Design of a Linear Synchronous Generator and Examination of the Driving Range for a Free-Piston Engine Linear Generator System

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A free-piston engine linear generator (FPEG) system is a linear generator, which generates electricity when a free piston reciprocates the combustion thrust produced by internal combustion. It is expected that this system can be applied to hybrid vehicles. In an FPEG system, the high combustion energy is instantly added to a free piston. Nevertheless, it is difficult for a linear synchronous generator (LSG) to convert combustion energy into electric energy by using the output of the LSG given the limit of the inverter capacity. Hence, it is necessary for an LSG to convert combustion energy into electric energy while distributing the combustion energy in one stroke. Moreover, if an LSG is driven at high velocity and high thrust within the limit of an inverter capacity, then the LSG converts the high combustion energy into electric energy. In this study, we propose a configuration of an LSG with a typical output of 10 kW and a generation efficiency of 97% for an FPEG, and we evaluate its static thrust and magnetic flux density distribution using finite element method (FEM) analysis. Moreover, we examine the driving range of the LSG for an FPEG system.

Keywords: FEM analysis, free-piston engine, HEV system, Linear Synchronous Generator, magnetic flux density distribution, static thrust distribution

1. Introduction

Automobiles have contributed to improvements in standards of living and economic growth. However, environmental problems including air pollution and global warming that are caused by automotive vehicles continues to pose serious issues—although reduced by the increase of hybrid electrical vehicles (HEVs) are still serious. To solve this environmental issue, it is essential to develop a new power train and HEV system to improve the overall efficiency of automobiles^{(1)–(4)}. Therefore, this study proposes an FPEG system.

An FPEG system generates electricity by using the free piston that reciprocates combustion thrust, and it possesses several important characteristics. The system experiences only small mechanical losses due to friction because it does not possess a crank mechanism. Additionally, it is possible for an FPEG system to exhibit high-efficiency movement due to a free piston that drive at resonant frequency. Furthermore, an FPEG system freely changes the stroke and compression ratio. Therefore, the thermal efficiency rises when compare with a conventional engine⁽⁵⁾. As mentioned above, an FPEG system is expected to exhibit higher efficiency when

compared to a hybrid systems and current HEV systems^{(5)–(7)}.

An FPEG system generates electricity by using the combustion thrust. Furthermore, high combustion energy is instantly added to a free-piston. Nevertheless, it is difficult for a linear synchronous generator (LSG) to convert combustion energy into electric energy by using the output of the LSG given the limit of the inverter capacity. Hence, it is necessary for an LSG to convert combustion energy into electric energy while distributing combustion energy in one-stroke. Moreover, if an LSG is driven at high-velocity and high-thrust in limit of an inverter capacity, then an LSG converts high combustion energy into electric energy. Thus, an LSG for an FPEG system satisfies the following requirements.

- 1) High thrust and high generation efficiency
- 2) Extension of the driving range

In this paper, with the aim of designing an LSG for FPEG system, described the following points regarding the FPEG system:

- (1) Basic structure of the FPEG system
- (2) Examination of driving range of the LSG

2. Basic Principle of the FPEG System

Figure 1 shows the physical models of the FPEG system. The free-piston moves to the bottom dead center by the combustion thrust at which point the thrust of the gas spring chamber increase. The piston is moved to the top dead center by the thrust of the gas spring chamber. This movement is repeated to reciprocate the free-piston. At this point, the equation of motion for the FPEG system is given by

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Fig. 1. Physical models of FPEG system

Table 1. Target specifications of LSG

Item	Symbol	Value	(unit)
Generating efficiency	η_e	95	(%)
Resistance of armature coil	R_a	200	(mΩ / phase)
Mass of mover	m	5	(kg)
Maximum static thrust	F	4.0	(kN)
Coil space factor	ζ	70	(%)
Maximum armature current	I	200	(A)
Maximum flux density	B_m	1.8	(T)
Drive frequency	f	20	(Hz)

$$m\ddot{x} = F_c - F_l - F_g - F_r \text{ (N)} \dots \dots \dots (1)$$

where m is the mass of the mover, x is the piston position, F_c is the combustion thrust, F_l is the thrust of generation braking, F_g is the thrust of the gas spring and F_r is the friction thrust of the piston.

The free-piston is reciprocated, and thus the back electromotive force occurs based on Faraday's law of induction. The generated electric current charge the battery through an inverter.

Currently, the system controls the d-axis current to 0 A by using the pulse width modulation (PWM) inverter to improve the generation efficiency.

3. Design of the LSG

3.1 Method of Examination Table 1 shows the target specifications of the LSG. The target of the static thrust is defined as the thrust necessary to stably move a free-piston. The thrust was calculated in the simulation. When a core is magnetically saturated, the difference in the magnetic permeability between the core and the gap becomes small. Additionally, the thrust does not increase even if the armature current increase⁽⁸⁾. Therefore, the objective of the maximum magnetic flux density involves to not exceeding the saturated magnetic flux density of the non-oriented electrical steel sheets that are used as the material of the cores.

Fig. 2. Design flow of the LSG

Fig. 3. Basic structures of FPEG system (unit: mm)

Furthermore, the objective space factor for the coils is 70% when insulation processing is considered.

Figure 2 shows the design flow of the LSG. We designed the LSG by following the design flow. Subsequently, the process of the design is as the follow. [1] Selection of the external dimensions of the LSG from the target of the output. [2] Selection of the pole pitch, number of poles, and slot combination. [3] Selection of the magnetomotive force of the permanent magnet. [4] Selection of the magnetic resistance to satisfy the target thrust. As stated above, the process is repeated to design the LSG.

3.2 Basic Structure of the LSG Figure 3 shows the basic structure of the LSG. Table 2 shows the specifications of the LSG. The stator comprises of a yoke and coils, and the mover comprises of a yoke and a permanent magnet. Therefore, the LSG is a magnet- movable model. Additionally, the number of slots and the number of pole pairs are 42 and

Table 2. Specifications of the LSG

Item	Symbol	Value	(unit)
External dimensions	-	168×263	(mm)
Internal dimensions	-	128×130	(mm)
Mass of mover	m	5.25	(kg)
Number of slots	N_s	42	
Depth of slot	l_D	13	(mm)
Width of slot	s_s	3.4	(mm)
Number of poles	P	14	
Pole pitch	2τ	18.6	(mm)
Width of coil	w_c	3	(mm)
Thickness of coil	t_c	2	(mm)
Number of coil turns	N	5	
Coil space factor	ζ	67.8	(%)
Resistance of armature coil	R_a	108	(mΩ / phase)
Inductance of armature coil	L_a	1.8	(mH / phase)

Fig. 4. Magnetic flux density distribution of LSG

7, respectively. Therefore, the LSG is also classified as an integral-slot model. The winding coefficient of the slot combination is 0.866. The coil features intensive winding, moreover, the coils features ring form shape. and this has the following advantages

- 1) It facilitates production.
- 2) It increases the coil space factor.
- 3) The copper loss is expected to decrease due to no coil ends.

Additionally, the coil wind-up spiral was shaped to fit into a single slot, which hides the coil end. Furthermore, a rectangular wire is adopted to increase the coil space factor, and the conductor cross section of the rectangular wire is selected by setting the limit of the current density while considering consecutive driving. The stator is divided into three parts to facilitate production. As a result, the armature resistance per phase is 108 mΩ per phase, which satisfies the target of less than 200 mΩ.

The permanent magnet use sintered neodymium magnet to enhance the magnetic loading. Moreover, the permanent magnet is lined to constitute a Halbach array and it can increase the air gap flux density.

3.3 Simulation Figure 4 shows the magnetic flux density of the LSG when the maximum armature current corresponds to 0 A and 200 A. When the armature current is 0 A,

(a) The detent thrust.

 (b) Static thrust ($I = 50, 100, 150, 200$ A)

Fig. 5. Static thrust of LSG

Fig. 6. Static thrust vs. current characteristic of LSG

the end of the armature teeth is magnetically saturated, and the magnetic flux density is 2.2 T. However, in the center of the armature teeth, the magnetic flux density is as high as the allowable magnetic flux density.

Because the magnetic flux density distribution in 200 A, which is lower than the prescribed maximum armature current of the FPEG system chosen to be less than the saturated magnetic flux distribution of non-oriental electromagnetic steel sheets. Thus, the LSG is confirmed to work stably.

Figure 5 shows the static thrust distribution toward each armature current for the pole pitch. When the armature current is 0 A, the detent thrust assumes a maximum value of 73 N. Moreover, the static thrust is constant for any mover position.

Figure 6 shows the static thrust versus the armature current that maintains a linear trend up to 200 A, which corresponds to the prescribed maximum armature current for the FPEG system. The achieved static thrust is 2.5 kN, which is the target value necessary for stable operation. The calculated thrust constant, it is 22 N/A, can be used to calculate the motor constant. The motor constant K_m is given by

$$K_m = \frac{K_f}{\sqrt{R_a}} \text{ (N/}\sqrt{\text{W}}\text{)} \dots \dots \dots (2)$$

where K_f is the thrust constant and R_a is the armature

Fig. 7. Block diagram of LSG

 Fig. 8. Generation efficiency map of LSG ($V_{dc} = 500$ V)

resistance.

The resulting calculating value for K_m is $66.9 \text{ N}/\sqrt{\text{W}}$.

From the above calculations, the system achieves the targets for thrust.

Subsequently, generation efficiency is examined. Figure 7 shows at block diagram to examine the generation efficiency of the LSG. The LSG is controlled by the PI controller of velocity and electric current by using the PWM inverter. The electric current controller uses a d-axis current zero controller and a decoupling controller. The generator efficiency is calculated from the output current and the output voltage when the piston velocity is in a steady state. At this point, the generation efficiency η_e is given by

$$\eta_e = \frac{I_o \times V_o}{F_e \times v} = \frac{P_o}{P_o + Q_c + Q_i} \quad (\%) \quad (3)$$

where I_o is output current of inverter, V_o is output voltage of Inverter, F_e is external thrust, P_o is output electric power, Q_c is copper loss and Q_i is iron loss,

Thus iron loss is given by

$$Q_i = Q_e + Q_h = k_e f_e^2 B_m^2 + k_h f_e B_m^{1.6} \quad (\text{W}) \quad (4)$$

where Q_e is eddy current loss, Q_h is hysteresis loss, k_e is proportional constant, f_e is frequency of the electric current, B_m is maximum magnetic flux density, and k_h is proportional constant.

Figure 8 shows the generator efficiency map for the LSG. A high generation efficiency exceeding 96% is provided in the low-thrust and high-velocity domain. Because only a small amount of generation braking thrust is necessary at low thrusts, and thus the electric current called off the coil

Table 3. Preconditions of the examination

Item	Symbol	Value	(unit)
Combustion energy	P_c	4	(kW)
Driving frequency	f	20	(Hz)
Piston stroke	s	100	(mm)
DC shrink voltage	V_{dc}	500	(V)

Fig. 9. Combustion thrust vs. position characteristic

is small and copper loss decreases. Additionally, the ratio of the copper loss increases because the output electric power decreases in the low-velocity domain. Furthermore, the ratio of copper loss decreases in the high-velocity domain, output electric power ratio increases, and generation efficiency improves.

From the above conclusions, the following points are obtained for control methods to produce high generating efficiencies:

- (1) Avoid generating electricity in the low-velocity domain
- (2) Generate electricity based on the generator efficiency map only at high-efficiency points.

4. Examination of the Driving Range of the LSG

An FPEG system generates electricity by using the combustion thrust. Moreover, high combustion energy is instantly added to a free-piston. However it is difficult for an LSG to convert combustion energy into electric energy by the output of the LSG and limits of the inverter capacity. Therefore, it is necessary for an LSG to convert combustion energy into electric energy while distributing combustion energy in one-stroke. Additionally, an LSG converts high combustion energy into electric energy if a LSG drives high-velocity and high-thrust at the limit of inverter capacity.

Therefore, we examine the driving range of the LSG at the limit of the inverter capacity.

4.1 Condition of the Examination Prior to performing the examination, preconditions are set to easily perform the same. Table 3 shows the preconditions of the examination, and Fig. 9 shows Combustion thrust versus piston position characteristic. Combustion energy P_c corresponds to the output of 4 kW by the combustion in the combustion chamber. The combustion hysteresis corresponds to the curve in Fig. 9. Subsequently, the free-piston is involve an assumption about sine wave driving in which driving frequency f is 20 Hz and the piston stroke s is 100 mm. The control system is composed of a PI controller of velocity and an electric current that uses PWM inverter is similar to that in Fig. 7.

Moreover, the PWM inverter uses the comparison with a triangular wave. The DC shrink voltage of the inverter is set as 500 V.

4.2 Influence of Pole Pitch At the setout, we examine the limit of the voltage. At the PWM control using comparison with triangular wave, the maximum armature voltage V_{amax} is given by

$$V_{\text{amax}} = \frac{1}{2} V_{\text{dc}} \cdot \sqrt{\frac{3}{2}} = 0.612 V_{\text{dc}} \quad (\text{V}) \dots \dots \dots (5)$$

Then, equation (5) holds that modulation factor of the PWM inverter is 1. Additionally, from equation (5), the maximum current phasor I_{amax} is given by

$$I_{\text{amax}} = \frac{V_{\text{amax}}}{R_a + \omega_e L_a} \quad (\text{A}) \dots \dots \dots (6)$$

where ω_e is the electric angular velocity.

Furthermore, the electric angular velocity ω_e is given by

$$\omega_e = \frac{\pi}{\tau} v \quad (\text{rad/s}) \dots \dots \dots (7)$$

Based on the equation (6) and (7), it is necessary to expand the pole pitch to expand driving range of the LSG in high-velocity domain. At the point, the combustion energy output 4 kW, and thus the LSG should generate 800 J in one-stroke. Therefore, we examine the thrust necessary to generate 800 J when the piston velocity is maximum. The necessary thrust when the piston velocity is maximum is given by

$$F = \frac{P_c \cdot 2s}{v_{\text{max}} \cdot \left(\frac{1}{f}\right)} \quad (\text{N}) \dots \dots \dots (8)$$

where v_{max} is the maximum piston velocity.

From the equation (8), when the free-piston is driven the sine wave which driving frequency is 20 Hz and piston stroke is 100 mm, The necessary thrust in the maximum piston velocity 6.28 m/s is 2547 N. However, this thrust is not satisfactory as shown in Fig. 7. Hence, we examine the change in the driving range when the pole pitch is modified.

4.3 Examination of Pole Pitch Table 4 shows the specifications of the LSG in which the pole pitch is modified. Each model is modified the pole pitch 21.6 mm and 26.1 mm which is 1.2 times and 1.4 times as long as 18.6 mm on condition that external dimensions of stator and mover is equation the LSG which 2τ is 18.6 mm. Subsequently, from equation (6), when the piston velocity is 6.28 m/s, the thrusts of the LSG in which 2τ corresponds to 21.6 mm and 26.1 mm are 2605 N and 2741 N, respectively.

4.4 Result of Simulation Figure 10 shows the static thrust versus armature current characteristic of the LSG which pole pitch is modified. The static thrust of each LSG maintains a linear trend up to 200 A, and the achieved static thrust is 2.5 kN. However, the thrust constant of the LSG which 2τ is 21.6 mm and 26.1 mm are 18.0 N/A and 14.7 N/A, respectively. Because to expand the pole pitch on condition that external dimensions of stator is equation the LSG which 2τ is 18.6 mm, number of slots is decreased. Thus, the resulting calculating value for K_m of the LSG which 2τ corresponds to 21.6 mm and 26.1 mm are 70.0 N/ $\sqrt{W}$ and

Table 4. Specifications of the LSG (The pole pitch is modified)

Item	Symbol	$2\tau = 21.6 \text{ mm}$	$2\tau = 26.1 \text{ mm}$
Number of slots	N_s	36	30
Depth of slot (mm)	l_D	13	13
Width of slot (mm)	s_s	3.4	5.0
Number of poles (mm)	P	12	10
Pole pitch	2τ	21.6	26.1
Width of coil (mm)	w_c	3.5	4.6
Thickness of coil (mm)	t_c	2	2
Number of coil turns	N	5	5
Coil space factor (%)	ζ	67.8	67.8
Resistance of armature coil (m Ω / phase)	R_a	66	42
Inductance of armature coil (mH / phase)	L_a	1.7	1.6

Fig. 10. Static thrust vs. current characteristic of LSG

71.8 N/ $\sqrt{W}$, respectively and they improve by 4% and 7%, respectively as high as the LSG which 2τ is 18.6 mm. This is because the armature resistance decreases due to the decrease in the number of slots.

Figure 11 shows the generation efficiency map of the LSG in which pole pitch is modified. The maximum generation efficiency of each LSG is 95%, and decreases by 1% when compared with the LSG in which 2τ is 18.6 mm. However the limits of the driving range are more extensive than the LSG in which 2τ is 18.6 mm because the impedance of the high-velocity domain decreases since pole pitch expands and the maximum current phasor increases. Therefore, when the piston velocity is 6.28 m/s, the thrust of the LSG in which 2τ is 21.6 mm and 26.1 mm are 2687 N and 2750 N, respectively, and the achieved thrust value is 2547 N. Moreover, each thrust corresponds to the calculated value by using equation (8). At the point, when a LSG is driven near the limit of the driving range, the generation efficiency decreases because of the field weakening. Thus, in this examination, the LSG in which 2τ is 21.6 mm is suitable for the FPEG system.

From the above, the pole pitch is by selected by using the equations (6), (7), and (8) based on the combustion energy, the FPEG system is driven within the driving range. And the FPEG system can accommodate to various fuel.

Fig. 11. Generation efficiency map of LSG (The pole pitch is modified)

5. Conclusions

In this study, the following results were obtained.

(1) Design of the LSG for the FPEG system

A configuration of the LSG for an FPEG was proposed for the ease of production. Magnetic saturation was not observed at the center of the armature teeth. Additionally, the static thrust versus armature current maintains linearity. A high generator efficiency exceeding 97% is provided in the low-thrust and high-velocity domains.

(2) Examination of driving range of the LSG

The pole pitch was selected based the combustion energy, and thus a suitable driving range was selected for the FPEG system. Therefore, combustion energy changes when fuel is used. Additionally, the FPEG system uses various fuel. Equations (6), (7), and (8) are used to design the LSG suitable for using fuel.

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