Power supply for medical implants by Wiegand pulse generated from magnetic wire

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Implantable medical devices are utilized in the human body for maintaining good health. As these devices are becoming increasingly functionalized, supplying power to them has become very important. Instead of batteries, technologies for wireless power supplies are being developed, such as inductive coupling or piezoelectric elements. However, we propose the use of magnetic wires for this purpose. Inside these wires, a fast magnetization reversal, called a “large Barkhausen jump,” occurs due to an applied magnetic field. This reversal induces a large pulse voltage in pick-up coils, which is called a “Wiegand pulse.” By applying this pulse as an electric source, a higher electric power is expected compared with the conventional method using a sinusoidal excitation field. A wire core coil was prepared, and open-circuit voltage was measured. In addition, DC voltage and electric power were measured by connecting the wire core coil to a rectifier. The experimental results confirmed the superiority of using a Wiegand pulse at an applied magnetic field intensity of 60 Oe and a frequency of lower than 10 kHz.

Keywords: magnetization reversal, large Barkhausen jump, FeCoV wire, Wiegand pulse, implantable medical device

1. Introduction

A large Barkhausen jump, which is known as the Wiegand effect, is a fast magnetization reversal in a magnetic wire that has bistable states. It induces a large pulse voltage, called a Wiegand pulse, in the pick-up coil when a magnetic field is applied. In this study, a twisted FeCoV wire made from an optimum material yielding this effect was used. The Wiegand effect has certain advantages: it does not need any external power supply, and the amplitude of the pulse voltage is still large at both high and low frequencies, while an ordinary sinusoidal electromotive force depends on the frequency of the applied magnetic field. This phenomenon has been used in many sensor applications, such as rotation sensors and speed sensors. Further, vibration-type energy-generating elements by exciting the magnetic wire through a single magnet are being developed.

In this study, a magnetic wire and Wiegand pulse were used as the power source, which provides DC voltage to the implant inside the body. Ordinary inductive power transfer systems typically use excitation frequency ranging from hundreds of kilohertz to several megahertz. At such high frequency, the excitation voltage, current, and size of the coil tend to be too large for applying enough magnetic field to deep the human body. Further, unexpected heating of the body surface caused by the eddy currents cannot be ignored. To eliminate these problems, we proposed the use of a magnetic wire. Using the wire as the core of the pick-up coil and generating a large Wiegand pulse by applying a magnetic field, enough electric power can be achieved at low excitation frequency. Then, reduction of not only the size of both excitation coil and pick-up coil, but also the required excitation voltage, can be realized.

2. Structure of Electricity Generation

2.1 FeCoV wire

An 11-mm-long FeCoV (Fe$_0.4$Co$_0.5$V$_{0.1}$) wire was used in this study. When torsion stress was applied to the wire, the outer shell near the surface became magnetically soft. When the stress was released, two layers appeared: the outer layer, called soft layer, which had a coercive force of 20 Oe, and the inner layer, called the hard core, which had a coercive force of 80 Oe. Details on the magnetic properties of twisted FeCoV wires and torsion stress dependence have been reported by Abe et al. This magnetic wire exhibits a uniaxial magnetic anisotropy along its length direction.

Figure 1 shows schematic diagrams of magnetic structure and magnetization process of the soft layer in the FeCoV wire used in this study. These characteristics
2.2 Wiegand pulse in wire core coil

By using the wire as a coil core and applying a magnetic field larger than 20 Oe, a Wiegand pulse is induced in the pick-up coil wound around the wire. Figure 2 shows a waveform of the measured Wiegand pulse during magnetization reversal of the soft layer excited by approaching a magnet in extremely slow movement. When the wire is excited by an AC magnetic field, sinusoidal electromotive force is also induced in the pick-up coil. Therefore, the waveform of the core coil by AC excitation combines these two waveforms, as shown in Fig. 3. The pick-up coil of 3000 turn was used in this measurement. Unlike the sinusoidal electromotive force, the width of a Wiegand pulse does not vary according to the excitation frequency. As seen in the figure, positive and negative Wiegand pulses are observed in one period, each of which results from two reversals of the soft layer: parallel to antiparallel and antiparallel to parallel. In the 1 kHz waveform shown in Fig. 3(a), only a Wiegand pulse is mostly observed, while in the 10 kHz waveform shown in Fig. 3(b), sinusoidal components can be slightly seen, but are still much less dominant compared to a Wiegand pulse.

In this study, a voltage-double rectifier was used, and a Wiegand pulse was converted to DC voltage assuming the electric power supplied to capsule endoscopy or many other implantable medical devices. Enough electric power at a low frequency was aimed using a Wiegand pulse generation. The excitation frequency was set to lower than 10 kHz in all experiments.

3. Experiment

3.1 Comparison of open-circuit voltage in wire and air core coil

A pick-up coil of 9 mm length and 3000 turns was wound around the FeCoV wire (length: 11 mm). The diameter of the wire was a few tenth of a millimeter. Its magnetic properties were essentially same with those of
The FeCoV wire of 0.25 mm diameter. The volumes of the soft and hard core were 23% and 77%, respectively. The excitation coil, with 25 mm length and 22 mm diameter, applied the AC magnetic field to the entire wire core coil. Each end of the core coil was connected to an oscilloscope and the peak of the open-circuit voltage was measured; subsequently, this peak was compared with that of the air coil. In the measurement of magnetic field intensity dependence, the field intensity ranged from 0 Oe to 100 Oe and the excitation frequency was set to 1 kHz. In the measurement of excitation frequency dependence, the frequency ranged from 100 Hz to 10 kHz and the field intensity was set to 60 Oe. As shown in Fig. 4, the peak of the Wiegand pulse was measured in the wire core coil, and the amplitude of the sinusoidal electromotive force was measured in the air coil.

3.2 Measurement of electric power obtained from Wiegand pulse

As shown in Fig. 5(a), the wire core pick-up coil was connected to a voltage-double rectifier, which consisted of two Schottky diodes and 1 μF capacitors and a load resistor. The excitation coil was arranged around the pick-up coil, and the size and number of turns of each coil were the same as those mentioned in the previous section. The Wiegand pulse was rectified and smoothed as shown in Fig. 5(b). Then, the load voltage and its ripple components were measured with the resistance value varying from 100 Ω to 1 MΩ, and electric power was calculated. Intensity of the AC magnetic field for excitation was set to 60 Oe, and two frequencies were used: 1 kHz and 10 kHz. The ripple rate was calculated using the following equation.

\[
\text{Ripple} = \frac{V_{\text{max}} - V_{\text{min}}}{V_{\text{ave}}} \times 100
\]

3.3 Comparison of electric power obtained from the wire and ferrite core coil

To confirm the usefulness of the Wiegand pulse at low frequency, a high-permeability magnetic material, MnZn ferrite, was used for the coil core and compared with the wire core coil. The ferrite core strengthened the magnetic flux around the pick-up coil, and the sinusoidal electromotive force itself increased. The size of the ferrite core used in this experiment was 1 × 1 × 10 mm³. The ferrite core and the wire were each wound by a pick-up coil of 400 turns. Each core coil was connected to the voltage-double rectifier and load resistor, as described in the previous section. Then, the load voltage was measured and electric power generated from the wire and the ferrite core was calculated and compared. Because the ferrite core and wire had different sizes, the measured data were normalized with their cross-sectional area. Load resistance was 1 MΩ and capacitance was 1 μF. The excitation magnetic field intensity was set to 60 Oe, which is enough to generate a Wiegand pulse. The excitation frequency ranged from 100 Hz to 10 kHz.

4. Results and Discussion

4.1 Comparison of open-circuit voltage with changing applied field intensity or frequency

Figure 6 shows the dependence of open-circuit voltage.
on magnetic field intensity at 1 kHz of excitation frequency and that of excitation frequency on 60 Oe of applied field intensity.

As shown in Fig. 6(a), when the excitation field was 20 Oe or more, the peak value of the wire core was far larger than that of the air coil. This implies that the Wiegand pulse was generated due to magnetization reversal in the soft layer; its peak value increased with the applied field intensity. When the applied field was within 20 Oe, because the Wiegand pulse was not generated, ordinary electromotive force was measured. At an applied field of 10 Oe, the peak value of the wire core was 84.2 mV, which was slightly larger than that of the air core (28.4 mV). It was found that because of the magnetic permeability of the wire, magnetic flux around the pick-up coil strengthened, and the electromotive force increased to a certain degree. The magnetization of the hard core was also reversed by the applied field above 80 Oe, which resulted in lower output voltage from the wire. The voltage was expected to be saturated or more decreasing even though the magnetic field exceeded 100 Oe. Magnetization reversal of the hard core is not necessary for generating the Wiegand pulse, and the field intensity should not be excessively strong. Then, the ideal intensity for generating the Wiegand pulse is around 60–80 Oe. Therefore, in this study, the applied field was set to 60 Oe, which fixed the field intensity.

In Fig. 6(b), at all measured frequencies, the peak value of the Wiegand pulse was far larger than the electromotive force of the air coil. As the frequency increased, the amplitude of the wire core coil also increased. We assumed that the sinusoidal component increased at higher frequency, and then, the peak value of the Wiegand pulse was increased.

From these results, higher electric power is expected to be secured at lower excitation frequency during conversion to DC voltage.

4.2 Electric power obtained from wire core coil

Figure 7 shows the results of the measured voltage

- (a) DC voltage and electric power with change in resistance.
- (b) Ripple rate of load voltage.

**Fig. 6** Dependence of open-circuit voltage of wire core coil and air core coil on applied field intensity and excitation frequency.

**Fig. 7** Dependence of DC voltage (average value) and electric power on resistance and its ripple rate, at 60 Oe of applied field intensity and 1 kHz of excitation frequency.
and electric power of load resistance (a) at 1 kHz excitation frequency, and its ripple (b). The maximum obtained electric power was 1.2 mW. The ripple rate deteriorated at lower resistances. In the case where the wire core coil receives power from the excitation coil and provides voltage to the implant device throughout operation in the human body, the fluctuation in the load voltage should be less, and thus, the capacitor should be optimized.

Figure 8 shows same results as Fig. 7 but at an excitation frequency of 10 kHz. The maximum electric power was approximately 21 mW. Under this excitation condition, there is enough possibility of feeding the power required to operate implantable medical devices (for example, power consumption of capsule endoscopy is 25 mW\(^9\), and is expected to lessen in the future). Further, the load voltage at the highest electric power was 1.56 V at 1 kHz and 8 V at 10 kHz excitation. Considering that the voltage of a button battery, the main power source of implantable medical devices, is around 1.5 V, DC voltage from the Wiegand pulse was also sufficient.

4.3 Comparison of electric power generated from wire core and ferrite core

Figure 9 shows a comparison of the electric power generated from the wire core coil and the ferrite core coil. The excitation frequency was 1 kHz. The ripple almost disappeared because the circuit parameters (capacitance and load resistance) and the time constant were large enough. Electric power from the Wiegand pulse increased significantly from the applied field intensity of 20 Oe or more. Even considering the demagnetizing field inside the ferrite, the power from the ferrite core coil remained smaller at almost all intensity values. The tendency of the wire core coil resembles that in Fig. 6(a), in that the peak of the applied field intensity was in the range of 70–80 Oe.

Figure 10 shows a comparison of the electric power generated from the wire core and ferrite core with changing excitation frequency. In frequencies lower than 10 kHz, the wire core coil had an advantage. Thus, the
usefulness of the Wiegand pulse and wire core coil at lower excitation frequency was confirmed. If the excitation frequency is increased beyond 10 kHz, the sinusoidal electromotive force will increase, and the ferrite core coil may become superior to the wire core coil.

5. Conclusion

This paper proposes a new method of power supply using an 11-mm-long FeCoV wire. A Wiegand pulse was induced in a pick-up coil wound around the wire by an AC magnetic field of the excitation coil. A comparison of the open-circuit voltage with the air core coil showed that the Wiegand pulse has much larger peak than the sinusoidal electromotive force at frequencies lower than 10 kHz. Subsequently, the Wiegand pulse was rectified and smoothed by a voltage-double rectifier, and it was confirmed that the wire core coil can provide enough electric power to implantable medical devices. Further, the wire core coil was compared to the ferrite core coil, which had high permeability, and higher electric power was obtained by the Wiegand pulse, even though the electromotive force was amplified by the ferrite core at the measured frequency. In addition, it was found that reduction in the size of pick-up and excitation coils, and reduction in the excitation frequency were expected.

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