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Development of a resonance generator utilizing incomplete tetanus of skeletal muscle*

T. Mochida, *Student Member, IEEE* and W. Hijikata, *Member, IEEE*

***Abstract*— Implantable energy harvesting system utilizing contraction of an electrically-stimulated skeletal muscle is proposed for alternative batteries of implantable medical devices. In order to realize high conversion efficiency, we propose a resonance generator utilizing vibration of the skeletal muscle, which is called as incomplete tetanus. Experimental results showed the incomplete tetanus was a suitable form for the energy harvesting and the stimulation at the frequency of 10 Hz was maximized the work of the muscle. Dimensions of the springs of the generator were designed so that its natural frequency was 10 Hz. On the simulation, the maximum generated power was achieved 122.5 μW, which is enough to power the IMDs.**

***Clinical Relevance*— The proposed system has a potential to eliminate conventional batteries in the implantable medical devices. It will be beneficial for patients since the periodical surgery for the battery replacement will be avoided.**

I. Introduction

Due to aging populations in the developed countries, there have been many people suffering from cardiovascular diseases, such as arrhythmias and bradycardia. This has led to high demand for implantable medical devices (IMDs) such as artificial cardiac pacemakers and implantable cardiac defibrillators (ICD). In general, the power to drive these devices consuming 30 – 100 μW [1] is supplied by batteries. One of the issues in these devices is the periodical surgery, which is required to replace the batteries at the end of their lifetimes. It is reported the surgery is conducted every 10 years for a pacemaker [2], 5 – 9 years for an ICD [3]. These replacement surgeries are physical and financial burdens for the patients [4].

One of the solutions for these problems is to supply electrical energy generated from some resources in the human body, which is called an implantable energy harvesting system. In order to realize this system, a generator utilizing a heartbeat has been developed so far [5]. Despite the powerful and continuous resource of mechanical energy, the possible breakdown of the devices may cause fatal damage since the heart is essential to maintaining life. In order to avoid this problem, we focused on an energy harvesting system utilizing a contraction of the electrically-stimulated muscle as shown in Fig. 1. In order to generate the electrical power continuously, the skeletal muscle is forced to contract by electrical stimulation supplied from a battery of the IMD. The generator converts the mechanical energy of the muscle contraction into the electrical energy and supplies it to the battery. Most of the

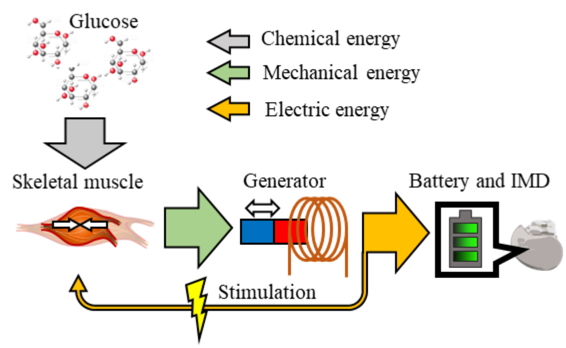

Figure 1. Energy flow of the proposed energy harvesting system

electrical energy is consumed by the IMD, and the rest is used to stimulate the skeletal muscle again. The power density of the contraction of the skeletal muscle is reported as about 1 mW/g [6], while the energy consumption of the stimulation on the skeletal muscle is several microwatts. This is because the energy resource of the muscle contraction is the glucose in the human body, not the electrical stimulation. Therefore, a few grams of the skeletal muscle can manage to supply the IMD.

The goal of this study is to realize an energy harvesting system utilizing the contraction of the skeletal muscle. Our research group previously developed electromagnetic generators utilizing the contraction of the muscles [7] [8]. Despite the positive net power, the experimental results showed power generated was not enough to drive IMDs. In order to increase the power, we propose a resonance generator utilizing incomplete tetanus of the skeletal muscle. Incomplete tetanus is a phenomenon such that the electrically-stimulated skeletal muscle repeats the contraction and relaxation at the stimulation frequency which is lower than that of complete tetanus. Since the energy consumption of the incomplete tetanus is less than that of the complete tetanus, the net power is expected to be improved. As a first step, the stimulation frequency condition of incomplete tetanus that is compatible for the generation was derived. Then, based on this frequency, we proposed the design method of the resonance electrostatic implantable generator whose power generated was maximized considering the dynamics of the mechanism.

II. Derivation of the Compatible Frequency Condition of Incomplete Tetanus

A. Experimental method

Utilizing the skeletal muscle of the toads (*Xenopus leavis*, $N = 2$) —the average weights of the whole body were 225.2 ±

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T. Mochida and W. Hijikata are with the Tokyo Institute of Technology, Ookayama, Meguro-ku, Tokyo, 1528550, Japan (corresponding author to provide phone/fax +81-3-5734-2200; Email: hijikata.w.aa@m.titech.ac.jp)

23.4 g—, the work of the muscle contraction at each frequency was compared in order to derive the frequency condition that is suitable for generation. An experimental setup is shown in Fig. 2. The toads were anesthetized with 0.2 wt% tricaine and 0.4 wt% sodium hydrogen carbonate to maintain a neutral pH when immersed. Since the legs of the toad were sufficiently well-developed, the gastrocnemius muscles of the toads were utilized for the skeletal muscles in our experiment. After 30 minutes, confirming that the toads did not react to any external stimulus, we made an incision in their legs, cut the Achilles tendons, and removed the muscles from the bones. The average weight of the gastrocnemius muscles was 4.3 ± 0.1 g and the average length was 31.5 ± 1.5 mm. After the operation, stimulation electrodes were threaded into the muscle and their legs were fixed on the lab jack by the cable ties. The muscle, a displacement marker, a spring with its spring constant of 80 N/m, and a force sensor (LTS-1KA, Kyowa Electronic Instruments Co., Ltd., Tokyo, Japan) for measurement of the contraction force were connected in series. The displacement of the muscle was measured by the displacement marker and the laser displacement sensor (LK-G155, KEYENCE Co., Osaka, Japan).

A two-phase rectangular wave with a pulse width of 0.2 ms was applied to the electrodes for stimulation from a function generator (IM3570, HIOKI E. E. Co., Nagano, Japan). In this experiment, the muscles were stimulated for 0.4 s, and the work of the muscle contraction was calculated based on the measured displacement and force. A preliminary experiment revealed that the peak contraction force becomes flat at the voltage amplitude of 5.5 V and complete tetanus occurs at a frequency of 20 Hz. Since it is assumed that the generator utilizes the incomplete tetanus, by varying the voltage amplitude in the extent of 2~5.5 V and frequency in the extent of 5~20 Hz, the work of the muscle contraction at each condition was compared. In this experiment, the muscles were stimulated at each condition in an interval of 1 minute so that the influence of the muscle fatigue was small.

B. *Experimental Result*

The work of the muscle contraction at each condition is shown in Fig. 3. The work of the muscle contraction was maximized at 10 Hz and 5.5 V. The work of the complete tetanus (20 Hz) was as much as that of the incomplete tetanus (10 Hz). However, according to the displacement of the muscle shown in Fig. 4, the displacement at 20 Hz increased immediately after stimulation and was kept constant. From these results, the work will become constant despite the longer duration time. On the other hand, since the displacement of the incomplete tetanus (5 ~ 15 Hz) was vibrated, the work will increase according to the duration time. Thus, the incomplete tetanus is supposed to be a compatible form of the contraction for the energy harvesting.

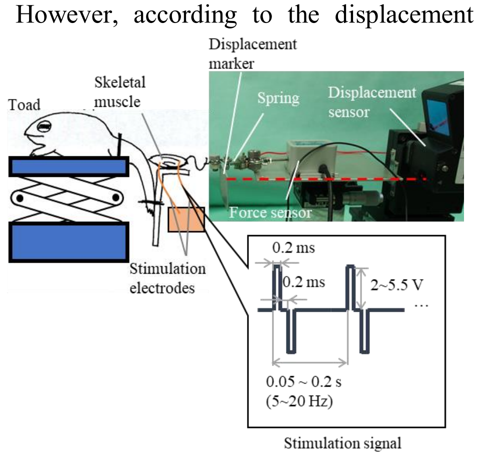

Figure 2. Experimental setup for the derivation of the optimized frequency condition

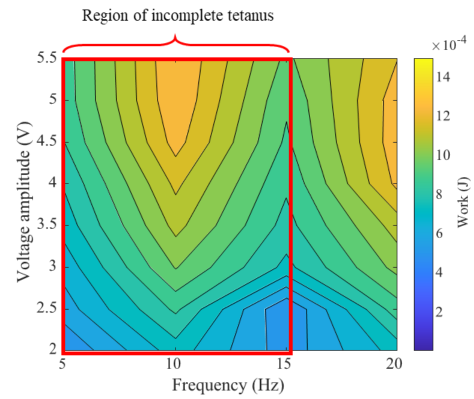

Figure. 3 Relationship among the voltage, frequency, and work by the skeletal muscle

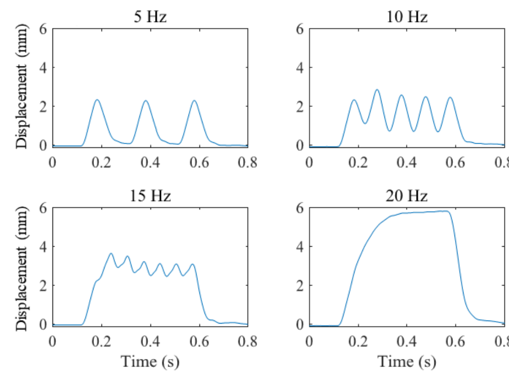

Figure 4. The displacement comparison of each frequency at the same voltage amplitude (5.5 V)

In the region of the incomplete tetanus, the more the stimulation frequency was, the more frequent the muscle contracted and relaxed. Hence, the work by the muscle was increased in the frequency of 5 ~ 10 Hz. When the frequency was increased higher than 10 Hz, however, the muscle contracted before relaxing completely. It resulted in the decrease of the amplitude of displacement and the work of the muscle contraction. Therefore, incomplete tetanus at 10 Hz was the most compatible frequency condition for generation.

III. Design of the Generator

A. *Configuration of the generator*

Based on the frequency condition of the incomplete tetanus derived from the previous section, we proposed design method of the generator. The concept of the self-resonant generator mechanism is shown in Fig. 5. The generator and the stimulation electrodes are mounted on the IMD and it is located on the skeletal muscle. During stimulation, the oscillator resonates with the incomplete tetanus and the generated electrical energy is supplied to the battery. In order to convert the mechanical energy of the vibration at low frequency into the electric energy efficiently, electromagnetic

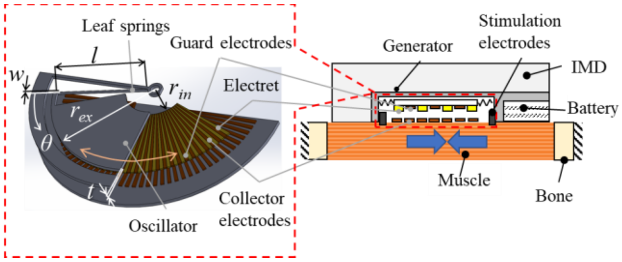

Figure 5. Concept of the proposed electrostatic generator

and electrostatic induction are candidates. In case of the electrostatic induction with electrets, electrodes and electrets can be miniaturized on tens of micrometer scale by MEMS (Micro Electro Mechanical Systems) process. It results that the mechanical energy at low frequency is converted into the electrical energy efficiently. Thus, the electrostatic induction was chosen as the energy conversion method. In order to increase the amplitude of the oscillator in limited space, the oscillator is a fan shape and leaf springs are located radially so that the oscillator can rotate. The dimensions of the leaf springs, especially the width, are to be small in order to adjust the natural frequency to the frequency of the incomplete tetanus, i.e., 10 Hz. Thus, MEMS process is utilized for the fabrication of the generator.

B. Design of the leaf springs

The equation of motion about the angle displacement θ of the oscillator is expressed as follows.

$$\left(I + \frac{3m\left(r_{ex}^2 + r_{in}^2\right)}{4} \right)\ddot{\theta} + c\dot{\theta} + k_\theta \theta = -m\frac{\sqrt{3\left(r_{ex}^2 + r_{in}^2\right)}}{2}\cos\theta \ddot{x}_m \quad (1)$$

Where, I is the moment of inertia, c is the damping coefficient including the electrostatic induction, k_θ is the rotational stiffness, x_m is the displacement of the muscle, and m is the mass of the oscillator expressed as follows.

$$m = \rho\varphi\left(r_{ex}^2 - r_{in}^2\right) \quad (2)$$

Where, r_{in}, and r_{ex} are the inner and the outer radius of the fan shape, φ is the central angle of the fan shape, and ρ is the density of Si substrates for MEMS process. According to (1), the natural frequency of the oscillator is expressed as follows.

$$\omega_n = \sqrt{\frac{4k_\theta}{4I + 3m\left(r_{ex}^2 + r_{in}^2\right)}} \quad (3)$$

The stiffness of the leaf springs k is expressed as follows [9].

$$k = nEh\left(\frac{t}{l}\right)^3 \quad (4)$$

Where, E is Young's modulus of Si, n, l, t, and h are the number, length, thickness, and height of the leaf spring, respectively. Here, h was 0.53 mm, which is the same value of Si substrate, and n was 2. When the leaf springs are located radially, the oscillator can rotate with a constant radius. Then, rotational stiffness k_θ is derived as follows by considering that the displacement in rotational direction as $l\theta$ when the oscillator rotates at θ.

$$k_\theta = \frac{nEht^3}{l} \quad (5)$$

Therefore, by substituting (2) and (5) into (3), the relation among the natural frequency and the dimensions of the leaf springs and the fan shape is obtained. On the other hand, it is concerned that the spring was deflected vertically against the direction of the oscillation due to the weight of the oscillator. It enlarges the gap between electrodes and electrets and results in the decrease of the power generated. Thus, the stiffness k_v in that direction expressed as follows is also important.

$$k_v = \frac{1}{4}nEt\left(\frac{h}{l}\right)^3 \quad (6)$$

Thus, calculated deflection x by the weight of the oscillator is expressed as follows.

$$x = \frac{\rho\varphi g(r_{ex}^2 - r_{in}^2)}{k_v} = \frac{4\rho\varphi g(r_{ex}^2 - r_{in}^2)}{nEt}\left(\frac{l}{h}\right)^3 \quad (7)$$

Generally, the gap between the electrodes and electrets ranges from tens of micrometers to 100 µm. Thus, the allowable deflection was set to 10 µm. Therefore, the thickness t, the length l, the inner radius r_{in}, the outer radius r_{ex}, and the central angle φ were determined as 31 µm, 12.5 mm, 4 mm, 14 mm, and 126° respectively so that the natural frequency of the oscillator corresponds to 10 Hz and the deflection by the weight was within 10 µm by using (3) and (7).

C. Estimation of the power generated

Fig. 6 shows the circuit model of the electrostatic generator with the electrets [10], where σ is the surface charge density, E is the Electrostatic field, d_{el} is the thickness of the electret, d is the gap between electret and collector electrodes, and S is the areas overlapping the collector electrodes. Subscripts *e, a,* and *b* represent the electret and the overlapping area with the electrets and guard electrodes. Applying Gauss's law at the electret surface, following equation is obtained.

$$-\varepsilon_0\varepsilon_r E_e + \varepsilon_0 E_a = \sigma \quad (8)$$

Where, ε_0 is the permittivity of the vacuum and ε_r is the relative permittivity of the electret material (ε_r=2.1). Then, using Kirchhoff's low, following equations related to the voltage drop are obtained.

$$V + d_{el}E_e + dE_a = 0 \quad (9)$$

$$V + \left(d + d_{el}\right)E_b = 0 \quad (10)$$

$$i(t) = \frac{V}{R} + C_p\frac{dV}{dt} \quad (11)$$

Where, V is the output voltage, R is the load resistance, and the C_p is the parasitic capacitor. The inducted current $i(t)$ is derived by the conservation of charges of the collector electrode as follows.

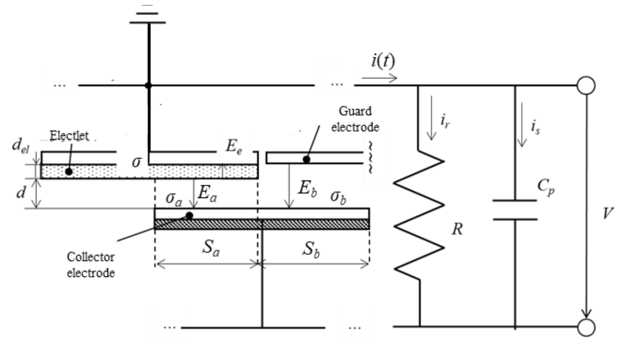

Figure 6. Circuit model of the electrostatic generator

$$n_e\left(\sigma_a S_a + \sigma_b S_b\right) + \int_0^t i(t)dt = Q(\text{const.}) \tag{12}$$

Where, n_e is the number of the collector electrodes, and σ_a and σ_b are the induced charge on the collector electrode, which are expressed as follows.

$$\sigma_a = -\varepsilon_0 E_a \tag{13}$$

$$\sigma_b = -\varepsilon_0 E_b \tag{14}$$

Substituting (8)-(11), (13), and (14) into (12) and differentiating (12), a differential equation related to the output voltage V is obtained. In this simulation, the displacement of the skeletal muscle was input, then calculating the power generated by solving (1) and (12). Assuming that the skeletal muscle was moved sinusoidally with the amplitude of 1.0 mm and frequency of 10 Hz so that the maximum stress applied to the mechanism was below the yield stress. The thickness of the electret d_{el} was 5 µm, the gap between the electret and collector d was 50 µm, the surface potential was -400 V, the parasitic capacitor C_p was 50 pF, and the collector, electret, and guard electret were arranged at every 0.1 degree. Then, varying the load resistance R in the extent of 0.01 ~10 MΩ, power generated at each condition was compared. As a result, the highest generated power was 122.5 µW at the resistance of 0.63 MΩ, which was enough to power the IMD. The thickness of the generator (0.53 mm) is much smaller than that of the battery of the IMD (some millimeters). Thus, it is expected that more power is obtained by stacking generators.

Fig. 7 shows a prototype of the oscillator based on the design process. The outer diameter was designed as 34 mm, which was within the outer dimension of the IMD. In order to confirm the difference in the natural frequency between the fabricated prototype and the designed value, it is necessary to evaluate frequency response.

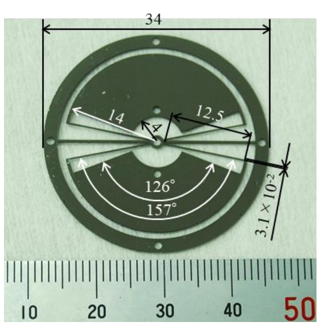

Figure 7. Prototype of the oscillator

IV. Conclusion

For the purpose of realization of an energy harvesting system utilizing the contraction of the skeletal muscle, a generator that resonates with the incomplete tetanus was proposed. Experimental results showed that the work of the incomplete tetanus at the frequency of 10 Hz was larger than that of the complete tetanus. The output power of the generator which resonates at 10 Hz was expected to generate 122.5 µW in the simulation, which was enough to power IMDs. In future work, the frequency response of the prototype oscillator will be evaluated. Then, the electrets and electrodes will be mounted on the oscillator, and the power generated will be evaluated when oscillating at 10 Hz. Furthermore, the net power considering the energy consumption of the stimulation will be evaluated by using an actual skeletal muscle. In addition, the effect of the electrical stimulation such as uncomfortableness for the patients and muscle fatigue will be investigated.

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