Characterization of Soft Actuation Through Ultrasonic Atomization

Han-Joo Lee and Kenneth J. Loh

Abstract Most biological systems fully take advantage of their soft tissues by quickly reacting and interacting with the environment. This exceptional performance is possible due to flexible muscles that can bend and contract in multiple degrees-of-freedom. Since traditional robots with rigid components cannot mimic these movements, soft robotic systems fabricated from flexible elastomers are starting to receive much attention. Similarly, developing actuation techniques that can control the movement of these soft materials in multiple degrees-of-freedom is also crucial. This study proposes a new soft actuation mechanism through the use of ultrasonic atomization and small piezoelectric transducers. Unlike conventional pneumatic-based systems, this soft structure is completely untethered, which can be actuated by simply placing it above an ultrasonic transducer. First, a hollow structure was fabricated by pouring uncured elastomer into a 3D-printed mold. Second, the structure was partially filled with a small amount of liquid and placed above a piezoelectric disc. Then, exciting the transducer generated ultrasonic waves that propagated through the wall of the structure. When the amplitude of the ultrasonic wave was high enough, the liquid inside the structure was atomized and ejected small droplets inside the closed, soft chamber. These droplets rapidly evaporated and deformed the soft structure. In this work, the experimental results were compared with finite element modeling to characterize the ultrasonic-atomization-induced soft structure actuation.

Keywords Phase transformation · Simulation · Soft robotics · Ultrasonic atomization

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Introduction

Cephalopods are a family of marine invertebrates with soft tissues that exhibit extraordinary performances. The most famous examples are the octopus and squid that can control the color, stiffness, and even roughness of their soft tissue [1–3]. These animals can fit through the smallest apertures by stretching their body to up to 70% of elongation [4]. The soft nature of their body deforms with a nearly infinite number of degrees-of-freedom without any joints, which enables extremely complex movements. In addition, its compliant property allows the octopus to handle objects of various shapes and sizes with ease. These remarkable motions are enabled by soft muscle fibers that dynamically shorten or generate force to apply load [5].

Inspired by these organisms, soft robots are receiving much attention to mimic their complex behaviors. By utilizing soft materials (such as elastomers), these systems can deform similar to their biological counterparts. The octopus, in particular, has inspired several soft robotic systems [6–8]. For example, a soft robotic octopus arm was developed by embedding cables and shape memory alloys (SMA) into the soft structure [7]. Pulling the cables deformed the structure in a bending motion, whereas actuating the SMA elongated the arm or increased its stiffness. Another example of soft robotic systems is the untethered robot that can crawl in extreme environments [9]. Silicone rubber of high elastic modulus was used to support the weight of the entire system, including a mini air compressor. In addition, the weight of the system was minimized by embedding hollow glass spheres into the elastomer.

An important feature of these soft actuators is the size of the required control system as compared to the size of the actuator. If the soft robotic system does not need to move long distances, it can simply be tethered to a stationary control system. However, the control system should be fully embedded in the soft structure for applications that require deploying the robot to distant locations. The aforementioned methods that utilize pulling cables or changing pressure normally require heavy and bulky components, such as motors and pneumatic pumps. The volume and weight of these components may lower the efficiency of the soft actuator.

Compared to these methods, actuation by ultrasonic atomization requires a small piezoelectric disc [10]. The method involves propagating ultrasonic waves into a hollow structure that is partially filled with liquid. The ultrasonic wave propagates through the wall of the structure, interacting with the embedded fluid, to eject small droplets into the chamber. The high surface area of these droplets enables rapid evaporation, which inflates and deforms the system.

The objective of this study is to characterize ultrasonic-atomization-induced actuation performance by comparing experimental results with finite element models (FEM). In short, a soft structure was fabricated and actuated through ultrasonic atomization. The deformation due to evaporation was recorded and compared with numerical simulations. The amount of gas that was generated throughout actuation was determined from this comparative analysis. This paper starts with a discussion of the fabrication process and the experimental test setup. Then, the numerical model that simulated inflation of the structure is explained. In the last section, the results of the experiment and the numerical model are compared to characterize actuation performance.

Experimental Details

Fabrication and Test Setup

Soft structures were fabricated with a soft elastomer to characterize and demonstrate actuation. The fabrication process was reported in a previous study [10]. In short, the soft structures were fabricated using Dragon skin FX-Pro (Smooth-On Inc.), which is soft and easy to deform. First, the structure to characterize atomization was designed to be as simple as possible. A two-part mold in the shape of a cuboid was 3D printed with polylactic acid (PLA). Uncured Dragon skin was poured into the mold to make a hollow cuboid structure. A thin metal sheet was used as a bottom layer to seal the opening. The metal sheet was selected to maximize the propagation of the ultrasonic wave into the structure. It is worth mentioning that the top layer was much thinner than other walls, so that deformation would be concentrated on the top surface upon inflation of the hollow chamber. Second, the structure to demonstrate actuation was designed to have the shape of a bellows structure. Similar to the cuboid structure, uncured Dragon skin was poured into a 3D-printed mold. After curing the elastomer into a bellows structure, the openings were sealed with the same metal sheet. During the sealing process of both structures, a small amount of ethanol (~5 mL) was injected inside.

The overall test setup of the system is shown in Fig. 1. The cuboid structure itself is not tethered, and it can be actuated by simply placing the soft structure with the metal sheet directly above an ultrasonic transducer. A coupling agent was applied at the interface to provide better contact for wave propagation. Figure 1 also shows that the top layer of the structure is thinner as compared to the other walls to concentrate deformation at the top. Then, the ultrasonic transducer was excited with a square wave generated by a Keysight 33600A function generator. The signal was amplified and excited the transducer with a frequency of ~2.7 MHz and a power of ~23 W.

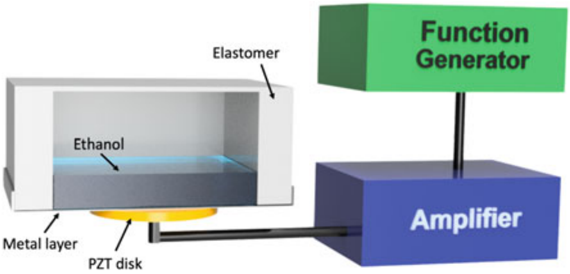

Fig. 1 Illustration shows the overall setup of the soft actuator

When conducting this test in open air (i.e., where the structure is open at the top), the setup was capable of atomizing ethanol at a rate of ~1.7 mg/s.

Numerical Model

An FEM model of the soft structure was implemented to simulate and correlate the displacement of the top with the amount of ethanol vapor generated inside the structure. The cuboid structure used in the experiment was replicated in COMSOL. The bottom plane of the structure was selected as the fixed boundary condition, and inflating the structure deformed the top thin layer. A hyperelastic model was used to characterize the soft elastomer, and the ideal gas model was employed for simulating the gas inside the chamber.

First, a tensile test was conducted on the soft material to characterize its physical properties. A hyperelastic model was used to characterize the nonlinear behavior of the material. The equation for the hyperelastic model is:

$$S = 2\frac{\partial W}{\partial C} \tag{1}$$

where S is the second Piola-Kirchhoff stress, W is the strain energy function, and C is the right Cauchy-Green deformation gradient tensor. Since the structure does not deform to extreme amounts of strain, the simplest Neo-Hookean model was used to characterize the stress–strain curve. The strain energy density for the Neo-Hookean model is:

$$W = C_1(I_1 - 3) \tag{2}$$

where C_1 is a material constant, and I_1 is the first invariant of the right Cauchy-Green deformation tensor. The material was assumed to be incompressible, and the material constant C_1 was determined from the tensile test.

The ideal gas law was applied to the inside of the structure to simulate inflation. The relationship between the pressure of gas, P, and volume, V, can be expressed as follows:

$$\frac{P}{P_0} = \left(\frac{V_0}{V}\right)^{\gamma} \tag{3}$$

where the subscript, 0, denotes the initial condition, and γ is the specific heat ratio. From Eq. (3), the pressure of each step was updated according to the corresponding change in volume.

Results and Discussion

Actuation Through Atomization

The demonstration of actuating the bellows structure is shown in Fig. 2. The thin metal sheet of the bottom layer was placed above the ultrasonic transducer, as shown in Fig. 2a. The setup was placed in front of a grid with lines separated by 5 mm. Exciting the transducer generated ultrasonic waves that propagated through the coupling agent and the thin metal sheet. Capillary waves were present throughout actuation and were directly observed through the translucent soft structure. Exciting the transducer for ~40 s inflated the structure, which is shown in Fig. 2b. This demonstration validated that ultrasonic atomization evaporated enough ethanol to deform the soft structure.

To characterize ultrasonic-atomization-induced soft structure actuation, the cuboid structure was actuated for ~20 s with the same condition. The simple geometry enabled easier analysis of deformation. Figure 3a shows a similar setup, where the bottom metal sheet was placed above the ultrasonic transducer. Similar to Fig. 2, exciting the transducer deformed the structure. Figure 3b shows the deformation of the top layer after ~20 s of actuation. In addition, the actuation of the structure was recorded with an infrared camera. The temperature distribution after ~20 s is shown in Fig. 3c. The high temperature of the bottom layer shows that the metal layer was subjected to ultrasonic heating, which is important when evaporating the ethanol droplets. In an open system, the droplets evaporated even when there was no temperature difference, since vapor pressure was not in equilibrium. However, the

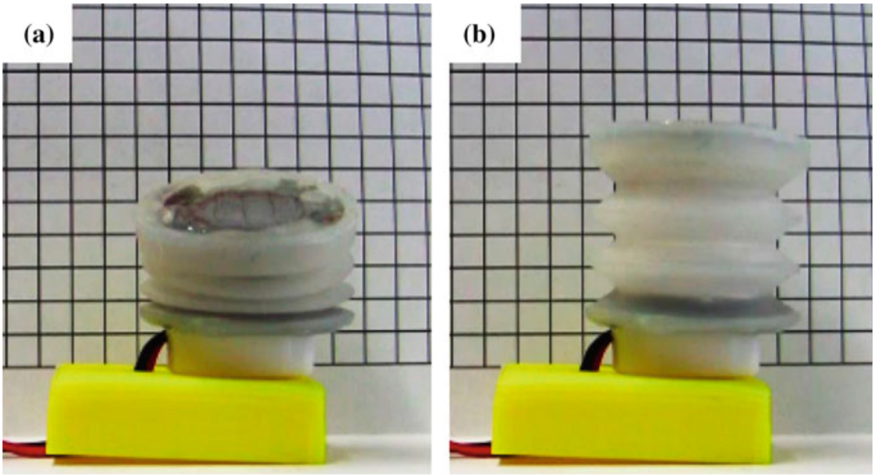

Fig. 2 Demonstration shows that the actuation method is capable of deforming a soft structure that is designed to maximize horizontal displacement. **a** A bellows structure filled with ethanol was placed above a piezoelectric disc. **b** Actuating the structure for ~40 s successfully inflated the structure

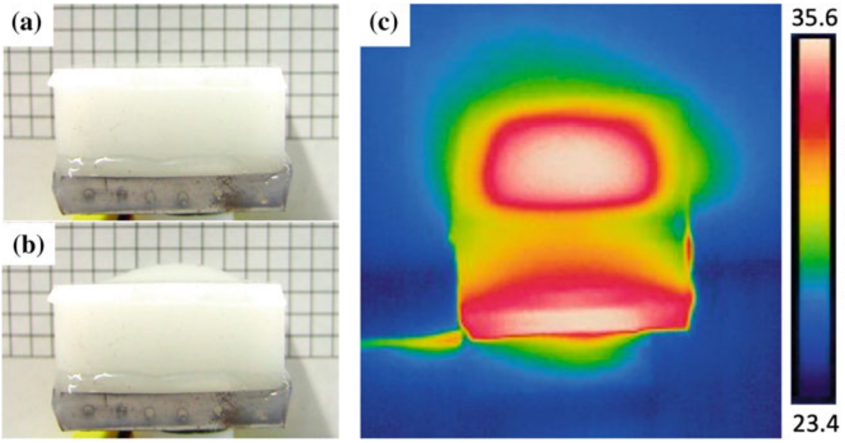

Fig. 3 **a** Fabricated structure was placed on top of a piezoelectric disc. **b** The displacement of the top layer reached ~5 mm after 20 s of actuation. **c** The image shows a temperature distribution of the structure after 20 s, and the maximum temperature was ~36 °C

evaporation rate and condensation rate of ethanol were already in equilibrium in a closed system. An additional driving force was required for the droplets to evaporate, and this driving force was provided by ultrasonic heating. It is also worth pointing out that the temperature of the top layer was similar to the temperature of the bottom layer. This indicates that the ultrasonic heating from the bottom layer heated the entire cavity, resulting in a uniform temperature distribution within the system.

The videos taken during the experiment was analyzed to plot the displacement and temperature change over time. The video that recorded the displacement of the top layer was analyzed using image processing to plot the displacement change of the top plane. The result is shown in Fig. 4a, where the displacement reached ~5 mm after ~20 s. The maximum temperature from the infrared camera was also recorded over time. The temperature change is plotted in Fig. 4b, where the maximum temperature reached ~36 °C after ~20 s.

Finite Element Model

A finite element model was used to study the experimental inflation of the structure. The stress–strain results of the soft elastomer were used to determine its physical property. COMSOL was used to ascertain the parameter for the Neo-Hookean model, which was ~65,000 Pa. After characterizing the physical property of the material, the ideal gas model was used to inflate the structure. Increasing the amount of gas inside the structure deformed the top layer of the structure. The simulation result is plotted in Fig. 5a, which shows the relationship between the increase in volume within the chamber and the displacement of the top layer. Through this relationship,

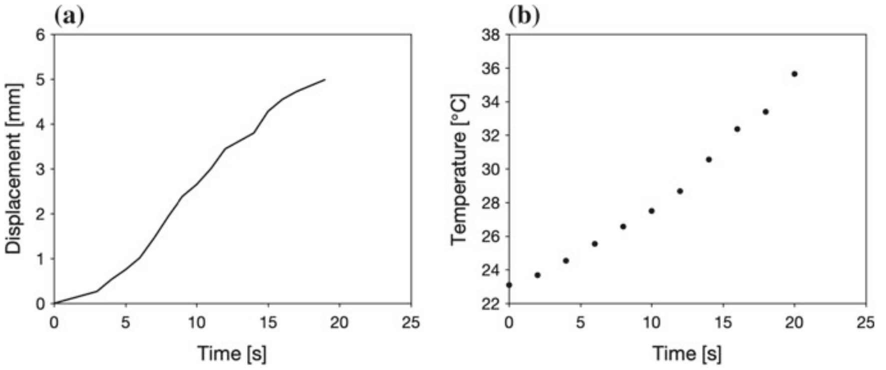

Fig. 4 **a** Image processing was used to measure the displacement of the top layer throughout soft structure actuation. **b** The temperature measured with the infrared camera was plotted with respect to time

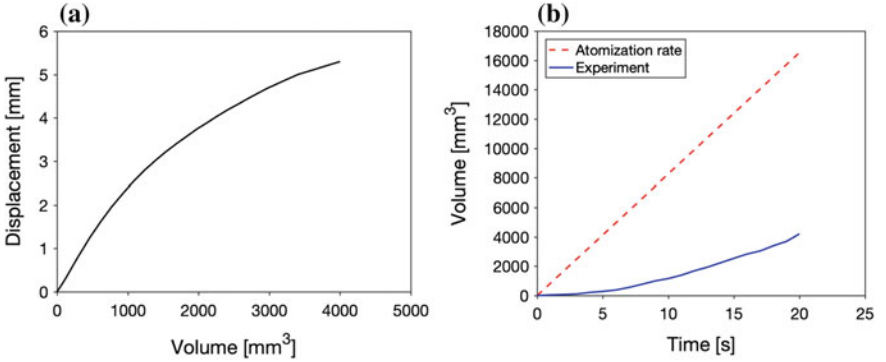

Fig. 5 **a** Hyperelastic and ideal gas models were used to simulate the relationship between the change in volume and the displacement of the top layer. **b** The simulation result was used to estimate the change in volume during the experiment. The dotted line indicates the change in volume of an ideal situation, assuming that all the droplets evaporated immediately

the displacement of the experimental result shown in Fig. 4a can be converted to change in volume. The result is plotted as a solid line in Fig. 5b. Since evaporation is highly related to temperature, the increasing trend of the volume was similar to the temperature plot in Fig. 4b.

It is worth pointing out that the system was capable of atomizing ethanol with a rate of ~1.7 mg/s in open air. Assuming a situation where 100% of the generated droplets evaporate immediately, the maximum volume change of the system can be calculated using the ideal gas law. This ideal case is plotted as a dotted line in Fig. 5b. The lower volume change during actuation indicates that only a portion of the generated droplets evaporated. Since temperature is highly related to evaporation, providing additional heat is expected to increase volume change during actuation.

This result also indicates that increasing the atomization rate will have little effect on increasing the actuation efficiency.

Conclusions

This paper demonstrates soft actuation through ultrasonic atomization and characterizes its performance through finite element modeling. First, a hollow structure was fabricated with a soft elastomer, and the bottom was sealed with a thin metal sheet. Second, a small amount of ethanol was injected into the structure to inflate the structure through evaporation. Third, the untethered structure was actuated by placing the metal sheet above an ultrasonic transducer. Ultrasonic waves propagated through the metal sheet and atomized the ethanol in the chamber. During this process, the bottom layer was heated by ultrasonic heating. This temperature rise evaporated the droplets and inflated the structure. Last, actuation performance was analyzed by comparing the experimental results with FEM simulations. The generated volume of gas inside the structure was obtained from simulations, and the results indicated that the actuation method could be improved by increasing the temperature difference.

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