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Solid–liquid coupled vibration characteristics of piezoelectric hydroacoustic devices

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ABSTRACT

This study investigated the vibration characteristics of piezoelectric bimorphs with regard to the solid–liquid coupling effect in piezoelectric–acoustical devices. Experimental measurements and finite element numerical calculations were used to determine the resonant frequencies and mode shapes of piezoelectric bimorphs, which could be used to promote the flow of air, water, and glycerin. Two piezoelectric devices were designed to verify the solid–liquid coupled vibrations of the piezoelectric bimorphs: (1) Type A with bimorph located above the surface of the fluid and (2) Type B with bimorph located within the fluid. The first type has a piezoelectric bimorph bonded to PDMS polymer, such that resonant vibrations produce changes in the volume of the chamber, which increases the flow of fluid. Another is a biomimetic design, in which a piezoelectric bimorph embedded in the chamber imitated the tail of a fish in order to promote the flow of liquid. Three experimental techniques were used to determine the solid–liquid coupled vibration characteristics. Electric speckle pattern interferometry (ESPI) was used to measure the resonant frequencies and mode shapes associated with the vibration of piezoelectric bimorphs interacting with fluids. Second, a laser Doppler vibrometer (LDV) was used to obtain the frequency spectrum of vibrating displacement using dynamic signal swept-sine analysis. The third experiment involved analyzing impedance in the piezoelectric bimorphs in order to identify the resonant frequencies and anti-resonant frequencies of the piezoelectric material under the influence of a fluid. Finite element method (FEM) was used for the analysis of vibration characteristics associated with the interaction between the fluids and piezoelectric-solid elements paired with (1) acoustic elements only or (2) acoustic elements and solid elements with viscoelastic properties. The numerical calculations of solid–acoustical coupled vibration are in good agreement with solid–liquid coupled experimentally results. The FEM solid elements with viscoelastic properties can be applied to predict the dynamic behaviors for lower frequency of the solid–acoustical coupled vibration. This study proposes an efficient methodology of the development of piezoelectric hydroacoustic devices by FEM, which has been verified by experimental measurements in this paper.

1. Introduction

Piezoelectric bimorph has larger deflection using on many application. One is micropumps being applied in solid–liquid couple devices such as biomedical diagnostics [1], fuel mixing [2], proton exchange in fuel cells [3], electronic heat transfer [4], and self-pumping mixers [5]. Electrostatic, piezoelectric, magnetostrictive, and thermoelectric actuators are used on micropumps with fluid channels and valves designed to enhance the rate of flow [6]. Series and parallel channel designs are used in peristaltic pump systems [7], such that the flow rate depends also on the sizes of the chambers and valves [8]. Even in valveless pumps, the design of the nozzle/diffuser greatly influences the efficiency of pumping [9]. The stroke of the actuator is among the most important factors determining the rate of flow through the pump. This paper used a solid–liquid coupled model as well as experimental measurements to elucidate deformation of piezoelectric devices, which operate at resonant frequencies and determine mode shapes.

Piezoelectric devices have been developed for use as miniaturized, high-frequency actuators in hydroacoustic elements. However, the small deflection of piezoelectric unimorphs is a disadvantage in devices due to the need for large volumetric changes in order to increase the rate of flow. Piezoelectric bimorphs capable of providing a larger deflection were first developed at Univer-

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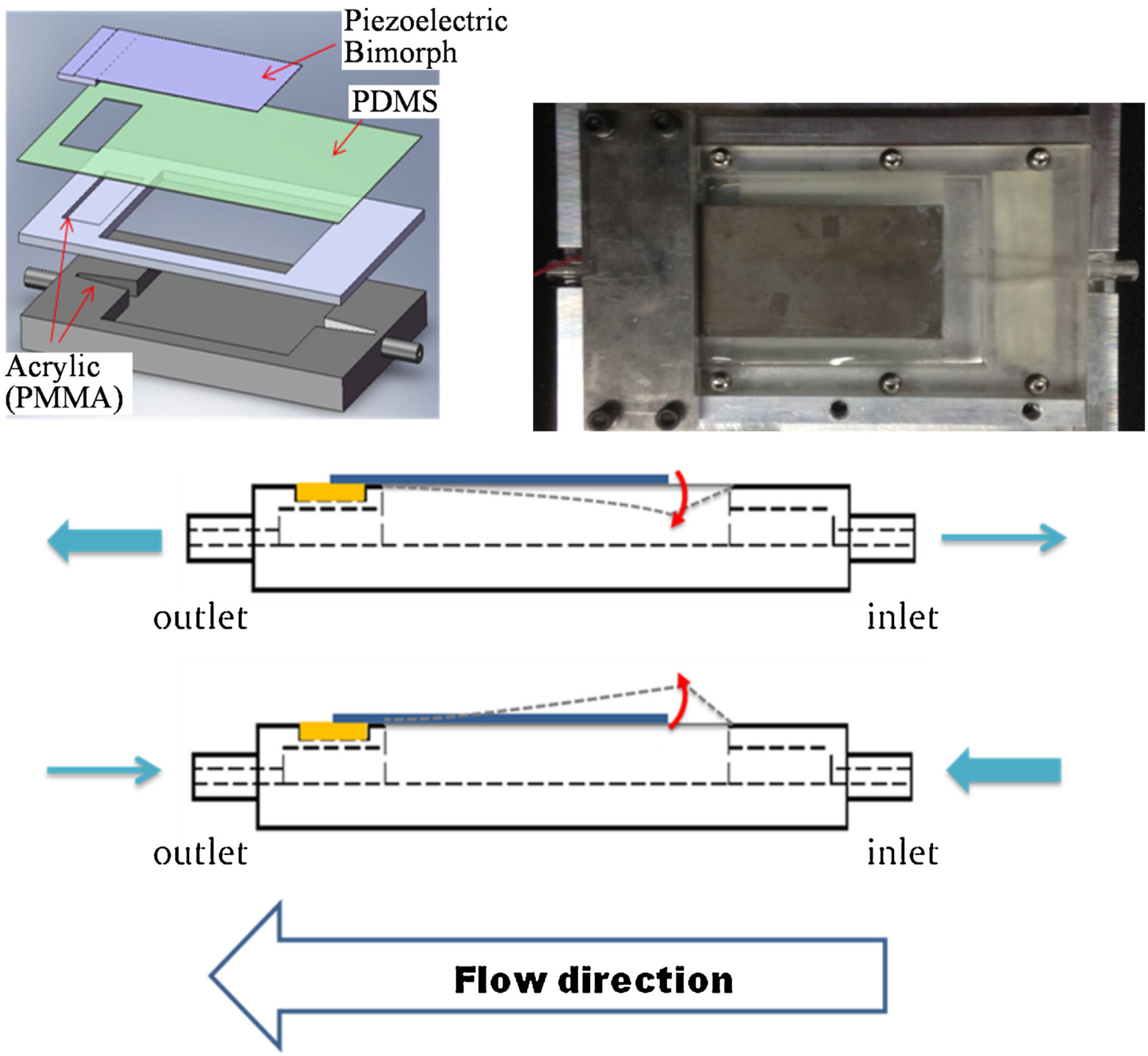

Fig. 1. The configuration and operating characteristics of piezoelectric hydroacoustic using piezoelectric bimorphs and PDMS membrane (Type A).

sity of Stanford in 1980 [10,11]. To enhance the flow efficiency, Ma et al. [8,9,and 12] used piezoelectric bimorphs in the study of micropumps with a variety of valves, nozzle/diffusers, and secondary chambers. This study used piezoelectric bimorph with two designs to investigate the solid–liquid coupling vibration in piezoelectric–acoustical device above and within various fluids. One piezoelectric device (Type A) was designed using a piezoelectric bimorph attached to the top of a chamber, as shown in Fig. 1. This is based on the design by Ma et al. [8] in which a water-resistant polymer membrane (Polydimethylsiloxane, PDMS) is applied at the interface between the piezoelectric device and the liquid. In accordance with the design of de Lima and coworkers [13,14], the other piezoelectric device (Type B) was designed to imitate the movement of a fish's tail; in this device, a piezoelectric bimorph is embedded within the chamber, as shown in Fig. 2. These researchers focused primarily on the determination of the operating frequencies using swept-frequency testing. Thus, this study investigates the solid–liquid coupling vibration of piezoelectric bimorphs in these two types of piezoelectric device above the fluid surface and within fluids.

Numerical methods have been widely applied for the characterization of piezoelectric materials. Ekeom et al. [15] proposed a numerical model to simulate the radiation of a piezoelectric transducer in a fluid-filled borehole in the frequency domain. Balabaev and Ivina [16] used the finite element boundary method to solve the problem of radiation in a water-filled piezoceramic cylinder [16]. The frequency characteristics of the transmitting response of the piezoelectric cylinder were obtained along with the frequency characteristics of the acoustic power, the directional characteristics, the velocity, and pressure distributions over the radiating cylindrical surfaces. Savin [17] presented a transport model for high-frequency vibration power flows, which was used in subsequent computations to numerically solve the transport equations for coupled heterogeneous structures. Fluidic devices have also been calculated numerically using theoretical analysis and finite element method. Wu and Lu [18] analyzed unimorph piezoelectric plates in valveless micropumps according to variations in frequency. Pan et al. [19] proposed a vibration model for fluid-membrane coupling to simulate the behavior of valveless pumps. Wang et al. [20] studied the operating frequency of a valveless micropump on the basis of its acoustic characteristics. Using FEM, the hydroacoustic element was driven at the frequency with the maximum flow rate, time was divided into increments of a quarter period in order to observe the streamline associated with the size of the channels at this frequency. Previous studies used only numerical analysis, thereby neglecting to obtain experimental measurements of the operating frequencies and corresponding mode shapes. In this study, we experimentally measured the reso-