Sensors and Actuators A 171 (2011) 317–323

Contents lists available at SciVerse ScienceDirect

Sensors and Actuators A: Physical

journal homepage: www.elsevier.com/locate/sna

Acoustically generated flows in microchannel flexural plate wave sensors: Effects of compressibility

Ersin Sayar, Bakhtier Farouk*

Mechanical Engineering and Mechanics, Drexel University, Philadelphia, PA 19104, USA

ARTICLE INFO

Article history:
Received 27 January 2011
Received in revised form 15 July 2011
Accepted 19 August 2011
Available online 26 August 2011

Keywords:
Flexural plate wave (FPW)
Acoustic streaming
Microchannel
Micropump
Acoustic waves
Fluid damping
Lamb wave

ABSTRACT

Acoustically generated flowfields in flexural plate wave sensors filled with a Newtonian liquid (water) are considered. A computational model based on compressible flow is developed for the sensor with a moving wall for pumping and mixing applications in microchannels. For the compressible flow formulation, an isothermal equation of state for water is employed. The velocity and pressure profiles for different parameters including flexural wall frequency, channel height, amplitude of the wave and wave length are investigated for four microchannel height/length geometries. It is found that the flowfield becomes pseudo-steady after sufficient number of flexural cycles. Both instantaneous and time averaged results show that an evanescent wave is generated in the microchannel. The predicted flows generated by the FPWs are compared with results available in the literature. The proposed device can be exploited to integrate micropumps with complex microfluidic chips improving the portability of micro-total-analysis systems.

1. Introduction

There is an increasing demand for small, reliable, disposable, and inexpensive sensors in industrial, medical, and a variety of other science and engineering fields [1]. Acoustic wave biosensors have been suggested as detection devices where the sensor utilizes acoustic waves as a detection mechanism to obtain medical information about the analyte of interest.

In this paper, we model acoustically generated flowfields in microchannels as found in flexural plate wave (FPW) devices—including the effects due to compressibility. FPWs are generated by the application of an alternating voltage signal to interdigitated transducers (IDTs) patterned on a piezoelectric substrate. In FPW sensors, the oscillating membrane is assumed thin compared to the wavelength of the vibrating mode so that the top and the bottom surfaces are strongly coupled and a single wave propagates along the membrane [2]. The present study focuses primarily on steady streaming results induced by the flexural plate waves (FPW).

2. Background and past work

Rayleigh waves (*a type of surface acoustic wave SAW that travels on solids*) can be produced by piezoelectric transducers. When guided in layers these waves are referred to as Lamb waves. FPW devices featuring Lamb waves have high signal to noise ratio [3]. The basic FPW sensor consists of a rectangular flow channel that has a thin membrane at the bottom. FPW devices are rectangular plates or diaphragms with structural layers (low-stress silicon nitride), a piezoelectric layer (zinc oxide or aluminum nitride or PZT) and interdigitated conducting combs (aluminum) for driving and sensing [4]. An FPW device is an actuator, in which an acoustic wave is excited in a thin membrane. FPW is hence a type of bulk acoustic wave (BAW) sensor. When a FPW propagates in membrane, a high intensity acoustic field appears in the fluid near the membrane. This acoustic field causes fluid flow in the direction of wave propagation. The principle of operation in the FPW devices has some advantages. The surface without the IDT is immersed in the targeted liquid and acts as the sensor, so the device will not suffer from corrosion problems as electrode plates do in biological solutions. The piezoelectric substrate has a typical thickness of 0.2–1.0 μm and it is usually coated with a 1.0–3.0 μm thick doped silicon rectangular diaphragm. Acoustic biosensors generally employ BAWs rather than surface acoustic waves SAWs as BAW devices generate waves that mainly propagate in the shear horizontal motion. Shear horizontal wave minimizes damping in the liquid operation.

* Corresponding author. Tel.: +1 215 895 2287; fax: +1 215 895 1478.
E-mail address: bfarouk@coe.drexel.edu (B. Farouk).

0924-4247/$ – see front matter © 2011 Elsevier B.V. All rights reserved.
doi:10.1016/j.sna.2011.08.018

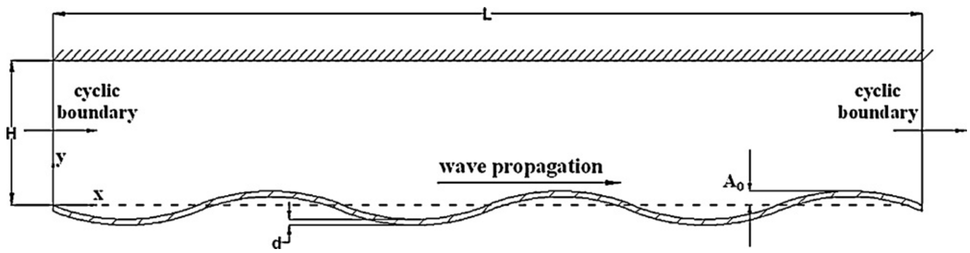

Fig. 1. Schematic of the FPW acoustic device considered.

Sankaranarayanan et al. [5] presented a computational and experimental study of the acoustic-streaming phenomenon induced by SAWs. A coupled-field fluid–structure interaction model of a SAW device based on a piezoelectric substrate (YZ-$LiNbO_3$) in contact with a liquid loading was developed to study the surface acoustic wave interaction with fluid loading. The simulation results [5] predicted strong coupling of surface waves on the substrate with the thin liquid layer causing wave mode conversion from Rayleigh (SAW) waves to leaky SAWs. The coupling leads to acoustic streaming. Trends in acoustic-streaming velocity were predicted for varying design parameters such as voltage intensity, device frequency, fluid viscosity, and density.

Moroney et al. [6] experimentally observed pumping of water induced by 4.7 MHz Lamb (BAW) waves traveling in a 4.0 μm-thick composite membrane of silicon nitride and zinc oxide. The observed pumping speed is determined to be proportional to the square of the wave amplitude. Acoustic streaming induced by ultrasonic flexural vibrations and the associated convection cooling enhancements were investigated by Loh et al. [7]. Analysis based on Nyborg's formulation was performed along with incompressible computational fluid dynamics (CFD) simulations. Acoustic streaming velocities obtained from CFD simulation based on the incompressible flow assumptions exceeded the theoretically estimated velocity by a factor ranging from 10 to 100, depending upon the location along the membrane. Both CFD simulation and analytical studies revealed that the acoustic streaming velocity is proportional to the square of the vibration amplitude and the wavelength of the vibrating membrane. Acoustic streaming velocity decreases with the excitation frequency. Acoustic streaming pattern, streaming velocity, and associated heat transfer characteristics were experimentally observed. Using acoustic streaming, a temperature drop of 40 °C with vibration amplitude of 25.0 μm at 28.4 kHz was experimentally achieved.

Numerical simulations of a micromachined pump based on acoustic streaming in water has also been reported [4,8]. Influences of channel height, wave amplitude, and backpressure on the velocity profile and flow rate were investigated assuming incompressible flow. Tsai and Leu [8] numerically investigated micropumping system generated by a traveling wave for a flexural plate wave (FPW) device. The time averaged velocity profiles over one period became a parabolic velocity profile when the channel height was less than l00 μm. When a channel height was higher than 200 μm, the time averaged velocity profiles deviated from the parabolic velocity profile. The pressure wave confinement effect in a microchannel with height less than 100 μm was noticed. The frequency of the FPW pump was found to control the flow rate.

In the past investigations [4,6–8], the FPW phase velocity is less than the speed of sound in the fluid. It was assumed that the acoustic radiation into the fluid would not occur. However, Weinberg et al. [9] noted that fluid effects on damping and effective mass are neglected by the assumptions in [4,6–8]. For the flows with acoustic excitations the energy dissipated by the oscillating wall is not only attenuated by the inertia and viscosity of the fluid, it is also attenuated through the density variations. Therefore, the compressibility of water needs to be considered in some sense.

This paper builds on and clarifies the results in [4,6–8] pertaining to progressive FPW operation in a compressible viscous liquid. In order to consider the FPW pumping capability, the dependence of velocity profile on the channel height, wave amplitude, wave length, and actuation frequency are investigated.

3. Problem description and geometry

An FPW device with an oscillating wall is shown in Fig. 1. For a flexural plate wave sensor (bottom surface in Fig. 1) induced perturbation propagates across the piezoelectric material thickness and the nature of the induced wave does not change along the thickness. Wave motion can be described by sinusoidal functions. The membrane (comprising of the piezoelectric material) has typical width of 3.0 mm and a length of 8.0 mm. A representative length ($L = 3\lambda$) is considered for the simulation domain where λ is the flexural wavelength. Since the nature of the device is periodic, the simulated length of the channel, L, can represent the device (using periodicity at both ends). The glass slide closing the flow domain is considered as rigid (top wall in Fig. 1). The bottom geometry can be defined by $A_0(t)$, the amplitude of the wave, height H, thickness of the membrane d, and length of the microchannel L, respectively.

For acoustically driven flows, the FPWs are generated by the application of an alternating voltage signal to the IDTs patterned on a piezoelectric substrate (bottom wall in Fig. 1). A vibrating membrane (bottom) perturbs a compressible fluid (Fig. 1). The vertical displacement Δy of the membrane is given by:

$$\Delta y = -A_0(t)\sin(\omega t - kx) \tag{1}$$

where $A_0(t)$ is the wave amplitude, $\omega = 2\pi f$ is the angular frequency of the wave, and f is the cyclic frequency (Hz), $k = 2\pi/\lambda$ is the wave number, $c_p = \lambda f$ is the phase velocity and λ is the wavelength. With a membrane thickness d, the horizontal wall displacement is

$$\Delta x = \left(\frac{A_0(t)\pi d}{\lambda}\right)\cos(\omega t - kx) \tag{2}$$

For the cases considered (Table 1), the FPW has a frequency of 1.0–3.0 MHz, and wave amplitude of 4.0–10.0 nm, a membrane thickness (d) of 3.0 μm and a wavelength λ of 100.0–150.0 μm. The channel considered as three wave-lengths long (3λ = 300.0–450.0 μm) for the cases investigated. Width of the channel is also varied between 5.0 and 100.0 μm. In order to consider a realistic initial condition and to eliminate immediate water hammer effects, the wave amplitude is described as a function of time: $A_0(t) = A_{max}(1 - \exp(-tf))$ i.e., the perturbation increases gradually from zero.

Table 1 lists the cases considered in the present study. In Case 1, the parameters are chosen from the values used in [4], H = 50.0 μm, L = 300.0 μm, and f = 3.0 MHz. In Case 2, a narrow microchannel (H = 5.0 μm) is considered. In Cases 3 and 4, the amplitude of the perturbations A_{max} is varied while keeping other parameters