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Wireless actuation with functional acoustic surfaces

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Miniaturization calls for micro-actuators that can be powered wirelessly and addressed individually. Here, we develop functional surfaces consisting of arrays of acoustically resonant micro-cavities, and we demonstrate their application as two-dimensional wireless actuators. When remotely powered by an acoustic field, the surfaces provide highly directional propulsive forces in fluids through acoustic streaming. A maximal force of ~0.45 mN is measured on a 4 × 4 mm² functional surface. The response of the surfaces with bubbles of different sizes is characterized experimentally. This shows a marked peak around the micro-bubbles’ resonance frequency, as estimated by both an analytical model and numerical simulations. The strong frequency dependence can be exploited to address different surfaces with different acoustic frequencies, thus achieving wireless actuation with multiple degrees of freedom. The use of the functional surfaces as wireless ready-to-attach actuators is demonstrated by implementing a wireless and bidirectional miniaturized rotary motor, which is 2.6 × 2.6 × 5 mm³ in size and generates a stall torque of ~0.5 mN-mm. The adoption of micro-structured surfaces as wireless actuators opens new possibilities in the development of miniaturized devices and tools for fluidic environments that are accessible by low intensity ultrasound fields.

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The miniaturization of active devices and robots is hindered by a lack of suitable actuators. Common actuators available at small scales (e.g., shape memory alloys, piezoelectric actuators, electro-active polymers) need a tethered power connection, which increases the system’s rigidity and complexity, and thus prevents effective downscaling. An alternative scheme is the wireless actuation via physical fields, such as magnetic fields, which provide large forces, fast response, and accurate control.1–5 However, magnetic fields are in general not sufficiently selective to address individual actuators at the same time,6 thus making multiple degrees-of-freedom (DoFs) control difficult.7 Recently, we have adopted a different approach based on structured light fields to realize many-DoFs soft sub-millimeter robots made of liquid crystalline elastomers.8 However, photo-thermal approaches are not suitable for applications that do not permit direct optical access to the working space. For these applications, ultrasound fields represent a more attractive means, as they can provide wireless power transfer through opaque media and also, in a range of frequencies and intensities, through biological tissue with negligible side-effects.9

Conversion of ultrasound into usable mechanical motion can proceed by (1) first converting the ultrasound to electricity using the piezoelectric effect, and then electrically powering an embedded actuator,10,11 or by (2) directly exploiting the acoustic energy to generate mechanical motion. In the former, the double energy transduction increases the system’s complexity and dramatically reduces its efficiency, making this method not suitable for small-scale devices. An example of the second approach is the use of geometrically asymmetric particles and inertial forces in fluids to generate steady stress on the particles, resulting in a finite propulsion speed, which was recently modeled by Lauga et al.12 and experimentally demonstrated by Mallouk et al.13,14 and Wang et al.15,16 A way to increase efficiency, while also enabling control of multiple DoFs, is to exploit acoustic resonances17 and frequency-division multiplexing. A spherical gas bubble submerged in a liquid, for instance, has a resonant frequency as described by the Rayleigh-Plesset equation,18 at which large volume oscillation is observed, and fluid streaming away from the bubble is induced.19,20 This phenomenon has recently been exploited to make microfluidic pumps, mixers,21 and self-propelling devices. For example, Dijkink et al. showed that a few oscillating bubbles (~φ250 μm × 3.4 mm) in tubes can power an “acoustic windmill” at the centimeter scale;22 Cho et al.23,24 and Huang et al.25 reported micro-swimmers at the scale of hundreds of microns that are propelled by streaming bubbles (50–100 μm in width and 100–700 μm in length). In all these examples, the acoustic streaming generated by one or a few bubbles has been adopted to propel devices that have a size comparable to the bubbles themselves. Acoustic streaming has so far not been exploited to develop general wireless actuators that can power devices much larger than the bubbles themselves, while also generating large forces and allowing for multiple DoFs.

In this letter, we report functional surfaces for the generation of acoustic streaming, and their exploitation as wireless and independently addressable two-dimensional (2D) actuators (Figs. 1(a) and 1(b)). They consist of arrays of thousands...
of resonant micro-scale bubbles, yet we use them for actuating a millimeter-scale device in a fluid. We show that under ultrasound excitation at the resonance frequency, the functional surface, which we call a Bubble Array Streaming Surface (BASS), generates a strong streaming flow and thus provides a propulsive force that can be used for actuation. The resonance frequency of an array is given by the dimension of the micro-bubbles and can therefore be accurately predicted analytically and by numerical simulations. We demonstrate that independent control of different BASS actuators can be achieved by frequency-division multiplexing.

The functional surfaces consisting of square 2D arrays of cylindrical cavities were fabricated by a photolithography process using a SU-8 photosensor (see supplementary material). The flow generated by a BASS actuator in the fluid was visualized by particle tracers and seen to stream away from the surface (Fig. 1(c) and Movie S1), and its velocity was measured by Particle Image Velocimetry (PIV). A maximum flow speed of $\sim 80\text{mm s}^{-1}$ was measured for a $4 \times 4\text{mm}^2$ functional surface consisting of a 2D array of $\sim 6200$ bubbles each 30 $\mu$m in diameter and 120 $\mu$m in length. To measure the propulsive force pushing the surface in the direction opposite to the streaming flow, the surface was attached to a force sensor (403 A, Aurora Scientific, Dublin, Ireland). A maximal force of about 0.45 mN was observed. As a negative control, a surface made with the same material but without any micro-cavities, i.e., no micro-bubbles, was tested under the same ultrasound excitation conditions. No streaming flow was observed by PIV (Fig. S2 and Movie S2), and the propulsive force remained negligible, which clearly demonstrates that direct actuation by the acoustic radiation force has a negligible role in our BASS actuators. Therefore, the propulsive force generated by the BASS actuators is indeed due to the acoustic streaming induced by the micro-bubbles under the external ultrasound field. As shown in Fig. 1(c), the streaming flow is roughly perpendicular to the surface and away from it; thus, the propulsive force is assumed to be normal to the surface. This is independent from the direction of the incident ultrasound wave, whose wavelength is much longer than the size of both the bubbles and the surface itself.

We observed that the streaming force generated by each BASS actuator is only significant in a narrow frequency range, showing a marked resonance peak. To compare the resonance frequency of the functional surfaces with that of their constitutive units, we derived a simple analytical model of the resonant frequency of a single cylindrical bubble. The schematic of the model considered below is illustrated in Fig. 2(a). As in Ref. 26, the bubble is treated as a harmonic oscillator with spring constant $k$ and mass $m$, having resonance frequency $f_0 = \frac{1}{2\pi} \sqrt{\frac{k}{m}}$. By considering that the bubble is confined to a rigid cylindrical cavity and oscillates only along its length, and by neglecting effects due to the surface tension, the equivalent spring constant can be expressed as

$$k \approx \frac{\pi}{3} R_c^3 \frac{P_0}{L_c},$$

where $\gamma$ is the adiabatic index (1.4 for air), $R_c$ and $L_c$ are the radius and length of the cavity, respectively, and $P_0$ is the atmospheric pressure (see supplementary material). As reported previously,26 the equivalent oscillator’s mass should be considered as consisting of the fluid mass in the cavity, $m_c$, plus an added mass $m_a$ that takes into account the fluid outside the cavity. As in our case, the bubble fills the cavity almost completely $m_c \approx 0$ and $m \approx m_a$. We assume that this mass corresponds to that of a thin disk of fluid that is right out of the cavity and having the same radius of the cavity (see Fig. 2(a) and supplementary material). Thus, the total mass of the bubble oscillator can be obtained as

$$m \approx m_a = \frac{8}{3} \rho R_c^3.$$

Therefore, the resonance frequency of a single bubble oscillating in a rigid cylindrical cavity is estimated as

$$f_0 \approx \frac{1}{2\pi} \sqrt{\frac{3\pi \gamma P_0}{8R_c L_c \rho}}.$$  

This expression allowed us to predict the resonance frequency of different bubble sizes, plotted as solid lines in Fig. 2(b). In order to more accurately determine the resonance
frequency of the cylindrical bubbles used in the experiment, numerical simulations were also conducted. A 2D axisymmetric model was developed, with the detailed geometry and materials illustrated in Fig. S1. The first natural frequencies for the different bubble sizes are plotted as dashed lines in Fig. 2(b).

To investigate the dependence of the resonance frequency of the BASS actuators on their constitutive bubbles’ size, functional surfaces with different cavity sizes were fabricated. In particular, cylindrical cavities with four lengths were fabricated, i.e., 30 \( \mu \)m, 55 \( \mu \)m, 120 \( \mu \)m, and 200 \( \mu \)m, and with different radii for each length (see Table S1 for detailed dimensions). A frequency sweep in 0.1 kHz steps was performed to determine the Frequency of the Peak Streaming Velocity (FPSV) for each bubble size (see supplementary material for detailed methods). This corresponds to the frequency at which the maximum streaming velocity was observed by PIV (Fig. 2(b)). The FPSV agrees well with the resonance frequency of the micro-bubbles, as determined both analytically and numerically. This confirms that the strongest acoustic streaming occurs upon resonance of the micro-bubbles. Interestingly, as predicted by Equation (3) and plotted in the inset of Fig. 2(b), the resonance frequency shows a linear relationship with the longitudinal cross-sectional area 2\( R_c L_c \) on a log-log scale. The error bars in Fig. 2(b) represent the bandwidth or operational range of the functional surfaces, namely, the minimum and maximum frequencies at which fluid streaming was observed by PIV. The bandwidth of each BASS is about 10 kHz; thus, in principle 18 independent actuation channels can be achieved by frequency-division multiplexing within a frequency range of 20–200 kHz. The continuous-wave ultrasound powering the BASS has a measured maximal pressure amplitude of 160 kPa, which corresponds to a maximal intensity of 1.7 W cm\(^{-2}\). Currently, there is no safety guideline for continuous ultrasound exposure; however, the intensity used here is two orders of magnitude lower than the threshold causing animal tissue injury as reported by a previous study. Nonetheless, further studies on the prolonged exposure to low-frequency ultrasounds are a prerequisite to develop safe actuators for biomedical applications.

To prove the flexibility of the functional surfaces as ready-to-attach wireless actuators, a miniaturized wireless motor is developed by equipping a passive device with two different kinds of BASS actuators. Fig. 3(a) shows a schematic of the mini-motor, which consists of a static shaft and a rotor 5 mm in length and a cross-sectional area of 2.6 \( \times \) 2.6 mm\(^2\). On each of the four surfaces of the rotor, two BASS actuators with cavities of different sizes are attached, which have different resonance frequencies and can therefore be addressed independently. The yellow surfaces have cavities that are 30 \( \mu \)m in diameter and 120 \( \mu \)m in length, which gives a resonance frequency \( f_1 = 51.3 \) kHz. The blue surface has cavities that are 10 \( \mu \)m in diameter and 55 \( \mu \)m in length, which corresponds to...
a resonance frequency of \( f_2 = 115.3 \, \text{kHz} \). When an acoustic signal of frequency \( f_1 \) is applied, the streaming only occurs from the yellow surfaces which generates a clockwise (CW) torque, and propels the rotor in the CW direction, as illustrated in the inset of Fig. 3(a) and shown during 1–8 s in Fig. 3(b) (see also Movie S3). Correspondingly, when the frequency is switched to \( f_2 \), the blue surface is activated, and the rotor spins in the opposite, counter-clockwise (CCW) direction (9–14 s in Fig. 3(b) and Movie S3).

The rotational speed of the motor was measured by a high speed camera. As shown in Fig. 3(c), the speed is proportional to the driving voltage of the ultrasound transducer at low voltage, and saturates at 100 V, consistent with the observed propulsive force of the BASS actuators. For the same acoustic pressure of around 110 kPa, the CW rotation observed propulsive force of the BASS actuators. For the general lead to a higher propulsive force for the same acoustic pressure, because a larger compressibility of the bubbles generally lead to a higher propulsive force for the same bubble area compared with a smaller compressibility of the bubbles results in a larger oscillation amplitude and thus stronger streaming. The mini-motor reaches a maximal rotation speed of about 1000 rpm under no load. The size of the motor is \( 2.6 \times 2.6 \times 5 \, \text{mm}^3 \), and 4 surfaces (\( 1 \times 5 \, \text{mm}^2 \) in size, \( \sim 0.2 \, \text{mN} \) maximal propulsive force each in stall—no drag—conditions, \( 2.6/4 \, \text{mm distance from the rotational axis} \) are used for one rotational direction. Thus, the stall torque of the mini-motor is estimated to be \( \sim 0.5 \, \text{mN} \cdot \text{mm} \). Even though the acoustic mini-motor cannot match a wired commercial electromagnetic motor of a similar size (\( \phi 1.9 \, \text{mm} \times 6 \, \text{mm}, \) which has a 100,000 rpm no-load speed and a 9.5 \( \text{mm} \cdot \text{mm} \) stall torque\(^{36}\)), it has the fundamental advantage of being wireless and operational underwater. In addition, the torques that can be provided by the two motors per unit mass are very comparable, which are 105 \( \text{mN} \cdot \text{mm} \cdot \text{g}^{-1} \) for the wired electromagnetic motor and 92 \( \text{mN} \cdot \text{mm} \cdot \text{g}^{-1} \) for the wireless BASS motor. It should also be noticed that, unlike the electromagnetic motor, the BASS motor can be readily miniaturized to the sub-millimeter scale, also showing a more favorable downsizing of the generated torque with respect to the electromagnetic motor.

In summary, we report the fabrication and characterization of 2D actuators consisting of functional surfaces that are wirelessly powered by ultrasounds in water and allow for actuation with multiple DoFs. The functional surfaces consist of arrays of micro-bubbles and serve as streaming-based wireless actuators that can be seamlessly integrated in otherwise passive millimeter-scale devices. In contrast to bulk actuators, no specific consideration is needed for the mechanical coupling and integration of the surface actuators, which also minimizes the volume and weight required for actuation, thus making them particularly well-suited for miniaturization. Moreover, if the surface actuators are made of a thin polymeric material, they can also be customized to match the shape of complicated three-dimensional object. The bubble array streaming surface (BASS) actuators developed here are scalable, easy to fabricate, and powered by low-intensity ultrasound fields. Future work will be devoted to assessing the actuators in biological fluids and body cavities, as well as to ensure the in vivo safety for the wireless actuation of micro-robots and miniaturized medical instruments.

See supplementary material for detailed methods, supplementary figures and videos.

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