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Stepwise Microactuators Powered by Ultrasonic Transfer

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Abstract

We propose a new way to deliver power to biomedical implants in order to address the higher energy requirements of microsystems with actuation functions such as drug release or mechanical adjustment of prosthetic devices. The method is based on ultrasonic power delivery, the novelty being that actuation is powered by ultrasound directly rather than via electrical form. The device consists of a mechanical oscillator which vibrates in response to incoming ultrasonic waves, and then converts these oscillations into stepwise motion of a mechanical actuator through oblique impact. Therefore, unlike conventional wireless power delivery or energy harvesting techniques, the proposed system is purely mechanical and does not include accumulation and storage of electrical energy or the conversion of energy from mechanical to electrical form, making it simpler and more efficient.

Keywords: Implantable microactuators; power transmission; ultrasonic power; ultrasound; wireless power delivery

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1. Introduction

Biomedical implants inside the human body can be broadly divided into two categories: diagnostic and therapeutic. These differ in the level of energy required for their operation. Diagnostic implants performing sensing and monitoring usually require little energy, while the therapeutic ones with actuation functions, such as electrical stimulation, mechanical motion or valve operation, need much more. Batteries as the primary power source perform very well; however, they typically dominate the size and the cost of the device. In addition, they have to be occasionally recharged or replaced which introduces significant burden and discomfort to the patient. An attractive alternative to batteries is energy harvesting, which deals with extracting electrical energy from different ambient sources such as solar power, thermal

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energy or various motion sources like body movement, machine and building vibrations. While a lot of effort is put into improving energy harvesters and raising their efficiency [1], the power output is still limited.

We aim to extend the range of battery-less implants to include therapeutic functions, and therefore propose an alternative technique to energize implants which is not to harvest ambient energy, but to provide it directly from a wireless source. The most widespread and well established method of wireless power delivery into the human body is via inductively coupled coils. However this method suffers from low efficiency at larger distances, in particular for smaller receiving devices [2]. Ultrasound is an attractive source of energy for miniature biomedical implants. It is considered more attractive and safer for implants located deeply inside the body near vital organs.

Ultrasound as a power source receives increased attention today and several groups have proposed solutions [3, 4]. However, the idea behind their systems does not deviate much from energy harvesting. The only difference is that the energy now comes from a dedicated piezoelectric transducer rather than the ambient environment. This mechanical energy is still converted into electrical form and has to be accumulated and stored before it can be used by an implant. For biomedical implants with the aforementioned actuation functions, we propose direct conversion of ultrasonic power to mechanical actuation, making energy accumulation and storage unnecessary.

In this paper we present a new concept of a stepwise movable microstructure mechanically actuated by ultrasound. We discuss its main components and operating principles as well as simulation results of its mechanical behavior. Key design challenges in building a simple and efficient system are also analyzed. Finally, we discuss main milestones for future work, including fabrication and characterization of the first prototype.

2. System design

The system is a purely mechanical oscillator remotely excited by ultrasound (Fig. 1). It is designed in such a way that under ultrasonic excitation the oscillator starts vibrating and during each cycle of these vibrations it strikes another device – the actuator – in a certain way in order to transmit to it some mechanical energy. Therefore the periodic vibration of an oscillator is converted into a stepwise motion of an actuator. It is this actuator that actually performs some useful motion and can be of different types depending on the application. If, for example, prosthesis mechanical adjustment was needed, the actuator could look similar to the one in Fig. 1, while for drug release system it could resemble a carousel.

A key design challenge is to effectively couple propagating acoustic waves to the discrete mechanical system. In order to avoid wave reflections and absorb most of the ultrasonic energy, we designed a system with the mechanical impedance closely matched to the acoustic impedance of the tissue, consisting of a membrane mechanically coupled to the oscillator body (Fig. 2). This coupling mechanism introduces asymmetry, and provides conversion of the membrane normal vibration to the oscillator in-plane motion.

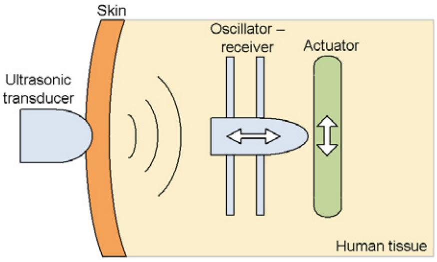

Fig. 1. Stepwise movable microsystem actuated by ultrasonic waves

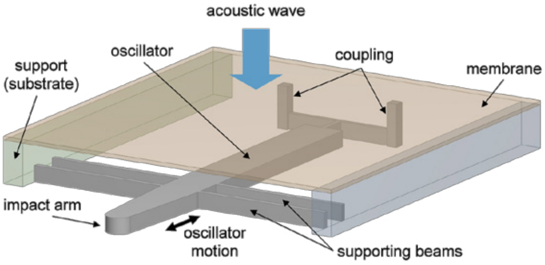

Fig. 2. Coupled mechanical oscillator

In addition, it increases the oscillator vibration amplitude. The receiving membrane has an area of 0.5 mm^2 and the overall device height is 60 µm.

Fig. 3 shows an actuator driven by four oscillators through oblique impact (as in [5]). It is simply a slider suspended on four springs with the oscillators located symmetrically on its opposite sides at a certain gap (2 to 15 µm in different configurations) and inclined at 45º. The first prototype of the system is 8.5 mm × 8.5 mm across. It will be driven by an ultrasonic source at a frequency of 200 kHz. The actuator is not connected to any load (medical device) as it is designed only to prove the concept of converting the ultrasonic energy into mechanical vibrations, and from there into continuous actuation.

3. Results

In order to simulate the mechanical behavior of the oscillating system it is necessary to perform its harmonic analysis first. This is done numerically using ANSYS finite element software. Fig. 4 illustrates the system vibrating at its first resonance (200 kHz), which corresponds to the in-plane motion of the oscillator impact arm. It is the main frequency at which the oscillator will be operating. The second resonance frequency corresponds to an out-of-plane (“parasitic”) component of impact arm motion. The third and higher resonance modes correspond mainly to the membrane bending where the oscillator does not move in the in-plane direction significantly.

The next step is to find the amplitude of the system mechanical vibration when it is driven by external ultrasound. The important input parameter in the simulation is the acoustic force experienced by the membrane coupled to the oscillator mechanically. This force is found by analyzing the problem of the pressure field generated by a plane-piston transducer [6]. Assuming that the receiver of ultrasonic energy is located in the natural focus of the transmitter (also called the Fresnel distance, separating near field and far field regions) and taking into account receiver geometry, a force of 0.2 N on its surface is estimated (for the 20 V_{p-p} transmitter excitation and the Fresnel distance of 2 cm).

To obtain reliable oblique impact, the membrane was coupled to the oscillator through a soft flexure. This allowed moving the first resonance frequency away from higher harmonics, as well as minimizing the out-of-plane component of the oscillator vibration. Fig. 5 shows the frequency response of the system (in-plane vibration of the impact arm) under an acoustic force of 0.2 N on the membrane surface. The maximum peak of vibration amplitude is 30 µm and it occurs at the first resonance frequency of 200 kHz. Peaks from higher harmonics are much less pronounced.

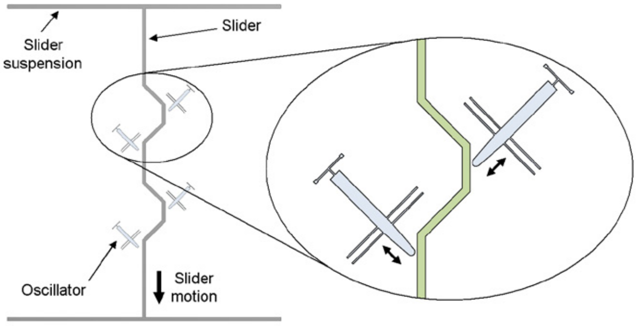

Fig. 3. Stepwise movable microsystem actuated by ultrasonic waves

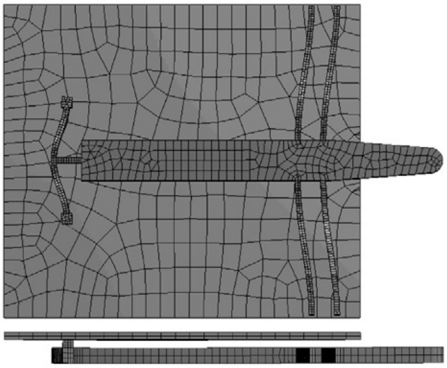

Fig. 4. First resonance frequency of the system (200 kHz) showing in-plane vibration

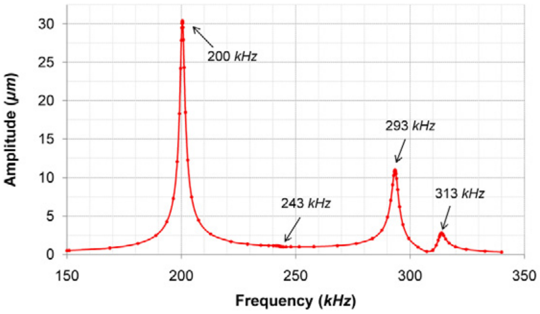

Fig. 5. Frequency response of the impact arm

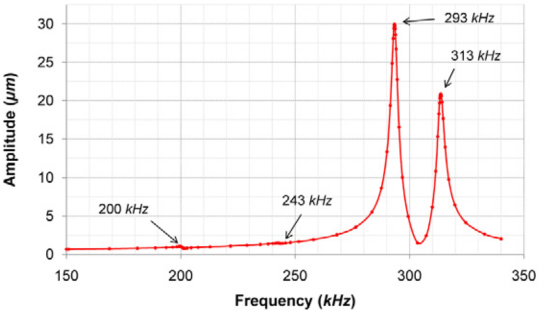

Fig. 6. Frequency response of the membrane

As already discussed, the mechanical impedance of the oscillating system has to be matched with the acoustic impedance of the medium in order to avoid wave reflections and provide efficient coupling. The mechanical impedance is related to the membrane vibration amplitude, so its frequency response was analyzed (Fig. 6). The peak amplitude at the first resonance frequency is 1 µm and it is exceeded by much more pronounced peaks at the higher harmonics. The acoustic impedance of an element with an area corresponding to the membrane is $Z_a = 0.64$ kg/s for soft human tissue [2], while the mechanical impedance of the system is $Z_m = 0.16$ kg/s [7]. This gives a pressure reflection coefficient, $R = (Z_m - Z_a) / (Z_m + Z_a) = -0.6$, and the power reflection coefficient, $R_{\Pi} = |R^2| = 0.36$.

Taking into account the reflected energy, the overall mechanical displacement of the impact arm is 12 µm. Therefore, more than a third of the acoustic energy is reflected back to the source, making it a challenging task to design an efficient acoustic coupler which minimizes the wave reflections and at the same time provides acceptable vibration amplitude.

4. Conclusion and future work

A new concept of energizing implantable biomedical devices by ultrasonic power delivery has been proposed. The first prototype of the stepwise rectilinear microactuator along with its fabrication process has been developed. Main milestones for future work include fabrication of the prototype and its characterization.

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