

Electric Power Acquisition from the Vibration of an Electric Vehicle Using a Permanent Magnetic Linear Power Generator

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Abstract

This study considers the possibilities of obtaining electric power from vibrational energy of an electric vehicle using a permanent magnetic linear power generator. A mover of the linear power generator can convert any mechanical vibration to electric power. A mover of the proposed linear power generator, which includes permanent magnets, is linearly driven through a stator by an external force, directly. Therefore, the generator can convert any mechanical vibrations into electrical power. 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 as the magnets. Alternate coils connected in a series were wound in opposite directions to the next coil. The stator was covered with a magnetic material cover, so that the magnetic flux is extended through the cover and reduces cancellation of the flux in the coils of the stator. The pilot generator was produced on the basis of numerical simulation results derived from the distribution of the magnetic field, electromotive force and uniaxial stress. The produced linear power generator was put in an experimental apparatus that emulated the function of suspension in a car. The characteristics of the generator were measured by adding various mechanical vibrations to the experimental apparatus.

Keywords

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

1. INTRODUCTION

The effective introductions of various new technologies are desirable for the protection of the earth's environments. Especially, the development of the electric vehicle has been advanced as a countermeasure against global warming. On the other hand, oil pressure apparatuses such as that used in the control of power steering, suspensions and so on, systematized electrically-driven so that the electricity consumption is increasing [Ishii et. al, 2002, KYB, 2005]. The introduction of high voltage automobile power supplies [Teratani, 2002] and fuel cells [Honma, 2003] are currently being studied.

When a mobile 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. The fundamental structure of the linear power generator is classified broadly into two types with magnets and plungers that linearly actuate; the line actuation type magnet and the straight line actuation type plunger [Boldea, 1999]. Wang et. al proposed a linear reciprocation generator, for a telemetry vibration monitoring system [Wang et. al, 1998]. It was a single-phase tubular device, which is capable of producing 20mW. It moved in a short stroke, driven with a normal frequency of 50 Hz.

In the present study, a linear power generator based on utilizing electromagnetic induction to be linearly driven by mechanical vibrations [Takahara et. al, 2004a, Takahara et. al, 2004b], is modified. The linear power generator consists of two main components, a stator and a mover. The mover which is made up of Nd Fe-B magnets and the outside steel cover of the stator give rise to radial magnetic field.

In this paper, the fundamental structure of the linear power generator will be described first. Subsequently, the differences in the distribution of the magnetic field

and uniaxial stress will be calculated by the difference of the cover, in order to determine the structure of the pilot generator. The linear power generators are then produced on the basis of the simulation and its performance will be tested by examinations.

2. LINEAR POWER GENERATOR AND MAGNETIC CHARACTERISTICS

2.1 Fundamental structure of linear power generator

Figure 1 shows the fundamental structure of the linear power generator. 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. Mild-steels are put between the magnets. The coils are placed in the stator with the same interval as the magnets. Alternate coils connected in series were wound in opposite directions to the next coil, so that the generated power synchronizes and becomes large. The stator was covered with a mild-steel cover that has pole pieces between the coils. The magnetic flux is extended through the poles and the cover, thereby reducing the cancellation of the flux in the coils of the stator.

The generator has a simple structure and can directly convert the vibrational energy to the electric power through the reciprocating motion of the mover.

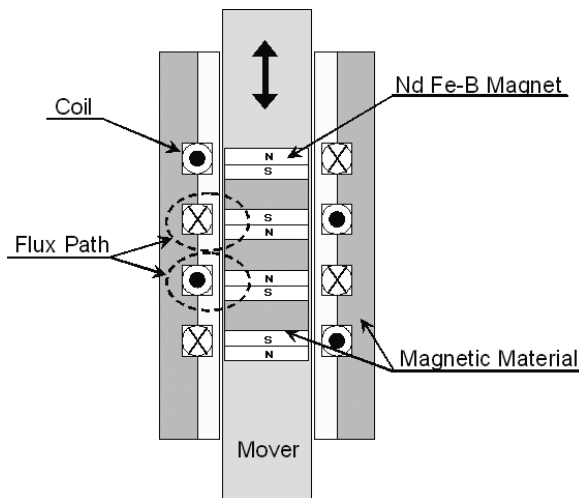


Fig. 1 Fundamental Structure of the Proposed Linear Power Generator

2.2 Transient magnetic analysis

Figure 2 illustrates the electromagnetic analytical model of the linear power generator. Because the axial symmetric generator makes an axial symmetric electromagnetic field the analytical model is expressed with 2 dimensions.

Button type Nd Fe-B magnets are used in the mover. The height of the button type Nd Fe-B magnet used is 10.5 [mm] and its diameter is 32 [mm] (the surface mag-

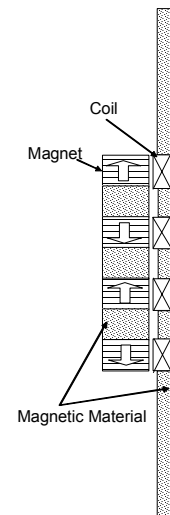
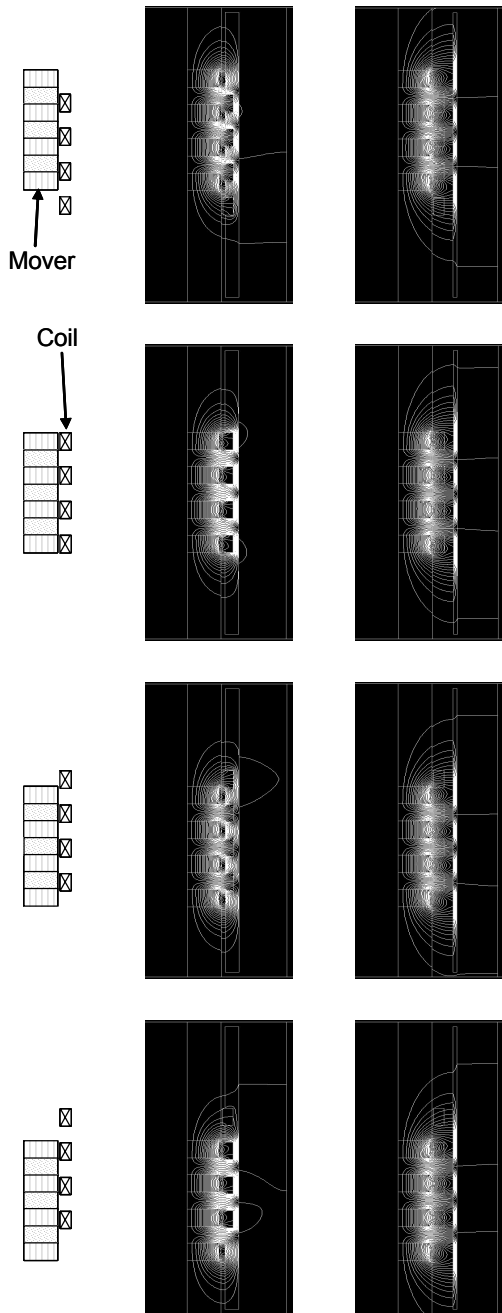


Fig. 2 Analysis Model of the Generator

netic flux density: 400 [mT], adsorption power: 26.0 [kgf]). The equivalent circle current of the above magnet obtained was 13500 [A] by measurements. The equivalent current was distributed at locations along 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 cover ($\mu = 200$ [H/m]). The magnetic fields were calculated by the 2-D transient magnetic analysis of the finite element method using ANSYS (Cybernet Systems Co.,Ltd.).

First, the changes of the magnetic path corresponding to the position of the mover were calculated. The calculated magnetic fields are shown in Figure 3. Here, the displacement of the mover and the vibrational frequency were set at 40 [mm] and 2.5 [Hz], respectively. Figure 3 (a) shows the positions of the mover and the coils. And Figure 3 (b) and (c) illustrate the differences in the magnetic fields according to the presence or absence of pole pieces in the case. These figures show that the magnetic material cover with pole pieces extends the magnetic path. That is, by using the cover with the pole pieces, the cancellation of the flux in the coils of the stator is reduced.

Tight flux paths increase the adsorption power between the mover and the cover. Secondly, the adsorption powers derived from the structure of the linear power generator were calculated. Figure 4 (a) shows the time variations of the adsorption power with air spaces between the mover and the cover from 3 [mm] to 11 [mm]. Here, it was assumed that both terminals were opened, so that the induced electric current was not passed through the coils, but the eddy current flowed through the mild-steel case. The power becomes largest where the mild-steels of the mover overlap the pole pieces of the cases. If the induced current and the eddy current flow zero, the adsorption power theoretically became zero when the cover

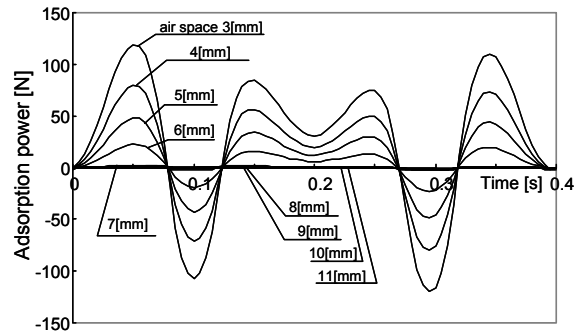


(a) position (b) with pole pieces (c) no pole pieces

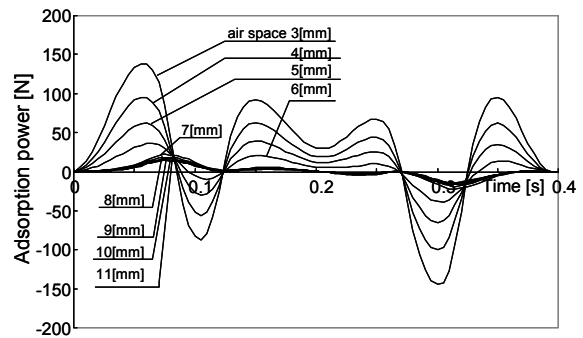
Fig. 3 Change of Magnetic Path corresponding to the position of the mover

is a steel pipe, and the air space of is 8 [mm] or more according to these calculations. On the other hand, the induced electric current generated by the short circuit of the coils and the eddy current through the steel pipe deformed the time variations of the adsorption powers as shown in Figure 4 (b). The absolute value of amplitude differs between positive and negative. Hence, the adsorption powers occur even when the air space is 8 [mm] or more.

The relation between the air spaces and the maximum



(a) In the case that induced electric current does not flow through the coils



(b) In the case that induced electric current flow through the coils

Fig. 4 Simulation of time variations of the adsorption power

values of the adsorption power including the influence of the induced electric current are compared to their relation with no electric current in Figure 5. The figure shows the influence that the induced currents exert on the adsorption power is not small. If the mover is not at the center of the actual generator the adsorptive power will increase. As the pole pieces of the cover are large and close to the mover, the magnetic paths are extended and the generated voltage also becomes large. However, the braking effect becomes large, when the spac-

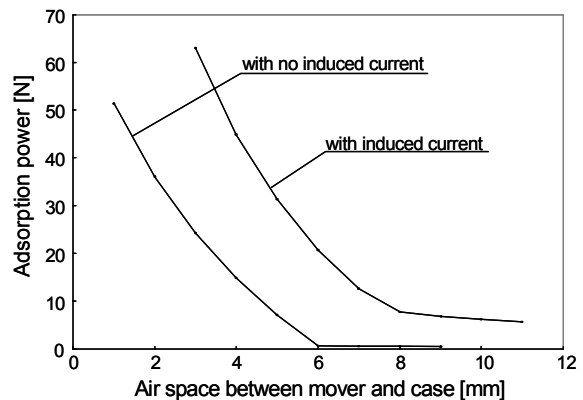


Fig. 5 Adsorption power to air space between mover and case

ing of the pole and mover become small. Figure 6 illustrates the relation the adsorption power and the amplitude of the open output voltage to air space between the mover and the case. Forming the flux path to improve generating efficiency restricts the actuation of mover and reduces production of electricity. Therefore, a steel pipe for the linear power generator is chosen as a magnetic material cover.

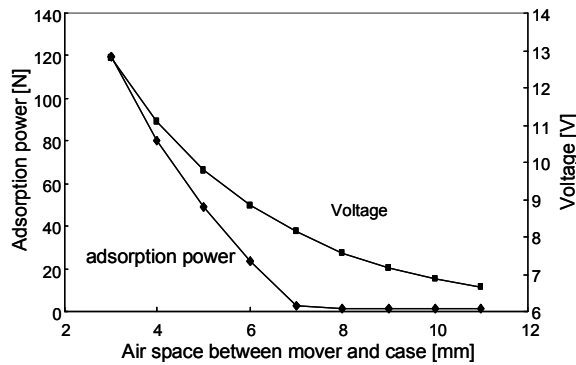


Fig. 6 Relation of adsorption power and the amplitude of the open output voltage to air space

The output performance of the linear power generator with the steel pipe was calculated. The volt-ampere characteristics of the designed linear power generator are shown in Figure 7. The obtained maximum power is 0.190 [W] at 3.33 [V] and 0.058 [A], when the eddy current is considered to traverse the steel cover. The maximum power of 0.522 [W] is obtained when the mover vibrates at 5 [Hz] with the same situation.

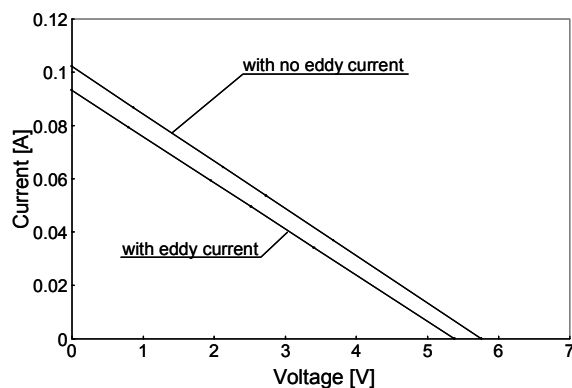


Fig. 7 Calculated volt-ampere characteristics of the designed linear power generator

A suspension of an automobile is evaluated with the frequencies of the ranges of about 5 [Hz] from 0.5 [Hz] and the relative displacement up to about 7 [cm] [KYB, 2005]. Consequently, the power of about 1 [W] from 0.2 [W] will be obtained using the designed generator under the condition of the above evaluation.

In the next section, the linear power generator will be produced and its performance will be tested by experiments.

3. PRODUCTION AND EXPERIMENTS OF LINEAR POWER GENERATOR

Figure 8 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 are placed at an interval of 10.5 [mm] so that the same magnetic poles face each other. The four coils, which are wound 450 turns, respectively, in the stator are arranged at an interval of 10.5 [mm], the same as the magnets, and are connected in series. The cover of the stator is a steel pipe. Insertion of a resinous guide between the mover and the cover made the motion of the mover smooth. Four linear generators are set on this apparatus and two springs (height: 140[mm], spring constant: 11.788 [N/mm], permissible load: 796.2 [N]) are put in between the movable board and the fixed board. The mover is driven by the mechanical vibration of the movable board and the electric power is generated.

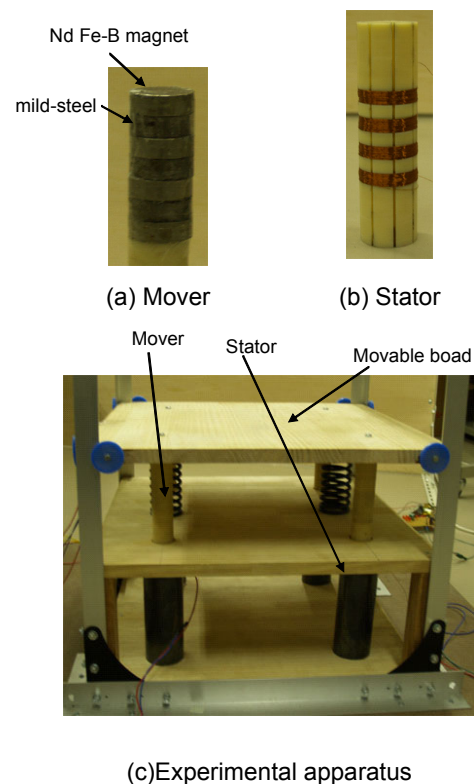


Fig. 8 Produced linear power generator and experimental materials

First, the free vibration of the movable board was measured, when a weight of 70 [kg] was removed. Figure 9 illustrates the example of the vibration of the movable

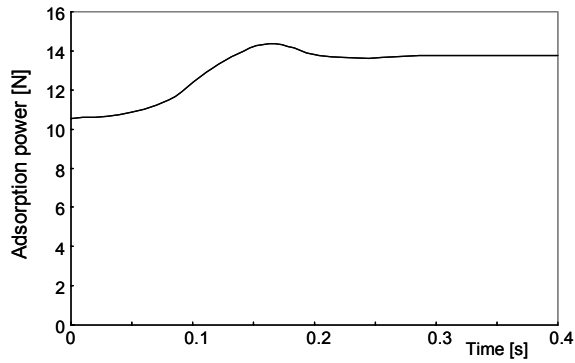
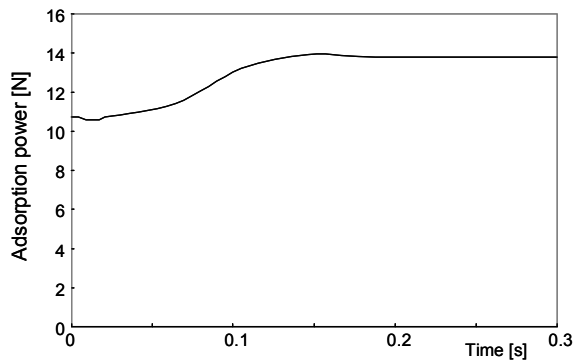
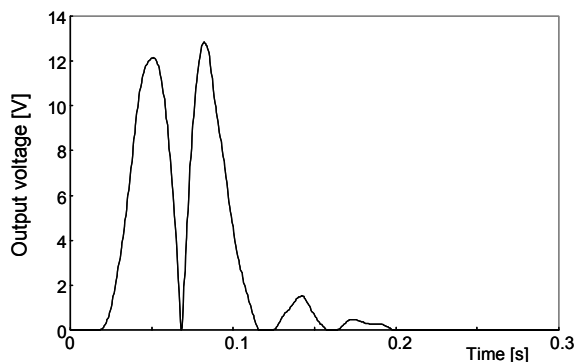


Fig. 9 Free vibration of the movable board with no electric load

board. The damping constant and the characteristic frequency of the experimental apparatus were approximately determined from the vibration waveform. Next, the movable board was vibrated using the same weight, and the four linear power generators were connected with each resistance of 51 [Ω]. The examples of the free vibration of the movable board and the output voltage variation are shown in Figure 10. Here, the output voltage was commutated by a diode bridge. The connection of an electric load made electric current flow through



(a) Free vibration of the movable board with connecting a resistance of 51 [Ω]



(b) Commutated output voltage

Fig. 10 Free vibration of the movable board and output voltage

the circuit and decreased the amplitude of the vibration. The generated powers were calculated using those experimental results. About 15 percent of the vibrational energy was converted to electric energy by four linear generators.

Figure 11 shows the comparison of the open voltage of the actual output and the calculated value with amplitude of 30 [mm] at 5 [Hz].

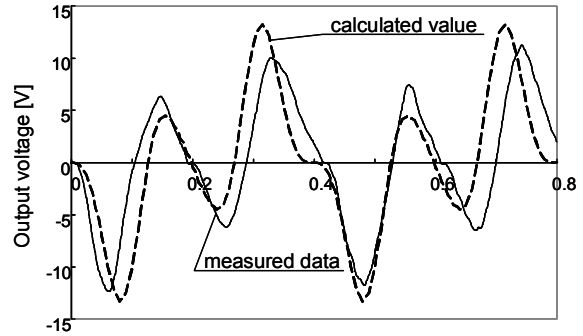


Fig. 11 Comparison of the open voltage of the actual output and the calculated value

Furthermore, the volt-ampere characteristics of the produced linear power generator are shown in Figure 12. The calculated values are shown in the same figure for comparison. Here, the output voltages were 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 maximum power of 181 [mW] was generated from Figure 12. And the impedance of the optimal operating point was 49.4 [Ω]. It is demonstrated that the calculated values approximate the measured values well.

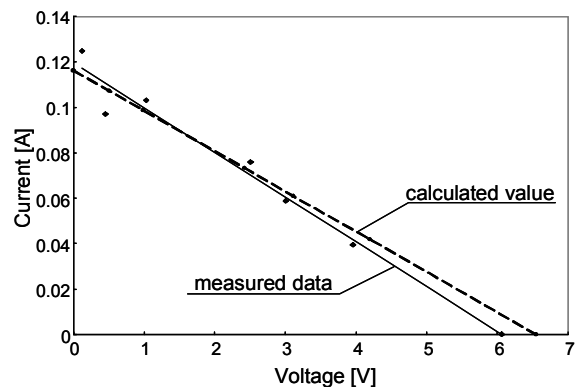
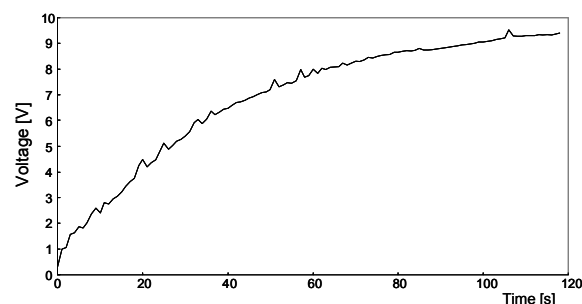


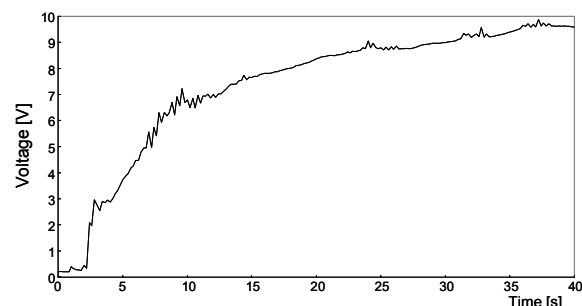
Fig. 12 Volt-ampere characteristics of the produced linear power generator

Figure 13 illustrates the change in the charging voltage to the electric double-layer capacitor (0.5[F], 10[V]). Figure 10 (a) shows the change of the charging voltage

of the linear power generator under the addition of vibration at the frequency 2.7 [Hz] with an amplitude of 30 [mm]. The equilibrium value of 9.7 [V] is obtained in about 2 [min]. The charge voltage using four generators that were connected in parallel is shown in the same figure (b). The equilibrium voltage is obtained in under 40 [s].



(a) Charging characteristic of generator (with magnetic material tube cover)



(b) Four generators in parallel (with magnetic material tube cover)

Fig. 13 Change of the charging voltage to the capacitor by the linear power generator

4. CONCLUSIONS

In this study, we modified a linear power generator using very strong Nd Fe-B magnets, which can convert any mechanical vibration energy produced by a vehicle to electric energy. The change of the magnetic path corresponding to the position of the mover was calculated by numerical simulations. The magnetic material cover with pole pieces and mild-steel between the magnets were confirmed to extend the magnetic path. The adsorption power between the pole of the cover and the magnets were calculated. The braking effect becomes large, when the spacing of the pole and mover become small, under these simulations. Furthermore, the simulation demonstrated that the induced current decrease the output voltage, so that the vibration of the mover was attenuated. It was realised that the steel pipe was desirable as the cover for effective power generation.

The linear power generator was produced on the basis of those simulations. The performance of the produced linear power generator was tested by experiments. Comparing the modified linear power generator and the previous production trial at the same frequency, the obtained electric power of the modified linear power generator is about fourteen times that of the previous production trial. The findings concerning the linear power generator were as follows:

- (1) The mover is 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 stator covered with a magnetic material makes the magnetic flux extended through the cover, reducing the cancellation of the flux in the coils of the stator. But, forming the flux path tightly restricts the actuation of mover and reduces production of electricity.
- (3) The effect of the eddy current through the magnetic material cover on the motion of the mover is conceivably low by the simulations. On the other hand, the induced currents increase the adsorption power and exert large influences on the movement of mover.

In order to generate larger electric power, 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 cover and so on. Smoothing the movement of mover will be viewed as a way to raise energy efficiency of the generator.

In addition, the changes of magnetic distribution show that there are some positions of mover that does not contribute to power generation. Therefore, 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.

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