglecting the effects of clamps. This resonance frequency is;

$$f_o = \frac{1}{2\pi R}\sqrt{\frac{Y}{\rho}} \quad (1)$$

where R denotes the curvature radius of PVDF film, Y is Young's Modulus, and ρ is the density. Refering to this theory, our ultrasonic transducer is designed using a PVDF film. Piezoelectric films are available in a variety of different sizes and thicknesses in the market and suitable for custom sensor design. In this work, a metallized PVDF film in 28 μm thickness is used [9]. In our early design tests, a sensor set was realized by curving, shown in Fig. 1, a film strip of uni-axially stretched PVDF in different lengths. Our early experimental results show that, with this semi-circular geometry, it is not possible to get a low Q and a broadband transducer. By these results,, we considered that the PVDF sensor should ensure a geometrical shape which includes all of the R values of the corresponding resonance frequencies in the desired band. This geometry matches with a semi-conical shape. To ensure the geometry, PVDF film was cut into one-quarter of the circle with a radius of 35 mm. Then, the film was curved and mounted on a PCB, such that the projection of the film has a shape of an equilateral triangle (Fig. 2). Since PVDF film loses its piezoelectric property above the 70°C and thus soldering is not possible, clamps were used to connect electrical wires to the PVDF film.

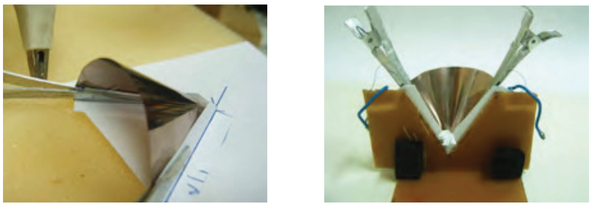

Fig. 2. Designed semi-conical PVDF sensor

3. Object Detection System

To compare the designed PVDF sensor with a ceramic sensor, an obstacle detection system is designed (Fig. 3). Basically, the system detects the obstacles in front of the sensor under test and measures the distances between the obstacles and the sensor.

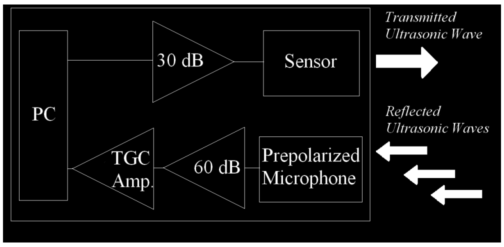

Fig. 3. Obstacle detection system

The PC generates a pulse signal and this signal is amplified via an audio amplifier (ST Microelectronics, TDA2040). Ultrasonic sensor (ceramic or PVDF) stimulated with this signal transmits an ultrasonic wave. Because of the impedance mismatch between the air and obstacles, travelling ultrasonic waves reflect and return back after a time period. This period is defined as Time-of-Flight (ToF). …-inch Pre-polarized free-field microphone (G.R.A.S. 40BE) receives the reflected ultrasonic waves and converts them to the electrical signals. Electrical signal is amplified via an operational amplifier (Analog Devices, AD843) and a discretely designed Time-Gain compensated amplifier. After signal processing, PC detects the obstacles and calculates their distances from the sensor.

3.1. Time-Gain Compensated Amplifier

Since the air absorbs the ultrasonic waves, they attenuate as well as they travel long ranges [10]. Obstacles far away from sensor or ultrasonic waves which have a long ToF cannot be detected because of the low SNR. Thus, high gain amplifiers must be used. If amplifier has a constant high gain, level of reflected waves from the nearest objects may be a high enough to saturate the amplifier. To increase SNR without saturating the amplifier, time-gain compensated amplifier must be used.

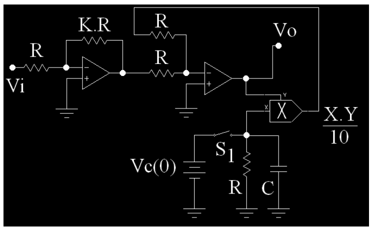

Fig. 4. Time-Gain compensated amplifier

To maintain a non-linear, time dependent gain, a divider that consists of an operational amplifier (Texas Ins., TL081) and a multiplier (Analog Devices, AD633) is designed (Fig. 4). When S_1 is switched off, voltage of the RC circuit with an initial Vc(0) is exponentially decreased. Since the circuit is a voltage divider, V_o increases with the following equation;

$$K(t) = \frac{Vo}{Vi} = \frac{10.K}{V_c(0)}.e^{\frac{t}{RC}} = K_O.e^{\frac{t}{RC}} \tag{2}$$

4. Experiments

In experiments, typical characteristics of the semi-conical PVDF sensor compared with a commercially available high performance 40 kHz MaxSonar [11] ceramic ultrasonic sensor by using the setup shown in Fig. 5. Generating, recording and processing of the signals were made using a laptop PC with a soundcard and MATLAB software.

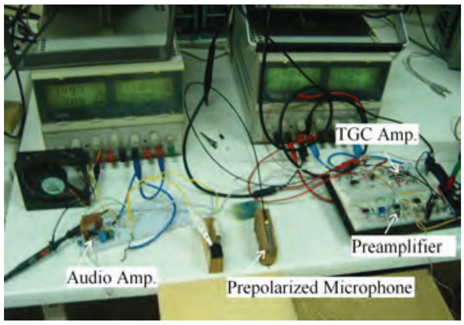

Fig. 5. Experimental setup

First, bandwidth of the PVDF and ceramic sensor were tested. A uniform noise with a 50 kHz bandwidth and a time duration of 10 seconds were generated and the sensors were simulated with this signal. The acoustic signal, generated from the sensors, was detected via calibrated microphone and recorded to the PC. To determine of the sensor bandwidths, Fast Fourier Transform of the recorded signals were used (Fig. 6).

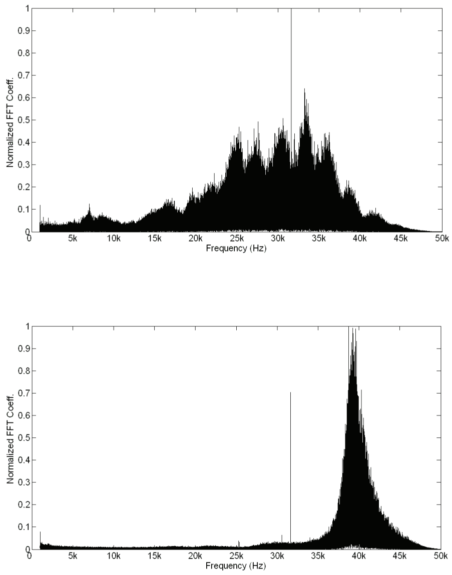

Fig. 6. Normalized FFT plots of noise recordings: PVDF sensor (top), ceramic sensor (bottom)

It can be seen from analysis that PVDF sensor has multiple resonance frequencies. Since we suppose a flat response from 24 kHz to 36 KHz, bandwidth of the PVDF sensor is 12 kHz. Ceramic sensor has a unique resonance frequency at 40 kHz and 4 kHz bandwidth.

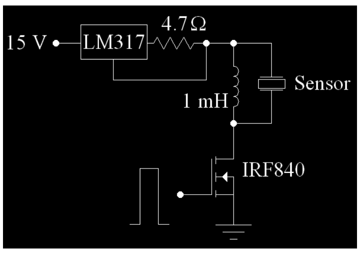

Fig. 7. Pulse response test circuit

To compare pulse response of the sensors, a test circuit shown in Fig. 7 was designed. 250 mA DC current source was realized using LM317T. N-Channel MOSFET was gated with a 0-10 V 0.3 Hz square wave. Since MOSFET turns on, DC current flows through the inductor. When gating voltage drops below the threshold voltage, current suddenly cuts off. This sudden change in current generates a high voltage pulse across the inductor terminals. Since sensor is parallel with inductor, this pulse vibrates the sensor. The acoustic signals , generated by sensors were detected with an away microphone from a distance which is 44 cm for ceramic sensor, and 12.5 cm for PVDF sensor (Fig. 8).

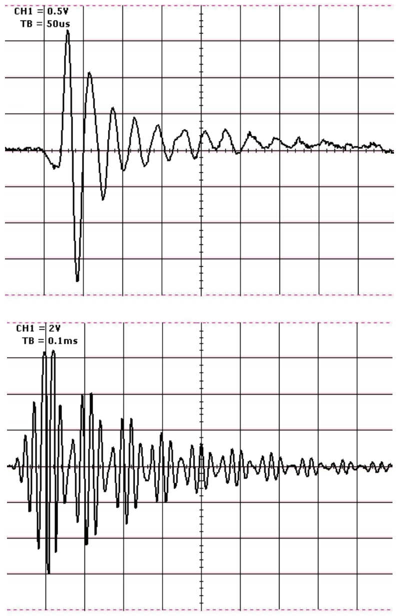

Fig. 8. Pulse response of PVDF (top) and ceramic sensor (bottom)

Despite ceramic sensor is farther away from microphone compared to PVDF sensor, it generates a higher voltage. But PVDF sensor has a shorter ringing time.

To compare resolution performance of the sensors, an experimental setup shown in Fig. 9 was built. Three peaces of PCB plates with sizes of 50 mm x 120 mm were placed 360 mm away from the sensor and the distance between them was 43 mm. Microphone was placed 75 mm away from sensor.

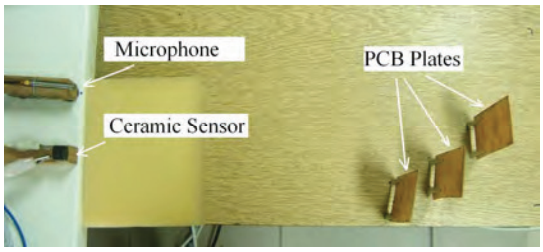

Fig. 9. Experimental setup for obstacle detection

Sensors were stimulated with a sinusoidal linear down-chirp signal which sweeps 37 kHz to 27 kHz for PVDF sensor and 42 kHz to 38 kHz for ceramic sensor since the bandwidths of sensors are not equal. Duration of the chirp signal was 0.5 ms. Output voltage of microphone amplifier was recorded with a sampling rate of 96 kHz. In Fig. 10, first peak was caused by ultrasonic waves coming directly from sensor through the microphone. After 180 samples, which correspond to 180/9600 seconds (1.875 ms), ultrasonic waves reflecting from PCB plates, or echo, were detected. But, from these plots, it is not possible to calculate the distances between plates since envelope of echo is not sharp. To apply pulse compression, a matched inverse filter is designed by producing time-reversed versions of the simulated chirp signals. Then, detected signals filtered with designed matched filter.

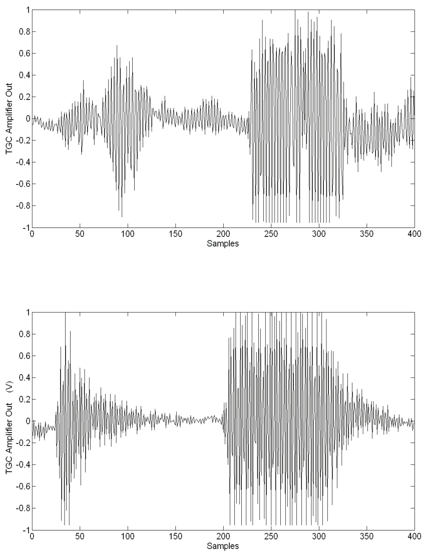

Fig. 10. Detected echo signals: PVDF sensor (top), ceramic sensor (bottom)

When using PVDF sensor, envelope of echo signal becomes amplified and distances between plates are clearly detectable after pulse compression (Fig. 11). Across 278th, 300th, 322nd samples, matched filter out is maximum since reflected waves are detected. Difference of 12 samples corresponds a time difference of 1.25 ms. With a 340 m/s wave velocity, this ToF corresponds a distance of 42.5 mm. But when using the ceramic sensor, envelope of echo signal still is not sharp enough to calculate distances between plates, since ceramic sensor has a long ringing time and stimulated with a narrowband chirp signal.

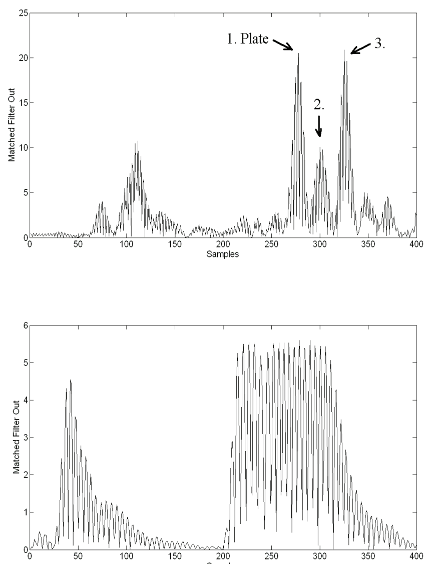

Fig. 11. Detected echo signals after pulse compression: PVDF sensor (top), ceramic sensor (bottom)

6. Conclusions

A low-cost broadband ultrasonic sensor is successfully designed using low-cost piezoelectric Polyvinylidene Fluoride (PVDF) film. The sensor has a semi-conical geometry, which provides high bandwidth, low ringing time compared to traditional high sensitive ceramic ultrasonic transducer. Experimental results show that, using this sensor it is possible to get higher axial resolution than ceramic ultrasonic transducer at short-range obstacle detection in air.

7. References

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