Abstract
Extra low-power magnetic suspension system is achieved using solely solar power. Presently, solar cells have become more efficient and cost-saving year by year. In this work, a solar power generation technique is combined with zero-power control magnetic suspension. The zero-power control is achieved by converging the control current to zero in the steady states where the bias force generated by a permanent magnet is balanced with the gravitational force. Therefore, the steady-states power consumption becomes virtually zero in this suspension system. However, peripheral devices including sensors and controllers need power in both transient and steady states. Hence, the power consumed in the peripheral devices becomes dominant. In this work, dedicated power-saving peripheral devices are fabricated. It is observed that the average power consumed by the electromagnet is 20[mW] for suspending a 90-gram mass, and the power consumed by the peripheral devices is 13[mW]. In contrast, a conventional system consumes a few watts to suspend a floator of the same dimensions. The solar cells used in the apparatus has a maximum power capacity of 2[W] under a typical summer sunlight (approximately 120[klx]). The fabricated system can achieve stable suspension even under a illuminance of a fluorescent lamp of 5[klx].

Key words: Magnetic Levitation, Magnetic Bearing, Electromagnetic Actuator, Solar Energy, Energy Saving

1. Introduction
Solar power generation systems need no mechanical motion, conventional fuel consumption and operating cost. These systems are widely used in houses recently because it is a countermeasure against global warming. Consequently, solar cells are becoming a popular and cost-saving green power generation source year by year[1]. Solar power systems are suitable for small outdoor standalone apparatus where electric power transmission infrastructure is not available. However, the power generated by a solar cell is sensitive to solar conditions because the generated solar power fluctuates due to illuminance. Hence, standalone systems powered by solar energy need buffered capacitors or batteries to operate even in low-illuminance environments including night and cloudy weathers while they are
charged during daylight. Such buffered techniques regarding energy storage have been also progressive and lower in cost recently.

Magnetic suspension systems are widely used in non-contact and friction-free suspension\(^{(2)}\). Magnetic suspension has various fields of applications such as ultra high rotational speed bearings\(^{(3)}\), rapid-transit vehicle\(^{(4)}\), guide for high-speed elevator\(^{(5)}\), carrier systems in clean room\(^{(6)}\), rotating gyroscopic sensors\(^{(7)}\), space instruments\(^{(8)}\) and blood pumps\(^{(9)}\). To control them, various control methods are proposed and applied. Among them, the zero-power control has been used in suspension system with hybrid magnets\(^{(10,11)}\). The zero-power control achieves the steady states in which the attractive force produced by the permanent magnets balances the weight of the suspended object (floator) and the control current converges to zero. Because there is no steady energy consumption at stable levitation, this method is used in energy saving devices.

In this study, solar power generate techniques are combined with an one-degree-of-freedom magnetic suspension system. An extra low-power magnetic suspension system is actualized by developing power-saving peripheral devices. The fabricated suspension system is powered by solar energy solely. The dimensions of the solar cells used in the fabricated system are selected based on the maximum power consumption necessary for stable suspension. Significantly dedicated low-power peripheral devices are developed. The average power consumption of the fabricated magnetic suspension system is 33[mW] in stable suspension. This power consumption is almost equal to that of a super luminosity LED of red-to-green wavelength. When commercial peripheral devices were used, the suspension system consumed 500[mW]. A conventional magnetic suspension system of the same dimensions supplied by a commercial power source consumes more than a few watts. In contrast, the fabricated system can achieve stable suspension even under a 5[klx]-illuminance of a fluorescent lamp.

The fabricated system is expected to be applied to a magnetic suspension carrier. The magnetic suspension carrier system can be categorized into two types: guide rail with coils and magnetic coils on board car. The type of guide rail with coils does not need supply to the car for suspension. However, this system needs a lot of magnetic coils along the rail. On the other hand, the type of magnetic coils on board needs a power supply to the carrier. There are two method of supplying power to the carrier. One is through contacts or wires and the other is a battery in the carrier. However, the non-contact characteristics are lost in the former, and stations for charging the battery are necessary in the latter. The solar magnetic suspension applied to the magnetic suspension carrier systems can achieve continuous levitation without any external power supply.

![Fig. 1 Outline of Solar Magnetic Suspension System.](image-url)
2. Solar magnetic suspension system

Figure 1 shows the outline of the fabricated solar magnetic suspension system including solar power generation. In this figure, solid and dashed lines represent signal and power supply, respectively. A conventional magnetic suspension system consist of a floator, a permanent magnet, an electromagnet, a displacement sensor, a power amplifier and a controller. The fabricated solar magnetic suspension system includes solar cells, a power storage device and a voltage stabilizing circuit for the peripheral devices in addition to the components of conventional magnetic suspension system. The electric power generated by solar cells supplies current to the electromagnet and the peripheral devices of the fabricated system via buffered capacitors. The buffered capacitors are used for reducing the power fluctuation caused by the variation of illuminance and instantaneous power consumption just after a disturbance acts in the floator. When large capacitors are used for the fabricated system, the system can suspend the floator for a long time. However, the leak current in the capacitors increases as the capacitance becomes larger. It indicates that the capacitance of
capacitor is must be chosen appropriately. If an excessively large capacitance were used, the power lost by the leak current, would be larger than the supplied power under in a low illuminance environment.

Figure 2 shows a photograph of the experimental apparatus. The height of the apparatus is 310[mm], and the diameter of the central part is 88[mm]. The central part has two arms and each arm carries four solar cells. In this apparatus, the single-degree-of-freedom vertical translational motion of the floator was actively controlled while the other motions are passively stabilized by the edge effects of the magnets used in the system.

Figure 3 shows a photograph of the floator. The floator is made of soft iron. It is a hollow sphere having an outer diameter of 43[mm] that is almost same in size as a golf ball. A disk-shaped permanent magnet is attached to the top of the floator that is made of ferrite material with a dimension of Φ15[mm] ×4[mm]. The force of attractive permanent magnet balances the gravitational force in the steady states. The electromagnet used in the fabricated apparatus has a solid core with the smallest cross section area of 180 [mm$^2$] that is made of soft iron. This electromagnet has 1200-turn coil. It is 0.3[mm] in diameter and made of copper enameled with polyvinyl. The direct-current resistance of the coil is 12[Ω].

Figure 4 shows the circuit diagram of a solar power generator. A solar array, consisting of four solar cells, is attached with each arm and the solar cells of each array are connected in parallel through a reverse blocking diode. The pair of solar array are connected in series. The circuit of solar generator shown by Fig.4 has three terminals at the top, center and ground with respect to the cells connection. The suspension power is supplied from the top terminal. The center terminal supplies the half of the top terminal voltage to the peripheral devices such as of a displacement sensor, a controller and a voltage stabilizing circuit. The solar cell used in the experimental apparatus is an amorphous silicon type. The shape of the solar cell is rectangular with an area of 75×55[mm$^2$] and a thickness of 2.3[mm]. Table 1 shows the typical ratings of the solar cell for the fabricated apparatus. These ratings were measured under a solar simulator of 50[klx] that is a preposition nominal condition\(^{(12)}\). In the experiments, the solar-cell power generation is recorded to be almost 2[W] under 100 to 120[klx] in direct summer sunlight. Moreover, magnetic suspension under a low illumination environment is achieved as well. The power generated under a low illuminance environment is:

\[
\text{Solar panel} \rightarrow \text{Displacement sensor} \rightarrow \text{Controller} \rightarrow \text{Voltage stabilizer} \rightarrow \text{Power distribution}
\]

Table 1 Nominal ratings of solar cell\(^{(12)}\).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Ratings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Typical open circuit voltage</td>
<td>7.7[V]</td>
</tr>
<tr>
<td>Typical short circuit current</td>
<td>22.3[mA]</td>
</tr>
<tr>
<td>Reference maximum power</td>
<td>114[mW]</td>
</tr>
</tbody>
</table>
will be discussed in the next chapter.

Figure 5 shows a photograph of the circuits of the peripheral devices that is placed in the cylindrical part of the apparatus at the top. The peripheral devices consists of a storage circuit, a displacement sensor, a controller, a stabilizing power supply and a power amplifier.

A power storage device is needed by to a standalone active systems using solely solar energy. The fabricated system uses electric-double-layer-capacitors for power storage. The energy density of typical electric-double-layer capacitors is hundreds to thousands times greater than that of a conventional electrolytic capacitor of the same dimensions. The storage circuit of the fabricated system has six series-connected capacitors with

![Figure 5 Photograph of the circuit of peripheral devices.](image1)

![Figure 6 Block diagram of the displacement sensor unit.](image2)

![Figure 7 Static characteristics of the displacement sensor.](image3)
parallel-connected balanced registers individually\(^{(13)}\). The leak currents are different among the capacitors. The voltage of series-connected capacitors varies individually according to the leak current.

Figure 6 shows the diagram of an inductive-type displacement sensor that is fabricated for power saving and built in the apparatus. A typical commercially available eddy-current displacement sensor consists of an oscillating circuit, a resonator, a rectifier, a smoothing circuit, a linearizer and a stabilized power supply. Even a power-saving type sensor consumes 200 to 300[mW] during operation\(^{(14)}\). In contrast, the fabricated displacement sensor only uses two bi-polar transistors in the oscillator and the resonator. Therefore fabricated sensor saves power consumption whereas the linearity is not good because the other circuits were removed. A stabilizing power supply for the sensor is shared with the PIC. It includes a current regulative diode and a shunt regulator. Figure 7 shows the static characteristics of the fabricated displacement sensor. A rather strong non-linear characteristics is observed. However, in the zero power control system, the floator is kept at the position where the gravity is balanced by the attractive force force of the permanent magnet. It indicates that the levitation gap is constant even if the displacement sensor fluctuates.

Figure 8 shows the fabricated pulse-width-moderation (PWM) amplifier with a peripheral interface controller (PIC) used as a controller. PICs are popular to industrial developers, hobby users and students because of low cost, low power, and wider availability. The PIC controller used in this apparatus has a single-channel A/D converter and five-channel digital I/Os. It is used to implement the zero-power control. The zero-power control is realized by feeding back the integral control voltage. The control signal is transmitted to a power amplifier through a PWM controller with a control period of 1[ms]. The PWM carrier frequency is equal to the control period. The amplifier is a voltage-controlled H-bridge that is constructed from two N-ch FETs, two P-ch FETs and two pre-high-side-driver FET (HSD in the figure) for the P-ch FETs. Figure 9 shows a

![Fig. 8 Block diagram of the controller and amplifier.](image)

![Fig. 9 Relation between the control input and the switching signals of FETs.](image)
conceptual diagram of the operation of the FETs considering the control input value. This amplifier has three modes to be switched according to the control value. When the control value is positive, $Q_{AH}$ and $Q_{AL}$ are in PWM operation and $Q_{BH}$ and $Q_{BL}$ are kept turned off, and vice versa. When the control value is zero, all the transistors are turned off.

3. Experimental result

3.1 Power consumption

The power consumption in the experimental apparatus was measured. In this experiment, two constant-voltage power supplies are substituted for the solar cells; a 12-volt one for suspension power and a 6-volt one for peripheral devices. The current is measured through a sensing resistor inserted into the circuit.

Figure 10 (a) and (b) show the displacement of the floator and the power consumption at the beginning of suspension. In these figures, the control for suspension started at a time of 0[s]. The power is consumed only by the peripheral devises before the control started. The total power consumption of the peripheral devices was 12.6[mW] in this state. The detailed consumption were 2.1[mW] in the PIC, 4.2[mW] in the displacement sensor and 6.3[mW] in the stabilizing power supply. The quiescent power of H-bridge amplifier was below 2[uW]. It is caused by the leak current of FETs (approximately 0.1[uA]). At the beginning of suspension, the maximum power consumption was 900[mW]. It was mainly consumed by the electromagnet to suspend the floator in the transient states. The vertical axis of the Fig. 10(a) is the displacement form the base. In the steady states, the floating position was 2[mm] form the base.

![Displacement of the floator.](image)

![Consumed power for suspension.](image)

Fig. 10 Transient characteristics when the suspension start at $t=0$s.
Figure 11 shows the consumed power of the apparatus in the steady-state suspension. The average total power consumption is approximately 33[mW]. The power consumption of the electromagnet is calculated by subtracting the power consumed by the peripheral devices and the operating amplifier from the total. The power consumption of the electromagnet for the static magnetic suspension is approximately 20[mW]. In addition, the apparatus of the standalone operation has a power loss of 10[mW] due to the leak currents of capacitors. The typical value is 0.5[mA/F]. Therefore, this system uses approximately 45[mW] to achieve suspension in the steady states.

In this system, the voltage of the solar generator changes due to solar conditions or a charging rate. Figure 12 shows the average power consumption for various values of the supply voltage in the steady states. In this figure, a white bar, a dark gray bar and the height of a bar represent the power consumption for suspension, the power of peripheral device and the total power, respectively. The power consumption in the peripheral devices is almost 40% of the total power consumption.

3.2 Generated power of single solar cell

Figure 13 shows the characteristics of the generated voltage with respect to the power and current produced by a single solar cell under a low illuminance. The single solar cell is connected to the load resistance that is varied from 1 to 20[kΩ]. The low illuminance is
realized by a fluorescent lamp of 5[klx] and the distance between the lamp and the solar cell was kept 500[mm]. The single solar cell has an output power of 5.7[mW] with the maximum efficiency under an illuminance of 5[klx]. It indicates that the solar cells of the fabricated system can generate 45[mW] under an illuminance of 5[klx].

3.3 Solar magnetic suspension under low illuminance

In the previous section, it was shown that the total power consumption of the system is smaller than the power generated by the solar cells even under a low illuminance of 5[klx]. Then stable suspension was tried by the standalone system under a low illuminance of 5[klx]. Figure 14 shows a time history of the charged suspension voltage at the top terminal (see Fig. 4). The initial value of the capacitors was zero (discharged). The charged voltage is risen by the power supplied from the solar generator during -205 to 0[min]. The charged voltage approaches to 12[V] at the time of 0[min] just before the suspension starts. The charged voltage decreased to 10.3[V] after 60[min]. The supply and demand power were balanced in this state.

3.4 Magnetic suspension supplied by charged power of capacitance

Figure 15 shows the time required for charging the capacitor fully in the standalone operation. The capacitors were charged under direct summer sun light. The charged voltage was risen up to 13.4[V] at 0[min]. Then the system started suspension and the power supply
for the solar generator stopped. The system continued the suspension for 40[min] supply for the charged voltage to 8.5[V].

4. Conclusions

A solar photovoltaic magnetic suspension system was fabricated. Dedicated power-saving peripheral devices were newly fabricated. The power consumption of the fabricated system was measured. The total power consumption was approximately 33[mW] in the steady-state suspension. The system achieved stable suspension even under the illuminance of a fluorescent lamp (5[klx]).

We plan to apply solar magnetic suspension to magnetic suspension carrier system without external power supply a wind-generated power generating system with magnetic bearing in future.

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