Piezoelectric Buzzer Optimization for Micropumps

A.G S. Barreto Neto[*1,2] , A.M.N. Lima[1], Francisco Tejo[1], Christian Precker[1] and C.S. Moreira[3]
[1]Universidade Federal de Campina Grande-DEE-UFCG, Campina Grande, Paraiba, Brazil
[2]IFPB, Cajazeiras, Paraíba, Brazil
[3]IFAL, Maceió, Alagoas, Brazil
*Corresponding author: arlindo.neto@ee.ufcg.edu.br

Abstract: Piezoelectric buzzers are low cost devices which can be used successfully as actuators in diaphragm-based micro-pumps. The buzzers are piezoelectric wafers (lead-zirconate-titanate-PZT) that are glued on a brass membrane and they are available within different sizes and thicknesses. For the best performance of a diaphragm pump, it is necessary to have a large displacement of the membrane. This can be achieved by obtaining the best relationships among the thicknesses and diameters, and types of PZT and membrane, which maximize the displacement of the actuator.

Keywords: maximum displacement, piezoelectric buzzer, finite elements, micropump

1. Introduction

Micro-scale flow propulsion devices, or simply micro-pumps, have been recently used for applications in bioengineering, as, for instance, the continuous injection of insulin in diabetic patients [1,3] and the pumping of biological fluids [2]. Another possibility is the design of portable equipments for reagents dosage in clinical applications [1,6].

An adequate candidate for miniaturized pumping devices is a piezoelectric micro-pump [1,2], which shows a better pumping performance, a relatively simple structure and without any warming problem. Therefore, piezoelectric ceramics (PZT) have been investigated as an interesting alternative for the construction of small size devices for precision pumping of small fluid volumes [3]. Buzzers have been used as an alternative to reduce final cost for piezoelectric actuators, without any reduction on performance. The piezoelectric buzzer consists of a brass disk glued with a piezoceramic layer (Figure 1 (a)).

Concentrated parameters modeling has been proposed to evaluate the deformation of the piezoelectric actuator [4,7]. However, that device is highly sensitive to changes on its mechanical (elasticity module, Poisson's coefficient and density) and electrical (piezoelectric coefficients: transversal - d_{31}; longitudinal – d_{33}) parameters. Small changes in these parameters greatly affect the final result.

In this paper, a computational investigation has been proposed to evaluate the relationship between the brass and the PZT diameters (D_p, D_{pzt}) and thicknesses (h_p, h_{pzt}), when the actuator is activated. Considering the geometric restrictions (chamber diameter) to the micro-pump, the best actuator will be defined as that which corresponds to the highest volume to contact area ratio.

2. Theoretical aspects

A piezoelectric element is able to convert electric energy into mechanical energy and vice - versa. When an electric voltage is applied to the piezoelectric disk terminals, it has the ability to deform in the direction of polarization, (**Figure 1** (b)). As the rim of the membrane is clamped (Figure 1 (c)), it presents a concave or convex deformation, which yields the pumping effect that generates fluid flow through the diaphragm pump chamber. In this case, the PZT shows a piston-like behavior. In other words, when the diaphragm moves down, reducing the pump chamber volume, the fluid is expelled; when the diaphragm moves up, increasing the pump chamber volume, the fluid is pulled into the chamber. Therefore, the deformation of the actuator is critical to the duty cycle of the micro-pump.

The following piezoelectric strain-charge constitutive equations were utilized in this work [8].

$$\mathbf{S} = \bar{\bar{\mathbf{s}}}_{\mathbf{E}} \,.\, \mathbf{T} + \bar{\bar{\mathbf{d}}}^{\mathbf{t}} .\, \mathbf{E} \qquad (1)$$

$$\mathbf{D} = \bar{\bar{\mathbf{d}}} \,.\, \mathbf{T} + \bar{\bar{\boldsymbol{\varepsilon}}}_{\mathbf{T}} .\, \mathbf{E} \qquad (2)$$

where $\mathbf{T}$ and $\mathbf{S}$ are the stress and strain vectors, respectively; $\mathbf{s_E}$ is the elastic compliance tensor. $\mathbf{D}$ is the electric displacement vector, $\mathbf{d}$ is the piezoelectric tensor, $\mathbf{E}$ is the electric field vector and $\boldsymbol{\varepsilon}_{\mathbf{T}}$ is the electric permittivity tensor for constant strain. The electric field in the piezoelectric layer is determined by solving Poisson's equation

$$-\nabla.(\mathbf{D}) = \rho_s \tag{3}$$

where $\mathbf{D} = -\varepsilon_0\varepsilon_r\nabla V$ and $\mathbf{E}$ =- gradV, with ρ_s is the surface change density; V is the electric potential and ε_r it the relative permittivity.

Numerical calculations have been performed using COMSOL 4.2a, in order to evaluate the buzzer deformation in terms of the geometrical parameters h_{pzt}, h_p, D_{pzt} e D_p (see Figure 1-(c)).

3. Simulation

Two questions were initially evaluated before the buzzer parametric analysis: the glue layer influence on deflection and the ceramic eccentricity related to the brass membrane.

The buzzer is formed by a sandwich of materials (piezoelectric ceramic + glue layer + brass membrane). However, if the glue layer has a minor influence on the displacement, it can be neglected which reduces the computational cost.

The meshes used in the simulations were of two types: for the piezoelectric ceramic, one has used the swept meshing mode, where the quality is fine; for the membrane, one has used a mesh with tetrahedral elements. As far as the membrane mechanical characteristics are concerned, one has chosen free displacement boundary conditions everywhere, except at its edge, which was clamped. On the other hand, for the piezoelectric ceramic, one has defined an electrical potential at its top and ground at its bottom. All simulations are performed in steady state in the 3D model.

3.1 *Glue layer analysis*

Taking a variation from 20 µm to 40 µm for the glue layer thickness, a simulation has been executed using the *Piezoelectric Device (pzd)* module in stationary regime. One has chosen PZT-5A as the piezoelectric ceramic and copper (Cu) for the membrane. The epoxy resin has elasticity module and the Poisson coefficient equal to E= 4.38 GPa and γ=0.28, respectively.

The influence of the glue layer thickness on the maximum displacement is shown in Figure 2. Considering the glue layer thickness as 20 µm, the difference (with and without glue layer) is less than 4% for all cases. However, considering the worst case (40 µm), that difference becomes 10%, considering h_{pzt}=0.15mm. Normally, the glue layer thickness is lesser than 20 µm. Therefore, depending on the model complexity, the glue layer can or can not be neglected.

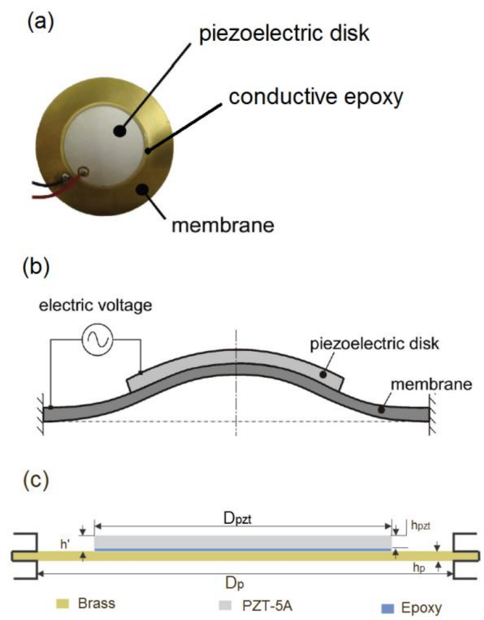

Figure 1. (a) Buzzer piezoelectric, (b) Side view of actuator displacement, subjected to an electrical potential difference and (c) resting state.

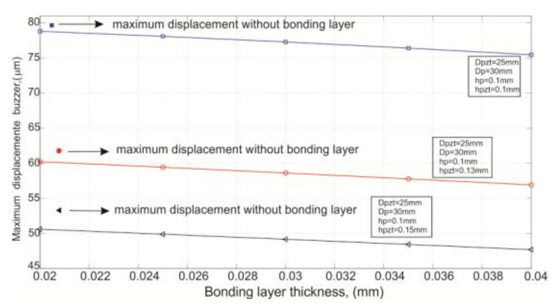

Figure 2: : Maximum displacement with and without bonding layer, considering three cases: hpzt = 0.1 mm; h_{pzt}= 0.13 mm and h_{pzt} = 0.15 mm. In all cases, D_{pzt} = 25 mm, D_p = 30 mm and h_p = 0.1mm. The variation of the glue layer is from 20 µm to 40 µm.

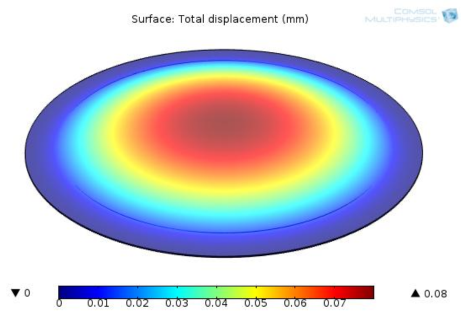

Figure 3. Simulation result for the displacement of the piezoelectric actuator. The maximum amplitude of the displacement occurs in the centered actuator.

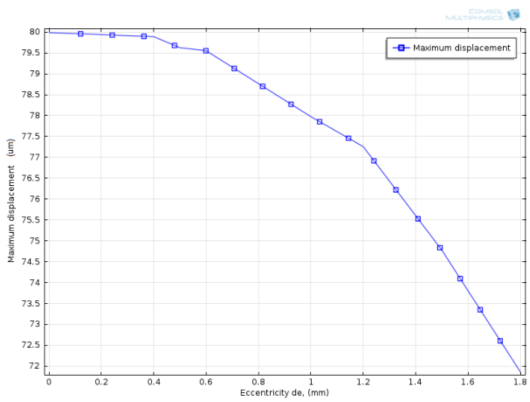

Figure 4. Influence of eccentricity d_e on the amplitude of the displacement.

3.2 *Analysis of PZT ceramic eccentricity*

The maximum deformation always occurs in the middle of the piezoelectric ceramic (Figure 3). However, if the membrane and ceramic are not centered, the maximum deformation value will be modified.

The parameter d_e is defined as the distance between the membrane and the ceramic centers. If d_e=0 they are centered and otherwise the buzzer has an eccentricity (see Figure 4).

The eccentricity is an important parameter that affects the maximum displacement of actuator. Nevertheless, a visual inspection is necessary to eliminate it. Therefore, the maximum deflection occurs when d_e=0.

3.3 *Analysis of the buzzer thickness*

Another important parameter for the design of a robust micro-pump is the *compression ratio* (ε), defined as the ratio between the volume stroke (ΔV) and the dead volume of the chamber (V_0), that is $\varepsilon = \Delta V/V_0$. Self-priming capability and bubble tolerance can be determined if the compression ratio is ε>0.075 [5]. However, the variation of the volume stroke is a function of the geometrical parameters D_{pzt}, D_p, h_p and h_{pzt}, for a constant voltage. Therefore, the choice of a suitable buzzer actuator could be critical to the micro-pump performance

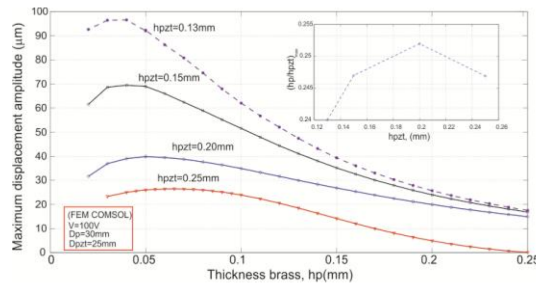

Figure 5. Amplitude variation, "*A*", of the PZT with the membrane thickness (h_p). The inset represents the ratio h_p / h_{pzt} that maximizes the displacement

There is a relationship between the membrane and ceramic tablet thicknesses, which maximizes the deformation amplitude (Figure 5). The maximum value, $(h_p/h_{pzt})_{max}$, can be obtained from the amplitude derivative curve, that is $\frac{\partial A(h_p)}{\partial h_p} = 0$. Then, h_p/h_{pzt} can be calculated for a range from 0.24 to 0.252, corresponding to $0.24 \leq (h_p/h_{pzt})_{max} \leq 0.252$. Therefore, one can adopt $(h_p/h_{pzt})_{max}$= 0.25 as a design criterion.

3.4 *Analysis of the buzzer diameter*

Figure 6 depicts the behavior of the maximum amplitude as a function of the ceramic radius (R_{pzt}), for membrane diameters of 15 mm, 20 mm, 27 mm, 35 mm, and 50 mm. By analogy with Figure 5, one can establish a variation range for which the actuator displacement is maximized, that is, by imposing $(\partial h_{pzt}/\partial h_p)_{max}$=0. Thus, one could choose $0.83 \leq (\partial h_{pzt}/\partial h_p)_{max} \leq 0.88$. Therefore $(\partial h_{pzt}/\partial h_p)$=0.85 has been chosen as another criterion for design. Since this variation range of displacements is not too critical, any value in the interval from 0.83 to 0.88 could be used, for diameters of the brass membrane in the range from 15 to 50 mm.

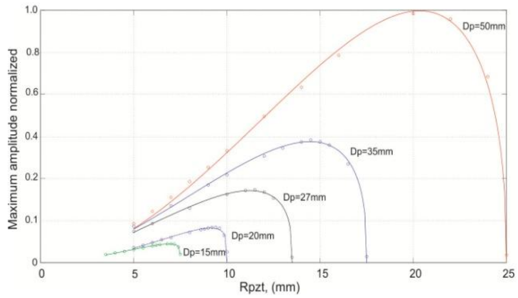

Figure 6. Maximum amplitude normalized for D_p equal to 15 mm, 20 mm, 27 mm, 35 mm, and 50 mm, using $(h_p/h_{pzt})_{max}$ =0.25.

One notice that the maximum displacement of the buzzer also depends on the applied voltage (see Figure 7). This variation allows the use of a micropump control system to define the flow-rate as a function of the applied voltage to the buzzer.

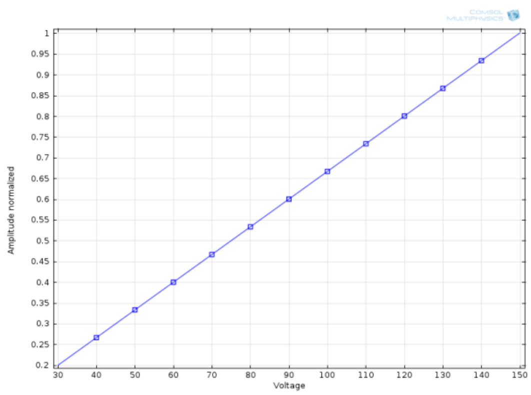

Figure 7. Linear behavior of the maximum displacement of the buzzer, depending linearly on the applied voltage.

4. Conclusions

The piezoelectric buzzer is a low-cost actuator that is an alternative to micro-pumps driving. Nevertheless, it requires one to make a visual inspection in order to evaluate the ceramic eccentricity, as well as to check if any unnecessary glue layer is present. Both variables affect the maximum displacement behavior. On the other hand, a commercial buzzer can be adequately chosen, taking into account the buzzer diameter and thickness ratios. Therefore, assuring the maximum displacement of the actuator makes it easier to satisfy the compressibility relation (ε>0.075), without having to decrease too much the micro-pump chamber height. This, in turn, facilitates the micro-pump construction.

5. References

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