Subminiature Underwater Propeller with Electrical Controllability of Steering

Lurui Zhao and Eun Sok Kim
Department of Electrical and Computer Engineering
University of Southern California
Los Angeles, CA

***Abstract*— This paper describes a subminiature underwater ultrasonic propeller with electrically controllability over its propulsion direction. Built on a 200-micron thick nickel-coated lead zirconate titanate (PZT) substrate, the propeller consists of 28 sectors of individually accessible Fresnel lens that are composed of Parylene air-cavity-reflectors on top of the front-side nickel electrode. A backside Fresnel air-reflector is added to prevent any propulsion from the backside that may cancel the propulsion from the front side. The fabricated propeller (4 x 4 mm^2 in size and 37.5 mg in weight) is demonstrated to have control over its advancing direction when assembled on an air-filled capsule.**

Keywords*— *ultrasonic propeller, controllable direction, micro-propeller, underwater

I. Introduction

Self-focused ultrasonic transducer has recently been developed for multiple purposes including acoustic tweezers [1-3], immersive propellers [4-5], and liquid ejectors with tunable focal length [6-7]. By electrically controlling the transducer's ultrasonic source, the generated acoustic beam could form specific focal pattern for versatile applications.

Immersive micro-propeller has potential applications in drug delivery, microfluidics, robotics, etc. In microfluidic systems or in systems where any mechanical damage as well as wear and tear has to be minimized, a quasi-static propeller with no moving parts is much desired. Ultrasonic propeller, based on focused ultrasound capable of producing acoustic streaming, requires no moving parts, and a micro-propeller based on focused ultrasound has been reported to have a thrust ratio of 19:1 (i.e., thrust force over the weight) [5]. However, it produced a thrust force only in one direction. Electrical controllability over its propulsion direction is highly desirable for the propeller to navigate around in liquid. We previously reported a micro-propeller with electrical controllability over propulsion direction [4]. However, the earlier design required a set of electrical wires to keep the propeller from falling to the bottom. The new device described here incorporates an air-filled capsule to float the propeller over liquid surface.

II. Design

A. Working Principele

A focused ultrasound transducer immersed in liquid produces an intensified acoustic beam at the focal point, which delivers momentum to the liquid, resulting in propulsion force on the transducer, as the propelled liquid mass is replenished from the surrounding region (Fig. 1). With Fresnel lens based on annular rings (Fig. 2), the in-plane or lateral acoustic forces cancel each other out, leading to a thrust force perpendicular to the lens surface. However, if the annular rings are sectored into pie shape and the actuation on one sector is weaker than other sector(s), there exists unbalanced acoustic force, which will result in a lateral thrust. By controlling the actuation amplitudes on all the sectors, the propelling direction can be finely tuned.

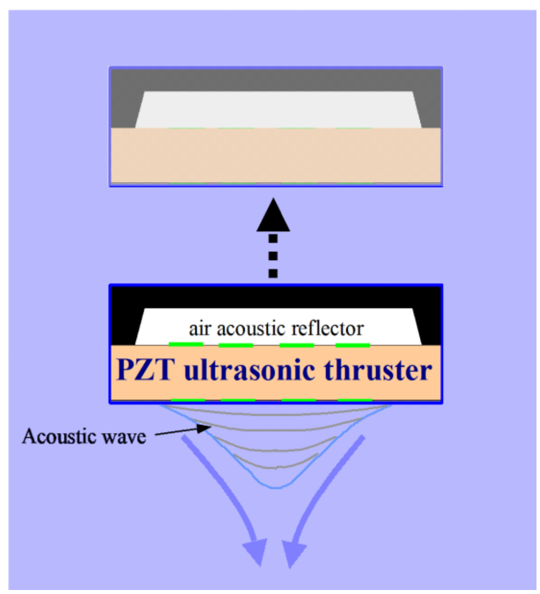

Fig. 1. Conceptual illustration of a simple PZT-based self focusing ultrasonic transducer with air cavity reflector for acoustic propulsion.

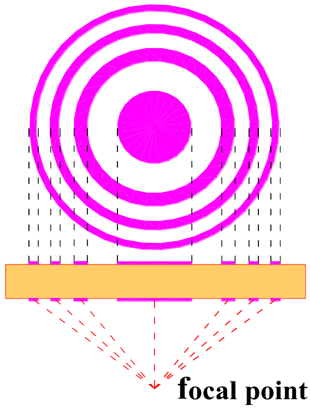

Fig. 2. Self-focusing ultrasonic transducer with a set of full Fresnel rings that can focus ultrasonic wave to a single focal point.

B. Transducer Design

The transducer is built on a PZT with (1) a set of sectored electrodes and a Fresnel air-cavity lens (on top of the electrodes) on the PZT's one surface (say, top side) and (2) a circular electrode on the other surface (bottom side). The sectored electrodes and one type of the Fresnel air-cavity lens are illustrated in Fig. 3. When any of the top sectored electrodes and the bottom circular electrodes are applied with a sinusoidal voltage with frequency matching the PZT's thickness-mode resonance frequency, the PZT produces longitudinal acoustic waves, which pass through the Fresnel air-cavity lens designed to allow only the acoustic waves (that would constructively interfere at the focal point) to pass through. Acoustic streaming effect from the focused ultrasound pushes the medium where the transducer is immersed, and propels the transducer in the direction opposite to the wave propagation direction.

If the top electrode is patterned into a circle similar to the bottom electrode, the lateral propulsion forces cancel each other out, leading to a thrust force perpendicular to the lens surface. However, when the top electrode is sectored into pie shape and the actuation from one sector is weaker or stronger than the other sector(s), there exists unbalanced propulsion force, which thrusts the transducer in a direction that is not perpendicular to the surface. By controlling the actuation amplitudes on the sectors, the propulsion direction can be electrically controlled, as the ratio of the lateral and perpendicular thrust is varied. If the Fresnel air-cavity lens also is sectored (rather than the annular rings as shown in Fig. 3), the sectors of the Fresnel lens can be designed for different focal lengths, and the thrust torque can be changed due to the unequal arm, making it possible for the propeller to rotate itself when it is fully suspended in liquid without any wire hindering the rotation.

We have designed a micropropeller to be built on a 200μm thick PZT substrate (having a fundamental thickness-mode resonance at 11.42MHz), with 28 sectors of individually accessible electrodes and Fresnel air-cavity lens composed of Parylene sealed air cavities. The 28 sectors of the electrodes are designed in 3 symmetric groups with different focal lengths (with the Fresnel air-cavity lens also sectored). Upon actuation, intensified acoustic intensity is delivered at the transducer's focal point in liquid medium, where acoustic streaming effect pushes the medium and propels the transducer in the opposite direction of the wave propagation. As the sectors do not have the circular symmetry, when the sectors (or a pair of the sectors) are driven with unequal voltages, the lateral propulsion forces do not cancel each other, resulting in a directional thrust. Thus, the direction of the propulsion can be controlled in either by selecting different sectors or by varying applied voltage level. A large air-reflector is added on the bottom side of the PZT (the side opposite to the top side where the sectors of the Fresnel lens are formed), in order to prevent any propulsion from the backside that may cancel the propulsion from the front side.

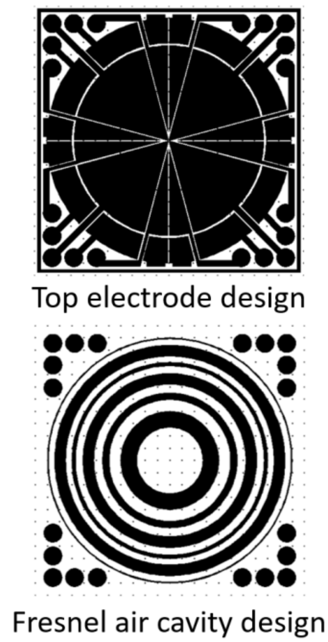

Fig. 3. (Top) Electrode design with 28 sectors on the top side of the PZT. (Bottom) Design of the air-cavity lens to be made on top of the top sectored-electrodes.

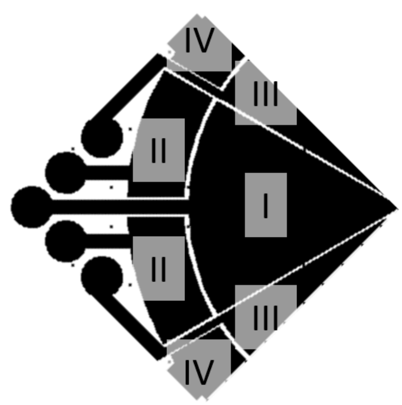

Fig. 4. Close-up view of a quarter of the sectored electrode: the region I providing main thrust, the region II providing two main boosters for increased thrust, the region III offering fine tuning of the proulsion direction when only one main thruster is on, and the region IV providing fine tuning when both main thruster and booster are on.

III. Fabrication

A. Micro-fabrication

As illustrated in the brief fabrication process shown in Fig. 5, we use a 200µm thick PSI-5A4E PZT with nickel layer sputter-deposited on its both sides as the substrate to start with. Photoresist is spin-coated for both the front side and backside for electrode patterning. During photolithography, front-to-backside alignment is done by aligning at a pre-defined dicing edge of the PZT substrate.

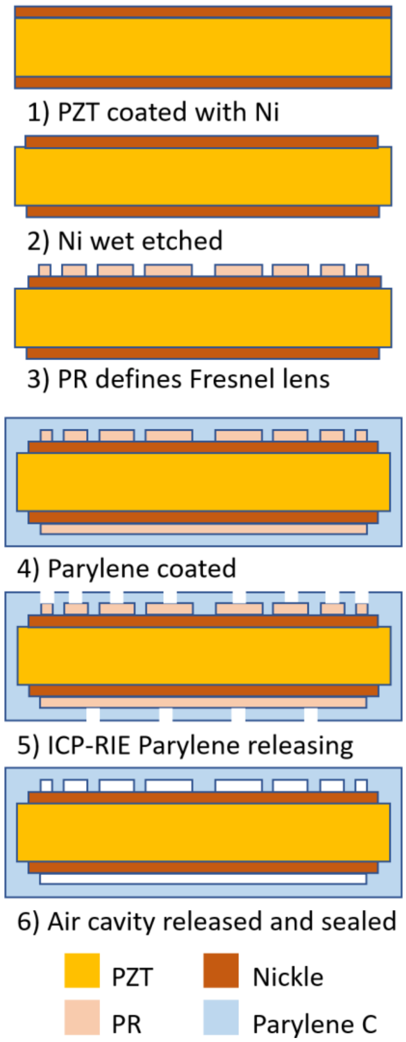

Fig. 5. Brief microfabrication steps of the propeller.

The sectored electrodes (with its sub-regions) are patterned on the front side. After wet-etching the nickel layer, a second layer of photoresist is coated for a sacrificial layer in forming air cavities which block unwanted acoustic waves and form the sectored Fresnel lens pattern. Then, while protecting the backside electrode, we deposit 5µm thick Parylene film, and pattern release holes on the front side where air cavities are needed. Oxygen reactive ion etch (RIE) is used to etch the Parylene to form the releasing holes, and the sacrificial photoresist layer is removed by acetone through the release holes. A 24-hour desiccation time is added to allow the air cavity to become fully dry. Then a second layer of Parylene film is deposited to seal the holes to complete the air-cavity reflectors as well as to provide the transducer with electrical insulation for liquid immersive operations. The finished transducer is shown in Figure 6.

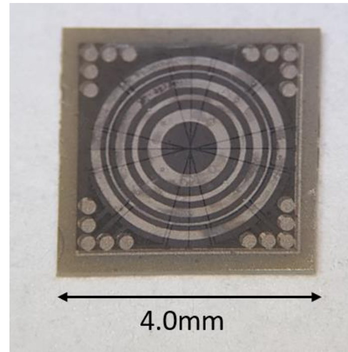

Fig. 6. Photo of a fabricated propeller.

B. Packaging

The fabricated propeller is soldered with ultra-flexible wires from its nickel pads. Then another layer of Parylene film is evaporated over the device for electrode insulation for the device to work when immersed in liquid. The subminiature propeller is attached to a buoyance-adjustable capsule, which is made by attaching a ballast to an air-filled Advil™ capsule. The ballast ensures that the propeller is positioned with two quarter-sectors horizontally aligned (as depicted in Fig. 7) so that the static state of the propeller system is immersed in water with two quarter-sectors controlling down (A) and up (B) and the other two quarter-sectors controlling right (C) and left (D).

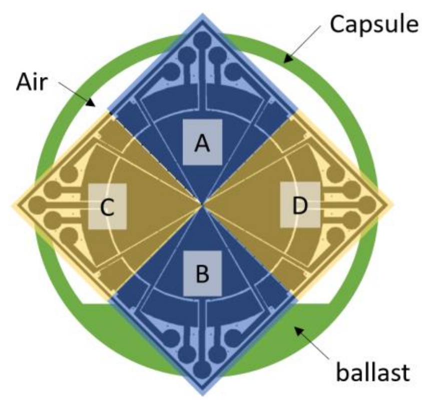

Fig. 7. Cross-sectional view (from the tail end of the system) of the propeller mounted to an air capsule. The four quarter-sectors are designated to control the attitude. The two blue regions (A for downward, B for upward) can adjust the up and down position of the propeller and yellow regions can adjust the steering (C for turning right and D for left).

Fig. 8. Photo of the propeller mounted to an air-filled Advil™ capsule (without bonding wires) with the buoyance of the capsule being adjusted so that the whole system may be immersive without sinking to the bottom of liquid.

IV. Result

The packaged propeller with the buoyance-adjustable capsule is tested in water with flexible wires through which 11.42MHz electrical power is delivered. Upon excitation, the propeller leaves its equilibrium position. As the driving voltage increase, the thrust gains proportionally. The steering is achieved by either selecting the active driving section, introducing the unbalanced propulsion, or applying different driving voltage on symmetric sectors (Fig. 9). A thrust along a straight line is achieved by driving all the sectors simultaneously (Fig. 10).

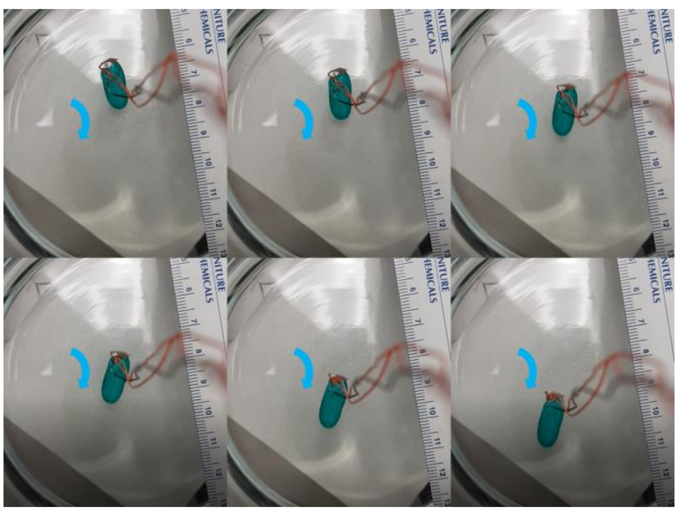

Fig. 9. Sequential photos showing that when the asymetric sectors are actuated (driving region C only), the unbalanced propulsion force drives the device to move along a not-straight direction.

Fig. 10. Squential photos showing that when the symmetric sectors are actuated, the thrust is along a straight line.

V. Summary

We have designed, fabricated and demonstrated a 11.42MHz ultrasonic underwater propeller with individually accessible 28 sectors of the electrodes along with sectored Fresnel air-cavity lens. Actuating the sectors with different voltages or in different combination leads to unbalanced lateral thrust, producing directional propulsion. We have added an air-filled capsule to the propeller for adjustable buoyancy, and obtained a directional propulsion with the capsule on the propeller.

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