Development of Linear Power Generator: Conversion of Vibration Energy of a Vehicle to Electric Power

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Abstract

This paper proposes a linear power generator, which can convert any mechanical vibration energy of a vehicle to electric energy. A mover of the proposed linear power generator, which includes permanent magnets, is linearly driven through a stator, by vibrations. Nd Fe-B magnets in the mover are placed so that the same magnetic poles face each other, in order to make the large change in magnetic flux in the coils of the stator. The coils are placed in the stator with the same interval of magnets. Alternate coils connected in a series were wound in opposite directions to the next coil. The stator was covered with a magnetic material case that has pole pieces between the coils. Therefore, the magnetic flux is extended through the case and reduces cancellation of the flux in the coils of the stator. At first, a button type magnet was substituted with equivalent electric current in accordance with measurements from simulations. The distribution of the magnetic field and electromotive force were calculated by numerical simulations in order to determine the ideal size of the linear power generator. The linear power generator and an experimental apparatus were then produced on the basis of this simulation. The performance of the linear power generator was tested by experiments and showed that the power generation ability was 4 times greater in comparison with the magnetic metal case without the pole pieces. The proposed linear power generator is considered to be useful for the conversion of mechanical vibration energy to electric energy.

Keywords

linear power generator, electromagnetic field analysis, calculus of finite differences, power generation, vibration

1. INTRODUCTION

Vibrations occur when a mobile like a bicycle, car or a train moves. The vibrations appear as reactive power, which should be consumed by moving a mobile, according to the dynamic characteristics of the mobile and/or its driving environment. The vibrations of a mobile are absorbed by the suspension and shock absorbers and converted to heat, in order to give good ride quality and/or protect goods in a mobile. It is therefore conceivable that efficient energy application could be achieved if this vibration energy is converted to electricity energy.

A method for converting vibrations to electric power by a piezoelectric element has been proposed [Sasaki et. al, 2002,]. Two fitted sheets of piezoelectricity ceramics generate electric power by external forces. The generated power is considered to be suitable for illuminating LED and driving sensors and so on. Also, a method that converts vibrations that occur in a building to electric power was studied in order to drive a LSI [HITACHI News release, 2003].

In the present study, a linear power generator based on utilizing electromagnetic induction will be proposed, which is linearly driven by mechanical vibrations [Takahara et. al, 2004a, Takahara et. al, 2004b]. To obtain electric power from linear motions is a natural conception, as Faraday's law [Jackson, 1975] can be illustrated by repetitively approaching and withdrawing a bar magnet from a coil [Hirai, 1989]. In those years, a flashlight was commercialized to light up a LED for use at times of disaster, in which a magnet is swung up and down within. But, simply moving a magnet through a coil does not generate power efficiently.

The mover of the proposed linear power generator is devised to increase the change in magnetic flux, in order to generate power more efficiently. To be specific, the mover structure consists of Nd Fe-B magnets placed so that the same magnetic poles face each other. The stator was covered with a magnetic metal case that has pole pieces between the coils [Ohsaki et. al, 2004]. Therefore, the magnetic flux is extended through the case and reduces cancellation of the flux in the coils of the stator.

In this paper, the fundamental structure of the linear power generator will be described. Numerical simulations were used to calculate the distribution of the magnetic field and electromotive force in order to determine the ideal size of the linear power generator. The linear power generator and an experimental apparatus were then produced on the basis of this simulation. Its effectiveness in power generation will be confirmed by examinations.

2. DESIGN OF LINEAR POWER GENERATOR

2.1 Fundamental structure of linear power generator

The mover of the proposed linear power generator consists of permanent magnets and moves up and down in a stator of wound coils. The electromotive force is generated in proportion to the change of magnetic flux in unit time in the equation (1), in accordance with the Faraday's law.

$$e = -\frac{d\phi}{dt} \tag{1}$$

Therefore, it is a natural conception that a magnet can be linearly moved up and down in a coil to obtain electric power. However, high power generation performance is not obtained by simply moving a magnet in a coil. Because, it is not easy to obtain a larger change in magnetic flux by such a power generation method, in comparison with a rotating machine.

Here, in this study, a mover is made using Nd Fe-B magnets, which are placed so that the same magnetic poles face each other, as shown in Figure 1. The coils are placed in the stator with the same interval of magnets. Alternate coils connected in series were wound in opposite directions to the next coil, as the generated power synchronizes and becomes large. This structure can enlarge the change of magnetic flux in the coils together with the movement of the mover. The stator was covered with a magnetic metal case that has pole pieces between the coils. Therefore, the magnetic flux is extended through the case and reduces cancellation of the flux in the coils of the stator.

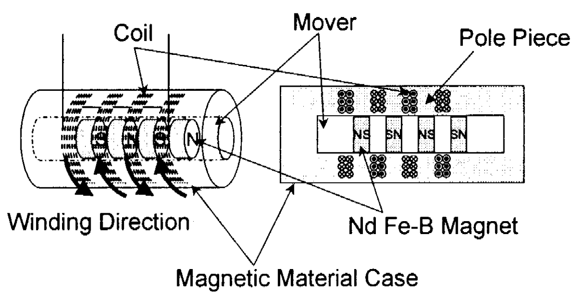

Fig. 1 Fundamental structure of the proposed linear power generator

2.2 Numerical simulations

Sufficient power generation performance will be not obtained by this arrangement of the magnets and coils, although the fundamental structure described in the above section will in theory increase time variability of magnetic flux. Here, a more efficient arrangement will be determined by numerical simulations.

Button type Nd Fe-B magnets are used in this study. The magnetic field is calculated in accordance with the following equations (2) and (3) in a static magnetic field, because a button type magnet can be replaced by a circle current.

$$\mathbf{B} = \nabla \times \mathbf{A} \tag{2}$$

$$\nabla \times \left(\frac{1}{\mu} \nabla \times \mathbf{A} \right) = \mathbf{J} \tag{3}$$

Here, $\boldsymbol{B}$: magnetic flux density [T], $\boldsymbol{A}$: vector potential, $\boldsymbol{J}$: current density [A/m^2], μ : magnetic permeability [H/m], respectively.

Magnetic fields of Nd Fe-B magnets are calculated by equations (2) and (3) by a calculus of finite differences. The height of the button type Nd Fe-B magnet used is 5 [mm] and its diameter is 10 [mm] (the surface magnetic flux density: 350 [mT], adsorption power: 2.2 [kgf]). The equivalent circle current of the above magnet obtained was 4171 [A] by measurements. The equivalent current was distributed in the position on the circumference of the button type Nd Fe-B magnet.

The mover is composed of 4 magnets and its outside is covered with a magnetic material frame (μ = 200 [H/m]). First, the difference of the magnetic path was calculated with and without the pole pieces of the frame. The calculated magnetic fields are shown in Figure 2. Here, the space was divided by 1 [mm]. In the case that the calculation in the resolution below 1 [mm] is necessary the linear interpolation was used. In the figure, the magnetic substance is shown in the grating states. Figure 2 shows that the magnetic material frame with pole pieces extends the magnetic path. That is, by using the frame with the pole pieces, the cancellation of the flux in the coils of the stator is reduced.

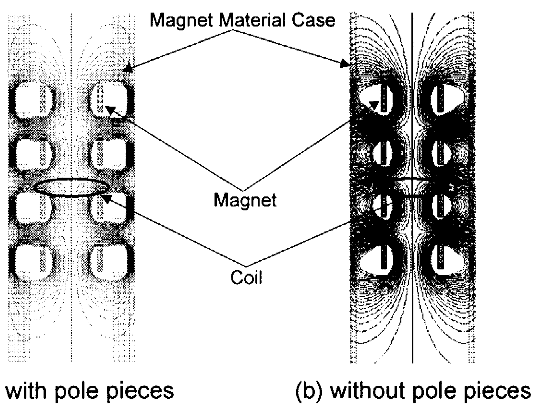

Fig. 2 Comparison of the magnetic field by the presence or absence of pole pieces in the case

Next, the differences in the magnetic fields created by the interval differences of the magnets were calculated and shown in Figure 3. The magnetic path spreads more broadly as the interval of the magnet increases, as shown in the figure. Therefore, the cancellation of the flux in the coils of the stator is reduced, as the intervals of the magnets increases when a coil is put between the magnets and case. On the other hand, the rate of change of the magnetic flux becomes large, as the intervals of magnets decreases. Here, the intervals of magnets were chosen to be 5 [mm].

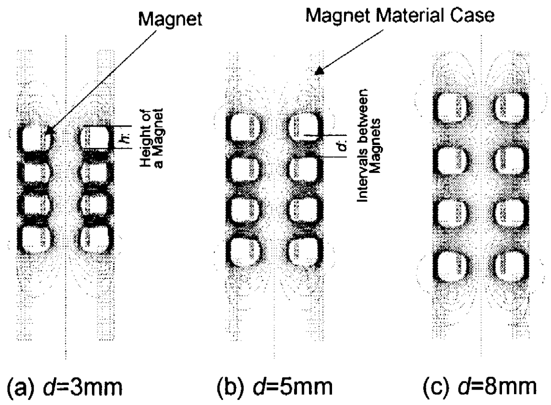

Fig. 3 Comparison of the magnetic fields created by varying the interval differences of the magnets

Furthermore, the electromotive force was calculated based on Faraday's law. The magnets of height 5 [mm] are placed at intervals of 5 [mm] within the mover, according to the above simulations. The velocity of the mover is described by equation (4), since it was caused by the crank mechanism of the experimental device, as described later, imitating vibrations.

$$v(t) = r\omega(\sin \omega t + r \sin 2\omega t / 2l) \quad (4)$$

Here, ω : the number of revolutions of the crank [rad/s], l : the length of the connecting rod [m], r : the length of the crank. The revolution frequency of the crank was set at 5 [Hz] and l and r are 0.03 [m] and 0.1 [m], respectively.

The coils were placed in the stator with the same interval of magnets. Alternate coils connected in a series were wound in opposite directions to the next coil. The size of the electromotive force generated is limited in reality, although in theory it should become large along with the increase of a coil turns. Because the outside diameter of the coil increases with the number of coil turns and becomes distant from the magnets [Takahara et. al, 2004b]. Therefore, the coil of the outside does not contribute to electromotive force generation. Here, the four coils of the stator were arranged at the interval of 5 [mm] as the magnets and coil turns were set at 350 turns. On the other hand, the outside diameter of this case was set at 25 [mm].

The size of the pole piece in the case exerts a large influence on the formation of the magnetic paths and power generation. Figure 4 shows the amplitude value of the output voltage in relation to the size of the pole piece. As the pole piece is large and close to the mover, the magnetic paths are extended and the generated voltage also becomes large. However, the mover becomes difficult to move up and down, because an adsorption power between the proposed case and the mover becomes large as the pole piece increases. Here, the height of the pole piece was set to 3 [mm]. Figure 6 shows the voltage change that was calculated for the condition when the mover moves up and down in accordance with equation (4).

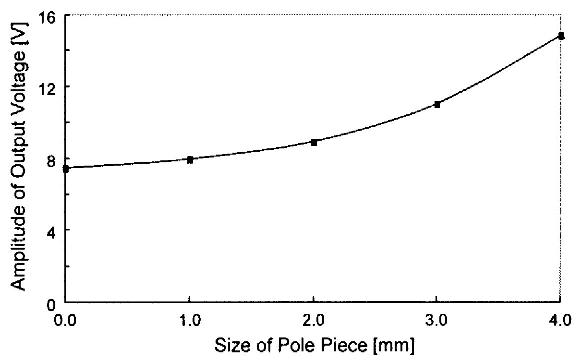

Fig. 4 Amplitude value of output voltage to the size of pole piece

It is likely to be difficult to obtain stable alternating current electromotive forces since the proposed linear power generator will be driven by the vibration of a mobile. Therefore, the output powers will be used as direct currents through a full-wave rectifier and a smoothing circuit. The amplitude of the voltage wave as shown in Figure 5 is 11.4 [V] and the full-wave rectified effective value of is 4.4 [V]. In comparison, the amplitude of the

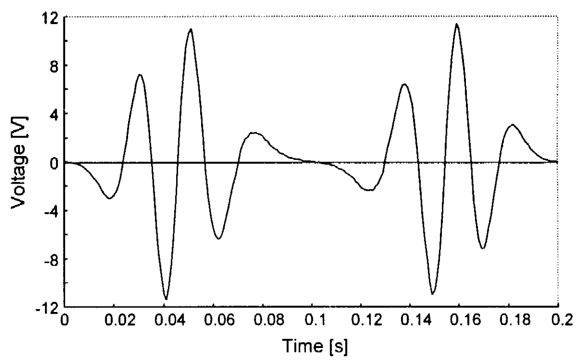

Fig. 5 Calculated induced electromotive force associated with the motion of the mover

electromotive force using a case without pole pieces is 6.0 [V] and the effective value of full-wave rectification is 2.83 [V]. Therefore, it is conceivable that the proposed linear power generator will be able to generate power with high efficiency.
In the next section, the proposed linear power generator will produced and its effectiveness will be tested by experiments.

3. PRODUCTION AND EXPERIMENTS OF LINEAR POWER GENERATOR

Figure 6 shows the experimentally produced linear power generator, on the basis of the simulation results in the above section, and the experimental apparatus. Four Nd Fe-B magnets in the mover were placed in the interval of 5 [mm] so that the same magnetic poles face each other. The four coils, which were wound 350 turns, respectively, in the stator were arranged at the interval of 5 [mm], as same as the magnets, and were connected in series. The outside of the stator was covered with the case containing the pole pieces. Insertion of a resinous guide between the mover and the case made the motion of the mover smooth.

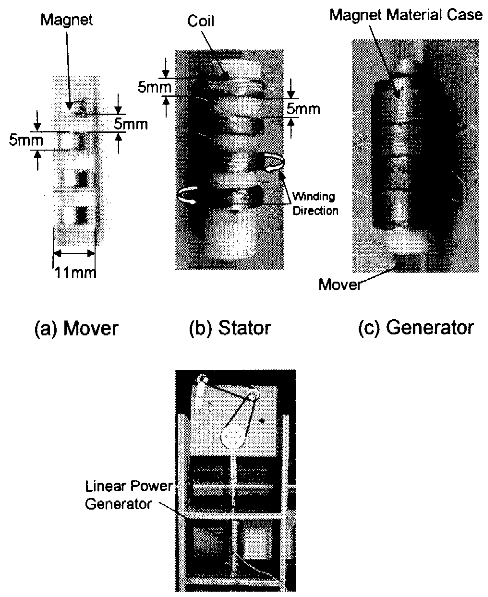

Fig. 6 The developed linear power generator and experimental apparatus.

The changes of the output voltage are shown in Figure 7 when the crank was driven with 5.4 [Hz]. Here, the obtained voltage amplitude was 6.0 [V].
In comparison with Figure 5, although part of the output voltage waveform was different, as the motion direction of the mover was changed, the experimental results were similar to the simulation results. The difference between the mover's starting point and the stator centre, and in the elasticity of the belt that actuates the crank and so on might be the cause of the difference in the voltage waveforms from the simulations in the produced machine. Amplitude of 5.0 [V] was obtained, in the same experiment using the case without the pole pieces in comparison. Therefore, our results confirm that using the case with the pole pieces generated power more efficiently.
The output voltage was smoothed and energized to a variable resistance, and its voltage-current characteristics measured by changing the value of the resistance. Each effective value was obtained from the measured voltage and electric current. The voltage-current characteristics are shown in Figure 8. The maximum power of 36 [mW] was generated from Figure 8. And the impedance of the optimal operating point was 78 Ω. The input power to drive the crank mechanism was 356 [mW]. Therefore, the total efficiency of this generator from the energy of movement to the electric power is regarded to be 10 [%].

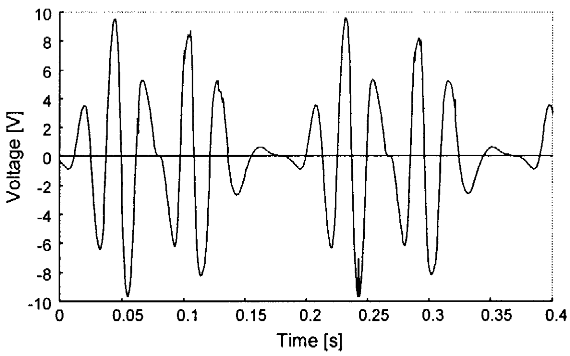

Fig. 7 Output voltage of the linear power generator

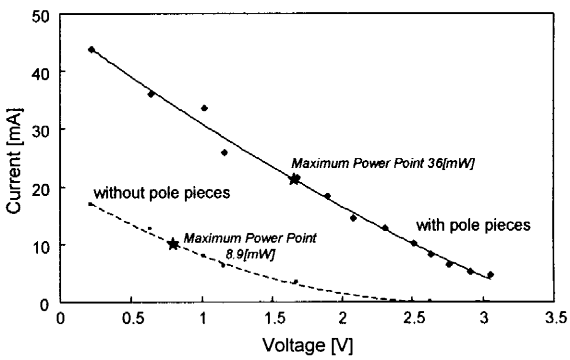

Fig. 8 Voltage-current characteristics of produced linear power generator

The voltage-current characteristics using the magnetic material case without pole pieces is shown in the same figure. The case with the pole pieces enabled the power generation of at least 4 times that of the case without the pole pieces. Figure 9 illustrates the change in the charging voltage to the capacitor.
These experimental results show the efficacy of the proposed linear power generator.

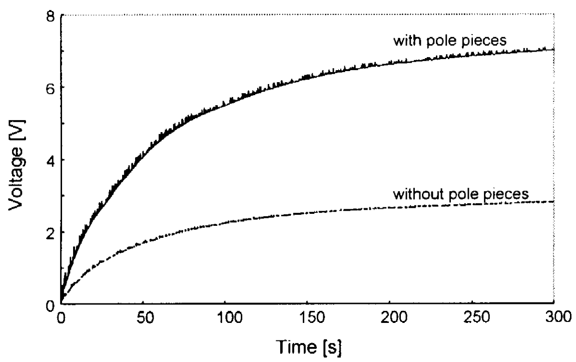

Fig. 9 Change of the charging voltage to the capacitor by the linear power generator

4. CONCLUSIONS

In this study, we proposed a linear power generator, which can convert any mechanical vibration energy produced by a vehicle to electric energy. The distribution of the magnetic field and electromotive force were calculated by numerical simulations in order to design the linear power generator. The linear power generator was produced on the basis of this simulation. Its performance was tested by experiments.

The proposed linear power generator has the following characteristics:

(1) The mover was composed of Nd Fe-B magnets, which are placed so that the same magnetic poles face each other in order to make the large change in magnetic flux in the coils of the stator.

(2) The coils were turned in opposite directions to the next coil in the stator with the same interval of magnets and connected in a series to increase the electromotive force.

(3) The stator was covered with a magnetic material case with pole pieces between the coils so that the magnetic flux was extended through the case, reducing the cancellation of the flux in the coils of the stator.

The efficiency of the above characteristics of the proposed linear power generator was confirmed by the numerical simulations and experiments. Because the generated power was small, we will make further simulations of the performance of the linear power generator to make improvements, including examination with regard to the selection of the magnets, arrangement of coils, material choice and structure of the case and so on. The electromotive force was calculated under the condition that there was no-load and no electric current in the coils. Therefore, the simulation results did not include the influences of turbulence created in the magnetic fields by load current and the back electromotive forces. The development of computer-aided design software that considers such influences will be our future work. The use of changes in the magnetic flux of the radial direction will be considered in addition to the magnetic flux of the motion direction of the mover to improve the efficiency of power generation.

The proposed linear power generator is envisaged to be built into the suspension of a vehicle. It is therefore conceivable that measurements and analysis of the oscillation frequency of a mobile will be necessary, for the experiments of power generation using the linear power generator on a mobile. And, it is conceivable that the proposed linear power generator can also include the application of a damper by controlling impedance if its power generation efficiency improves. Furthermore, it is conceivable that this technology might be applied to an active suspension, by passing an electric current through the coil.

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