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PVDF corrugated transducer for ultrasonic ranging sensor

Minoru Toda [a,*], Jerry Dahl [b]

[a] Measurement Specialties, Inc., 460 E. Swedesford Road, Ste. 2010, Wayne, PA 19087, USA
[b] General Dynamics, Corp., 4205 Westinghouse Commomn Drive, Charlotte, NC 28273, USA

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Abstract

This paper describes a method to design and build ultrasonic transceivers using low-cost polyvinylidene fluoride (PVDF) corrugated film. The corrugated transducer features multiple curved sections, which provide a higher acoustic output compared to traditional ultrasonic transducer design using a single curved PVDF film section. We have built and demonstrated a prototype 200 kHz transducer and found it to be practical for applications requiring short-range distance measurement (20–300 mm) with SNR of 20 dB for 200 mm target. The prototype uses a single transducer that operated as both an ultrasonic transmitter and a receiver and provides a beam directivity of $\pm 7^{\circ}$ at -6 dB point using a 160 Vpp drive pulse. The transmitter output is 6.6 Pa (rms) at 30 cm with relative bandwidth of 33% and the receiver sensitivity is 0.55 mV/Pa. A microprocessor provides the timing signals, measures the time of flight from the transmitted pulse to the received echo, and calculates the distance.
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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 (robotics), etc. Most of commercially available air ultrasonic transducers are ceramic based and operate at 40 kHz. Transducers that operate at higher frequencies such as at 200 kHz are more limited and more expensive. However, various research reports in the range of 100 kHz to 5 MHz air ultrasonic transducer are available. Examples are for 1–3 connectivity ceramic composite [1], investigations of materials for matching layers [2], or electrostatic transducers [3].

Generally the overall sensitivity defined by receiver output versus unit voltage applied to transmitter is relatively low. At 30 cm separation and for 200 kHz commercial devices, the over all sensitivity is in the range of -60 to -70 dB. However, the resonance bandwidth is narrow ($\sim$3%). In this work, PVDF ultrasonic transducers of small size ($\sim$1 cm^2 area), high frequency (200 kHz), wide bandwidth ($\sim$30%) and narrow beam ($\pm 7^{\circ}$ at -6 dB) have been developed for a practical, low-cost, short-range measurement system for a target range of 20–300 mm. The overall sensitivity is lower (-90 to -86 dB) than ceramic transducers, but higher voltage pulses can be applied (up to 1000 Vpp) which provide 10–15 dB higher output than for ceramic transducers with maximum drive voltage. Therefore, using a high voltage transmitter drives significantly improves the receiver output and is comparable to that of ceramic transducers. In addition, the feature of wide bandwidth improves received signal even further if sharp pulses or coded signals are used.

Periodic concave–convex (corrugated) transducers using polyvinylidene fluoride (PVDF) were originally investigated and designed for large-area, high-intensity ultrasonic air transducers [4] that provided an ultra-highly-directional loudspeaker using a 40 kHz parametric array effect. Corrugated PVDF film transducers provide multiple sections of curved film, each having a common mechanical resonance. The structure is composed of single film with continuously formed multiple curved sections of a relatively large vibrating area. This corrugated design provides a higher acoustical output compared to a conventional circular film transducer. When the transducer is designed to operate in the 200–300 kHz range, it is difficult to accurately form the corrugation shape because of the fine periodicity. However, at lower frequencies the device size becomes too large because of the longer wavelength, and decreases the detection ability at

* Corresponding author. Tel.: +1 610 971 9893; fax: +1 610 971 9216.
E-mail address: minoru.toda@msiusa.com (M. Toda).

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short distances. For these reasons, 200–300 kHz is the optimal frequency range for short distance ranging sensor applications.

A number of researchers have investigated curved PVDF film transducers [5–11]. These transducers were designed using various structures including corrugated, curved film single section, cylindrical, multiple layers, disk, etc. In our design, the curved-film structure is equivalent to the half section of a cylindrical-film transmitter and the resonance frequency is inversely proportional to the film-curvature radius. This causes a relatively low output at higher frequencies because the small curvature radius leading to small transducer area.

Cylindrical film transmitters have also been investigated and reported to have a similar problem of a reduced output inversely proportional to the increasing frequencies [11]. In the case of ceramic transducers, multiple PZT plates embedded in polymer operated in length vibration mode (2–2 composite) were investigated for the 40–400 kHz range and designed for air-ranging application [12,13]. Another option is PZT disk transducers using radial-mode resonance (100–400 kHz) coupled with thickness-mode vibration. The output from radial-thickness coupled mode resonance is much stronger than from pure-thickness mode [14,15]. In this case a single transducer was used for both transmitter and receiver, and the drive/receive circuits were connected to the transducer through an electronic switch (TR switch).

Other researchers have built curved PVDF film-ranging sensors using separate transducers for the transmitter and receiver [5,8]. However, no one has succeeded in using a single PVDF transducer for both the transmitter and receiver. This paper reports the results of using a single corrugated transducer for both the transmitter and receiver.

It uses a novel TR diode switch to separate the transmitter and receiver functions and a 400 Vpp inductor–capacitor (PVDF) resonate drive circuit. Using a single transducer has the advantage of lower cost and size compared to using two transducers.

2. Basic design principle for corrugated transducers

Differential equations for curved piezoelectric film were solved and the detailed behaviors of vibrations and radiations were described in reference [7]. The same technique was applied to the corrugation transducer [4] with suitable boundary conditions; the resultant curves were obtained by numerical calculations. That process is mathematically rigorous but it cannot be reduced to simple useful relations. In this section, simple relations are derived from well-established concepts and useful equations are obtained, which help in the basic understanding and are also useful for design engineers.

2.1. Structure determination

A unique feature of PVDF is its length displacement along the molecular orientation direction (“1 direction”) induced by an electric field in the thickness direction. Because each section of PVDF film is curved in the 1 direction and has displacement in the length direction at the same time for all the section, the boundary line jointing each curved section cannot move at a high frequency and only allowed vibration direction is normal to the surface.

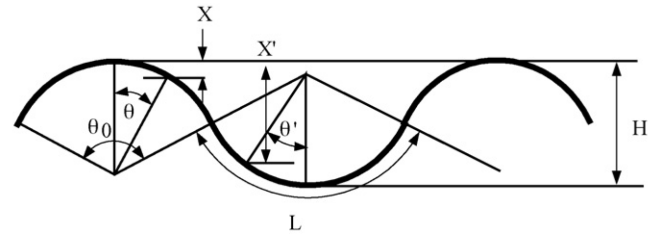

Fig. 1. A section of corrugation structure and parameters use for equations.

Because of the mass of the film and elasticity, curved PVDF film has mechanical resonance. In this model, the effect of higher order mode was neglected. As described in the basic theory [4,16] of single section of curved PVDF film, the fundamental resonance frequency f_0 is determined by the curvature radius R:

$$f_0 = \left(\frac{1}{2\pi R}\right)\sqrt{\frac{Y}{\rho_p}} \tag{1}$$

where Y is the Young’s modulus averaged over each layer and weighted for film thicknesses, and ρ_p is density averaged in the same way. For PVDF, $\sqrt{Y/\rho_p}$ is 1500 m/s and $R = 1.2$ mm for a 200 kHz transducer design. In practice, the silver ink used on the film influences both Y and ρ_p and better approximation values are $\sqrt{Y/\rho_p} = 1260$ m/s for 10 μm thick silver ink and $R = 1.0$ mm.

The basic concept for transducer design is the peak-to-valley corrugation height and is roughly equal to the half wavelength. The concave and convex regions vibrate with a 180° phase difference. However, the vibration is not only present at the top and bottom of the corrugation, but rather is spread over almost all the surface; the acoustic radiation is the sum of all the radiation from all the points. Therefore, the effective height, giving the 180° propagation path, should be less than actual height measured by peak to valley, and the exact height of corrugation should be a little more than a half wavelength (=0.86 mm) at 200 kHz. This optimum height both maximizes the output level and minimizes the side lobes as described in reference [4] in which case the frequency was ∼40 kHz. The structure used in this experiment has a corrugation height of 1.0 mm and the half wavelength is 86% of the height. This was experimentally determined by making different corrugation height with same R to choose one structure with highest output and lowest sidelobes, in which case resonance frequency (half wavelength) was almost constant because R was constant.

The numerical calculations in reference [4] show that 69% of the optimum corrugation height is equal to the half wavelength (see Fig. 8, curve F at 54 kHz) where the corrugation wave shape is sinusoidal. In this work, the shape of corrugation are jointed circles, as in Fig. 1, which have flatter regions at the top and bottom areas, making the half wavelength 86% of the height.

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