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Optimal linear generator with Halbach array for harvesting of vibration energy during human walking

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Abstract

In IT business, the capacity of the battery in smartphone was drastically improved to digest various functions such as communication, Internet, e-banking, and entertainment. Although the capacity of the battery is improved, it still needs to be upgraded due to customer's demands. In this article, we optimize the design of the linear generator with the Halbach array to improve the efficiency of harvesting vibration energy during human walking for the battery capacitance. We propose the optimal design of the tubular permanent magnet with the linear generator that uses a Halbach array. The approximate model is established using generic algorithm. Furthermore, we performed electromagnetic finite element analysis to predict the induced voltage.

Keywords

Smartphone, generator, Halbach array, permanent magnet, optimization

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Introduction

Due to the development of the information industry and related technologies, smartphone has many functions such as messages, Internet access, e-banking, and games. Although the entire battery capacity has been improved compared with that of old phone, the available usage time has decreased because of digesting various functions.

In order to address this problem, Park et al. developed an embedded linear generator for a self-rechargeable function. The linear generator is operated by resonance phenomenon. Electromagnetic force (EMF) is generated according to Faraday's law, and the battery is recharged by EMF. In an existing linear generator, the battery can be recharged in walking and shaking mode. However, the generated electric power is not adequate because of low efficiency. Optimizations and conversion of array of permanent magnet (PM) are studying to resolve this problem.[1]

There are many array types of PM in linear generator. The radial direction array was introduced by Ishiyama et al.[2] The magnets are placed face-to-face to generate mutual repulsion. However, the axial direction array, which is different from Ishiyama's design, was introduced by Murphy.[3] The Halbach array is an arrangement of magnets that increases the magnetic field on one side of the array, while offsetting the field to nearly zero on the other side. The different types of

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rotating pattern of PM (left, up, right, and down) are used.[4,5]

Our proposed optimal design attempts to maximize the generated induced voltage. We can obtain optimum values that maximize the objective function using optimal design under constraint conditions.[6]

In this study, we propose the Halbach array embedded in a smartphone in order to maximize generated induced voltage by applying to proper ratio of the radial and axial magnets. The optimum values, based on the commercial electromagnetic analysis software, ANSYS and Maxwell, show a more feasible design compared to the existing generator.

Generation system

Structure and principle of the Halbach array generator

Figure 1 shows the schematic diagram of the conventional tubular linear generator. It is composed of two main parts: a slider and stator. The slider is composed of PMs, and pole shoes serving as a conductor of magnetic flux. The stator is composed of the coils, housing, and two poles with three-phase coil windings. Two springs enable the slider to produce resonance.

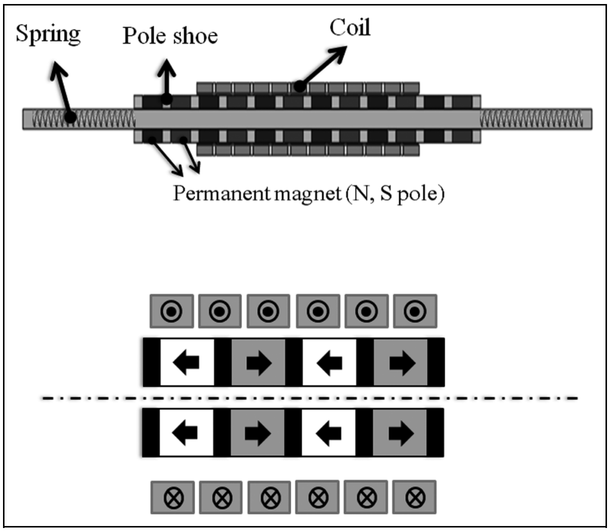

Figure 1. Schematic diagram of conventional tubular linear generator.

Figure 2 shows a schematic diagram of the Halbach-array-type linear generator. The Halbach array generator consists of PMs following axial- and radial-direction PMs. One-sided magnetic flux was introduced by Mallinson,[7] and the Halbach array was developed by Halbach.[8] In case of the Halbach array shown in Figure 3, if the axial and radial PMs were magnetized alternatively, magnetic flux is concentrated in only one direction[9–11] because the opposite direction is offset. Thus, it maximizes the amount of the power generated, compared to the conventional models without the addition of the magnetic material.[12] The pole shoe functions as a conductor of the magnetic field to replace the radial magnetized PM on a conventional model. The coil winding is formed with a four-pole three-phase that is different from the two-pole three-phase in existing generator.

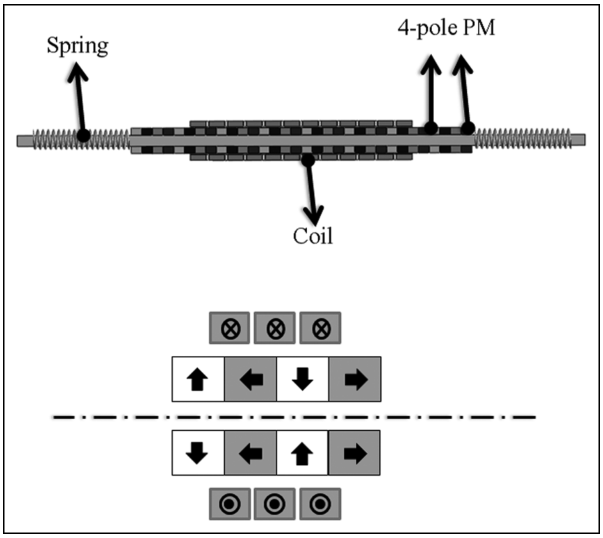

Figure 2. Schematic diagram of the Halbach array tubular linear generator.

Figure 4 shows the diagram of the energy conversion principle. The EMF is generated at the stator coil terminals as the slider vibrates by the walking and shaking motion of the user. The EMF is calculated by using Faraday's law and can be expressed as follows

$$e(t) = N\frac{d\phi}{dz}\frac{dz}{dt} \tag{1}$$

where N is the number of turns per coil, ϕ is the flux passing in each turn in real time t, dz/dt is the slider speed, and z is the distance along the z-direction. So, the EMF is proportional to the number of turns per coil, the variation of magnetic flux, and the speed of the slider.[13]

Analysis of the linear generator and resonance phenomenon

Excitation from the user's motion can be regarded as base excitation. Figure 5 shows a free-body diagram for the analysis, In Figure 5, m is the mass of the slider, k is the spring coefficient, and c is the coefficient of damping. The base excitation can be expressed by equation (2). $y(t)$ is $Y\sin\omega_b t$, representing the displacement of the base, and the displacement and velocity of the slider

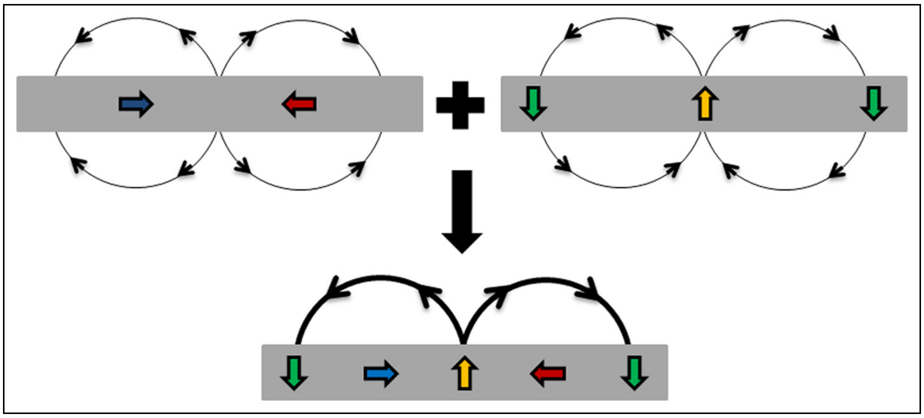

Figure 3. Principle of the Halbach array's superposition.

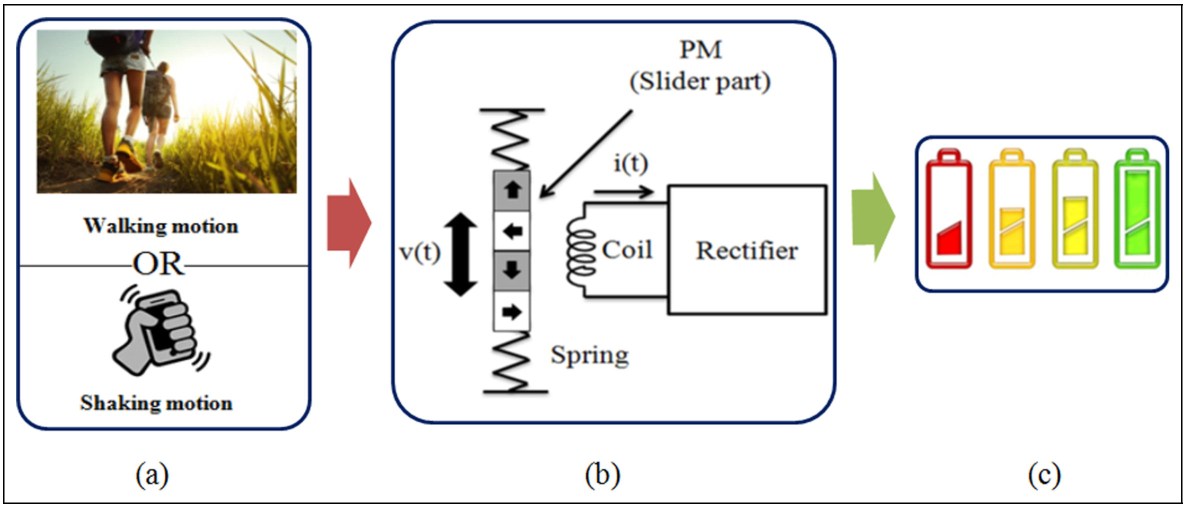

Figure 4. Diagram of energy conversion process: (a) User's motion; (b) Energy conversion and (c) Charging battery.

are denoted as $x(t)$ and $v(t)$, respectively. The amplitude of $x(t)$ is calculated using equation (3). In equation (3), ζ represents the damping ratio of the linear generator. The frequency of walking motion is in the range of 2–2.2 Hz,[14] and the frequency of shaking motion is in the range of 3–5 Hz[1]

$$m\ddot{x} + c(\dot{x} - \dot{y}) + k(x - y) = 0 \tag{2}$$

$$x = y\left[\frac{1 + (2\zeta r)^2}{(1 - r^2)^2 + (2\zeta r)^2}\right]^{\frac{1}{2}}, \quad r = \frac{\omega_n}{\omega_b} \tag{3}$$

where ω_n is the natural frequency and ω_b is the base excitation frequency.

In walking motion, the displacement amplitude of the base excitation is less than 2 cm, which does not create enough for adequate induced voltage. To maximize the energy, the resonance is exploited by matching the motion frequency to the natural frequency of the generator. It is possible to check the displacement amplitude in accordance with the input frequency using equation (3), as shown in Figure 6.

According to Figure 6, the vibration characteristics are different for each natural frequency. In walking or

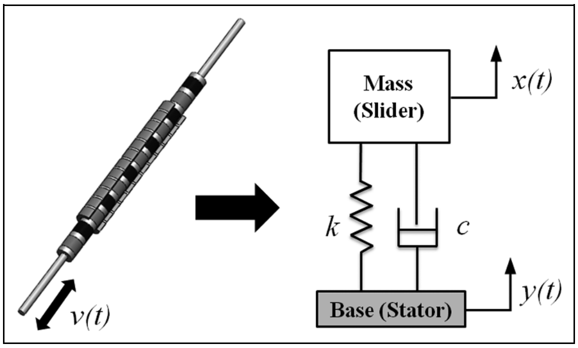

Figure 5. Free-body diagram for analysis of base excitation.

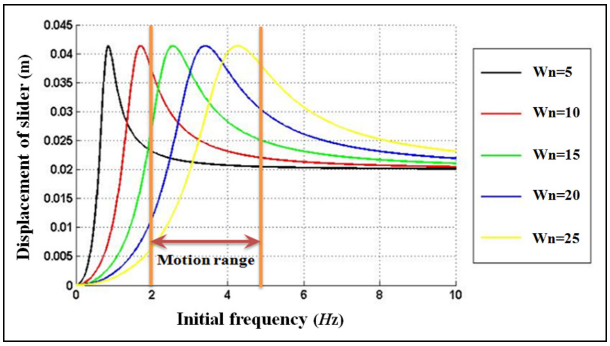

Figure 6. Displacement amplitude according to input frequencies.

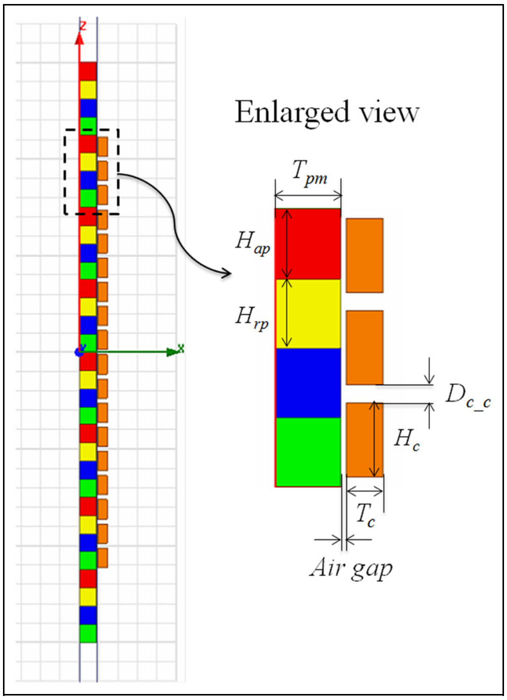

Figure 7. Initial model of linear generator on axial-symmetric view.

shaking motion (2–5 Hz), we confirmed that resonance occurs when the natural frequency (ω_n) is 15 rad/s. Then, we determined the optimal mass of the slider, the coefficient of the spring, and other specifications for sufficient vertical motion.

Electromagnetic analysis of initial model of linear generator

In order to analyze the electromagnetic performance of the linear generator, finite element analysis is performed using the commercial electromagnetic software, Maxwell. Figure 7 shows the initial two-dimensional (2D) model with the cylindrical coordinates for the analysis. Also, the specifications of axisymmetric model which is the initial model of linear generator are summarized in Table 1. The total number of magnets in the linear generator is 32, the height of axial PM (H_{ap}) and radial PM (H_{rp}) is 1.875 mm, and the thickness of PM (T_{pm}) is 1.75 mm. The thickness of coil (T_c) is 1 mm and the height of coil (H_c) is determined by H_{ap} and H_{rp} in linear generator because the magnet array of linear generator is composed of the continuous Halbach array. The heights of the magnets with the axial poles have all same length. In addition, the radial have the same shape. This structure of the Halbach array is matched with three coils having regular intervals. In other words, the structure of the magnet and the coil of the linear generator have one set which consisted of four magnets and three coils.

Table 1. Specifications of initial model.

Indication	Name	Specification (mm)
H_{ap}	Height of axial PM	1.875
H_{rp}	Height of radial PM	1.875
T_{pm}	Thickness of PM	1.75
H_c	Height of coil	2
T_c	Thickness of coil	1
D_{c_c}	Distance between the coils	0.5

PM: permanent magnet.

The height of the coil is represented by the following equation

$$2 \cdot \left(H_{ap} + H_{rp}\right) = 3 \cdot \left(H_c\right) + 3 \cdot 0.5$$

where the distance between the coils (D_{c_c}) is 0.5 mm. Therefore, H_c depends on H_{ap} and H_{rp}. The coil's cross-sectional area is estimated from T_c and H_c determined by H_{ap} and H_{rp}. Because the coil is coated to prevent short circuit, the thickness of the coating should be generally considered for calculating coil turns. In other words, it should consider the packing factor (F_p).

The number of coil turns is represented by the following equation

$$N = F_p \cdot \frac{T_c \cdot H_c}{\pi \cdot \left(\frac{D}{2}\right)^2}$$

where the packing factor (F_p) is generally set to 0.6[15] and D is the coil diameter. The used coil is AWG45 with 0.0453 mm in diameter. So, the number of coil turns is 744 in initial simulation. Then, it is applied in the simulation. Table 2 shows the properties of the magnet, coil, shaft, and the number of coil turns used in Maxwell. And, the PM's material is Nd-Fe (Neodymium–Ferrite) having more magnetic energy than ferrite or SmCo. The shaft is stainless as a non-magnetic material, and

Table 2. Initial model properties of linear generator.

Name	Properties		
Magnet	NdFe_35		
Shaft	Stainless		
Coil	Copper	Number of turns	744
		AWG 45	
		Diameter	0.0453 mm

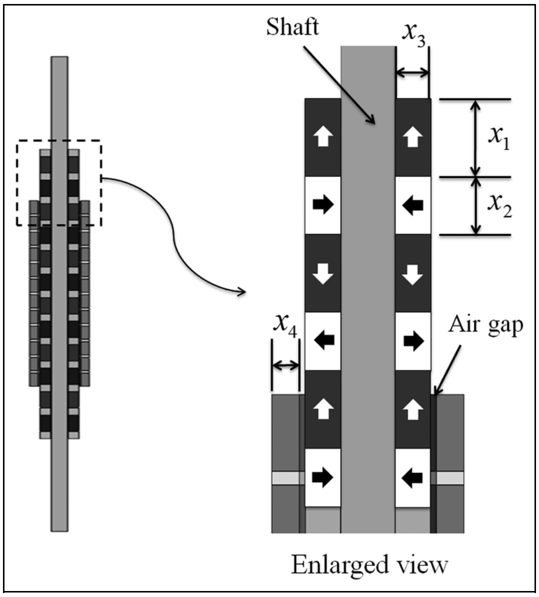

Figure 8. Design variables for optimal design.

the coil is copper. We apply an air-core winding without the magnetic material between the coils in this study.

Formulation of optimal design

Design variables and constraints

Figure 8 shows the design variables of the proposed Halbach array linear generator. We determined the following values: x_1 is the height of the axial PM, x_2 is the height of the radial PM, x_3 is the thickness of the PM, and x_4 is the thickness of coil. There are two constraints for the proposed linear generator because of the limited space in a smartphone.

First, there is the limited length of the smartphone. In order to place inside the smartphone, the length of the linear generator is limited. The length of the linear generator is determined by the height of the PM. The axial magnetized PMs have the same height. Also, the radial magnetized PMs have the same axial height. Thus, the length of the linear generator, considering the total length of the 32 magnets except for the shaft is shown as follows.

The length of the linear generator must be less than 60 mm

$$16 \cdot (x_1 + x_2) \leq 60\,\text{mm}$$

Second, there is the limited thickness of the smartphone. Thus, the thickness of the generator is limited to 7 mm, which is the maximum thickness of the smartphone. The diameter of the shaft and airgap is 0.5 and 0.15 mm, respectively.

The thickness of the linear generator must be less than 7 mm

$$2 \cdot (x_3 + x_4) + 2 \cdot 0.15 + 0.5 \leq 7\,\text{mm}$$

Table 3 shows the initial, lower, and upper value of each design variable.

Design requirements

The generated electro-motive force should be maximized. This is represented by the following equation

$$\text{Maximize induced voltage} = \left(V_i = -N \frac{d\phi}{dz} \frac{dz}{dt} \right)$$

Design formulation

The design problem for determining design variables that satisfy all design requirements can be formulated as follows

Find: x_1, x_2, x_3, x_4

to maximize: induced voltage

subject to: $16 \cdot (x_1 + x_2) \leq 60\,\text{mm}$

Table 3. Design variables for optimal design.

Design variables		Lower	Initial	Upper
x_1 (mm)	Height of axial PM	0.5	1.875	2.5
x_2 (mm)	Height of radial PM	0.5	1.875	2.5
x_3 (mm)	Thickness of PM	1	1.75	3
x_4 (mm)	Thickness of coil	1	1	3

PM: permanent magnet.

$$
\begin{aligned}
&2 \cdot (x_3 + x_4) + 2 \cdot 0.15 + 0.5 \leq 7\,\mathrm{mm}\\
&0.5 \leq x_1 \leq 2.5\\
&0.5 \leq x_2 \leq 2.5\\
&1 \leq x_3 \leq 3\\
&1 \leq x_4 \leq 3
\end{aligned}
$$

Analysis process and optimal design

Optimization was formulated in order to find the optimal values needed to maximize the induced voltage. We determined our design of experiments (DOE) using PIAnO (Process Integration, Automation, and Optimization), which is provided in the commercial software PIDO (Process Integration and Design Optimization). We performed electromagnetic analysis, and the induced voltage was determined using electromagnetic analysis software ANSYS Maxwell. Then, we selected the Kriging model and the evolution algorithm (EA) that is provided in PIAnO. Figure 9 shows the process of optimal design using PIAnO and ANSYS Maxwell.

DOE

We determined the DOE using $L_{25}(5^6)$ (an orthogonal array provided in PIAnO). An orthogonal array is a table that allows the DOE to be easily determined with a minimum of sampling points. Also, many factors can be arranged without enlarging the size of the experiment, and simulation data can be easily analyzed.[16] Therefore, we created 25 linear generator models according to the orthogonal array and performed electromagnetic analysis for each model.

Electromagnetic analysis

A total of 25 Halbach array linear generator models were created according to sampling points based on the DOE. Each model was analyzed using ANSYS Maxwell. Then, we created the approximate model. The electromagnetic analysis was processed manually. After the analysis, the design automation was processed using PIAnO.

Approximate model

The approximate model approximates relationship between the reaction value of the analysis model and the design variables. In this study, we determined the Kriging model. The Kriging model, a representative interpolation model, shows superb predictive performance under many design variables. Also, there are no parameters that depend on the experience and intuition of customers when choosing the design parameters because the Kriging model can optimize design parameters through maximum likelihood estimation (MLE).[17]

Optimization method

We selected the EA based on the optimization method provided in PIAnO. Discrete variables can be treated efficiently and can be applied regardless of the function's type because EA does not demand sensitivity of function. Although EA needs much more time than other optimization algorithms, it can be applied in our case because approximate model requires a short analysis time.

Results of optimization

In our results, all constraints including the length and thickness of the linear generator are satisfied. The induced voltage of optimal design compared with the initial design increases by 36%. We confirmed the design accuracy of the optimization result by actual analysis using Maxwell. Because the optimal design results can be changed based on using the metamodel

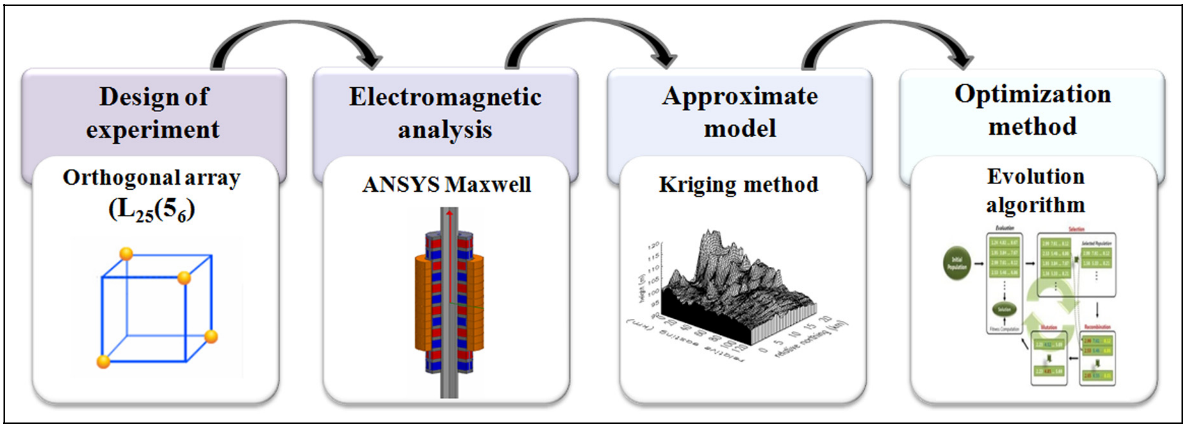

Figure 9. Process of optimal design.

Table 4. Initial and optimum value of design variables.

Design variables		Lower	Initial	Optimum	Upper
x_1 (mm)	Height of axial PM	0.5	1.875	1.75	2.5
x_2 (mm)	Height of radial PM	0.5	1.875	2	2.5
x_3 (mm)	Thickness of PM	1	1.75	1.75	3
x_4 (mm)	Thickness of coil	1	1	1.35	3

PM: permanent magnet.

Table 5. Optimum model properties of linear generator.

Name	Properties		
Magnet	NdFe_35		
Shaft	Stainless		
Coil	Copper	Number of turns	1005
		AWG 45	
		Diameter	0.0453 mm

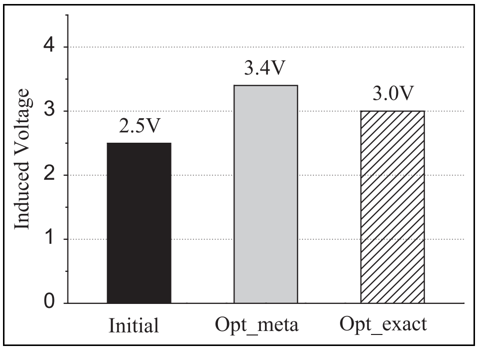

Figure 10. Comparison of the design accuracy.

instead of the actual analytical model in this research.[17] To do this, the Kriging model results (Opt_meta) of the optimal design variables and the analysis results from Maxwell (Opt_exact) were compared as shown in Figure 10. The Kriging model results (Opt_meta) and the Maxwell model results (Opt_exact) were similar. Therefore, we confirmed the high accuracy of the Kriging model's prediction.

We found the optimum value through the optimum design in limited range. Table 4 shows the initial and optimum values of the variables. As a result, the height of axial PM is decreased and radial PM is increased. Also, the number of the coil turns is increased by the thickness of coil. The maximum induced voltage generated in limited range. Table 5 shows the optimum properties of linear generator.

Conclusion

In this study, we performed optimization for a Halbach array linear generator for a smartphone. We determined the DOE and performed electromagnetic analysis. Then, we selected a Kriging model and EA. We maximized the induced voltage of the existing Halbach array linear generator using an approximate model. The following conclusions were drawn from our results:

1. We formulated the design problem in order to maximize the induced voltage of the Halbach array linear generator;
2. We determined the DOE based on an orthogonal array using optimization software PIAnO. Then, each linear generator designed by sampling points was analyzed using ANSYS Maxwell. A Kriging model, provided in PIAnO, was generated based on the simulation results;
3. The optimal design was determined using the EA. All constraints were satisfied, and we obtained optimum values. The average of RMS-induced voltage was increased by 16% in comparison with the existing model (average RMS of induced voltage: 3.0 V)
4. Our optimization improves the efficiency to harvest the vibration energy during human walking, and the results show the possibility for the tubular linear electric generator suitable for the practical use in cellular phone.

Declaration of conflicting interests

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