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Characteristics of a Magnetically Levitated Vehicle using a Small Number of Dry Cell Batteries

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Abstract – This paper describes magnetically levitated vehicle with hybrid magnets, which have been studied by the authors in place of streetcars or conveyance system. An experimental vehicle of 20kg was magnetically levitated by using a small number of dry-cell batteries, which consisted of 10 Ni-MH cells of 1900mAh in series. The magnets were activated sequentially, because the internal resistance of the batteries suppressed the maximum current. The vehicle was kept levitating for about 2 hours and was stable against disturbance due to instantaneous external force. In this paper, dynamic characteristics of the magnetically levitated vehicle using a small number of dry cell batteries are presented.

Keywords: Magnetically Levitated Vehicle, dry-cell batteries, non-contact, energy saving, Noiseless and Dustless.

1. Introduction

It should be possible to lower vibration and acoustic noise in towns by applying magnetically levitated vehicles to streetcars, subways or conveyance system. In addition, the maintenance cost would be re-strained because it is a contact free system. An experimental magnetically levitated truck was constructed that was equipped with hybrid magnets. Each magnet was mounted to the truck with a bearing; therefore the magnet was able to rotate along the magnetic rail. Then the truck was able to travel along a curved rail of a short radius [1]-[3].

The energy consumption accompanying magnetic levitation was restrained using divided iron type hybrid magnets and DC output control circuits. The magnetic flux of PM generates the attracting force in large part and the currents in the coils are used for levitation control.

It is advantageous to use a small number of batteries from an economical viewpoint because batteries are expensive and their lives are short. Batteries only store small amounts of energy and therefore it is important to design a levitation system that has low energy consumption [4]. Using a small number of batteries, the experimental truck was levitated and, furthermore, the levitation stability of the truck was studied. This paper describes dynamic characteristics of the magnetically levitated vehicle using a small number of dry cell batteries.

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2. Experimental Apparatus

2.1 Hybrid Magnet

The configuration of a hybrid magnet is shown in Fig.1. The hybrid magnet mounted iron cores in two rows, the clearance between the divided magnetic rails was greater than the clearance between the divided iron cores by 10 mm in order to dampen the lateral movement of the truck [1],[5]. Each divided iron core was equipped with a coil that was excited by a DC output drive circuit. One of the coils gave rise to the magnetic flux generated with the permanent magnet (PM) by increasing the electrical current in the coil, accordingly the magnet was able to levitate from

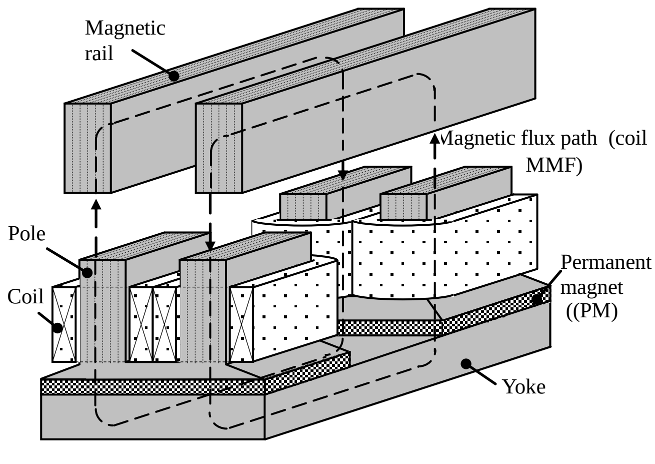

Fig.1. Hybrid magnet with divided iron cores.

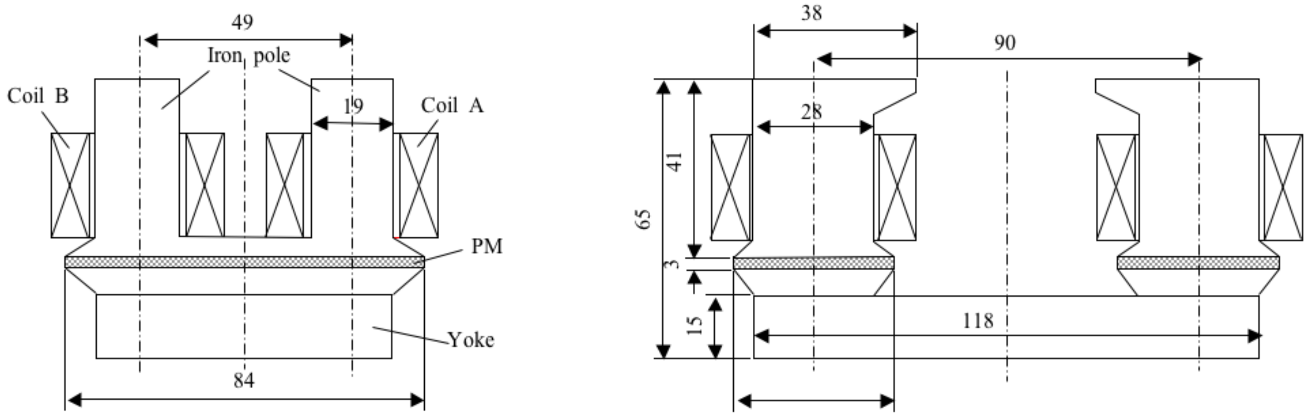

Fig.2. Outline of divided iron type hybrid magnet used for experiment.

Table 1. Dimensions and Coefficients of the Equipment

Items	units	value
Residual magnetic flux density of PM	T	1.384
Number of turns per pole		160
Resistance of a single side Coil *R*	Ω	1.2
Resistance of shunt *r*	Ω	0.1
Inductance of single side Coil *L*	H	0.012
Number of poles		2
Mass of levitated part *M*	kg	20
Amplitude of triangle voltage E_Δ	V	5
Voltage drop of IGBT E_{ce}	V	2
Voltage drop of diode E_d	V	2
Source voltage V_s	V	12
Feedback coefficient K_z	V/m	21000
Feedback coefficient K_v	V s/m	900
Battery (Ni-MH) EMF	V	1.2
Resistance of a battery	Ω	0.05
Capacity of a capacitor	mF	33
Resolution of a gap sensor	mm	1
[illegible]	mm/ V	[illegible]

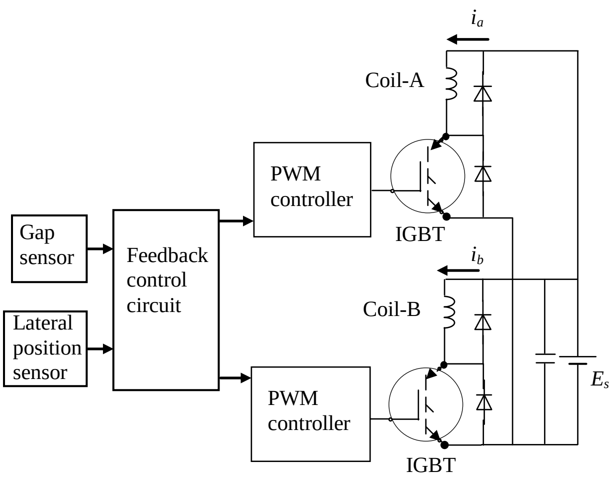

Fig.3. Schematic circuit diagram for levitation.

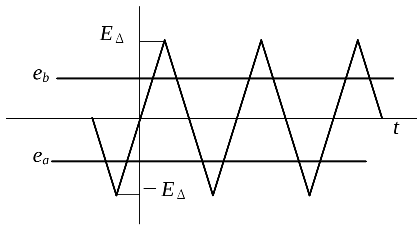

Fig.4. Comparison of signal to delta wave for PWM

touchdown. The other coil decreased the magnetic flux generated with the PM by increasing the coil current, then, the magnet was able to levitate from the contact position with the magnetic rails.

The experimental magnet for the truck is shown in Fig.2 and Table 1 shows the dimensions of the system. The coils are named Coil A and Coil B.

2.2 Levitation Control Circuit

A levitation control drive circuit of PWM type was used in the experiment. A DC output drive circuit is simple in comparison with an AC output drive circuit because only one IGBT is used in the DC output circuit, but an AC output drive circuit needs 4 IGBT's. DC output drive circuits were able to flow single polarity current only. Then two DC output drive circuits were used, and were connected to Coil A and Coil B separately.

Figure 3 shows the concept of the levitation control. The input signal of the comparator for Coil A circuit is shown in (1).

$$e_a = - E_a + K_z z + K_v \frac{dz}{dt} \quad (1)$$

Where E_b shows the bias voltage, z is the small displacement of the gap length between the magnet surface and the magnetic rail, K_z is the feedback coefficient of the gap length, K_v shows the time differential of the gap length. The large bias current yields large exciting loss in the coil circuit, then the bias current is set at about 0.5A. The input signal of the comparator for Coil B circuit is configured in the following expression.

$$e_b = 2E_b + e_a \tag{2}$$

2.3 Coil Current and Comparator Input Signal

The relation between the comparator signals and the triangular waveform is shown in Fig.4. The output of the comparator is as follows:

If $e_a > e_{\triangle}$ is correct, the IGBT for Coil A turns on electricity, and if $e_b < e_{\triangle}$ is correct, the IGBT for Coil B turns on electricity.

Dimensions of the experimental equipment are shown in Table 1.

3. Results of Experiments

3.1 Start-up of Levitation

The air gap fluctuation observed in running test of HSST-03 was below 2 mm [6]. The gap length in the levitated state of this equipment was about 12 mm in the case that the current of Coil A was equal to that of Coil B. Then the gap length in the contact state was set at 10 mm. Under this condition, the magnetic flux of PM only generated attracting force, and the total excitation loss was at the minimum value.

At the beginning of the experiments, one magnet only was activated from a gap length of 10 mm. where the set of batteries were connected 10 batteries in series.

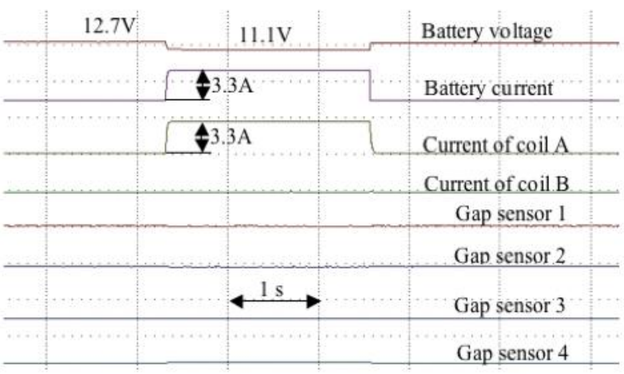

Fig.5 Variations at start up levitation.
(Battery only used. Initial gap length was 10mm)

Figure 5 shows the temporal response characteristic in the start-up using the batteries. The battery current, the coil cur-rent of No.4 magnet, the battery voltage, and the gap length are shown in this figure. In this case, the battery current was 3.6 A, but the magnet did not levitate.

The internal resistance of the set of batteries including the lead wire was 0.62 Ω, because the voltage drop of the battery was 2.23V while the battery current flowed.

The parallel capacitors of 33 mF were connected with the battery shown in Fig.7 and then the levitation control circuits were activated. The magnet levitated, where a maximum coil current of 3.8 A flowed, but the peak value of the battery cur-rent was only 3.3 A. The current from the

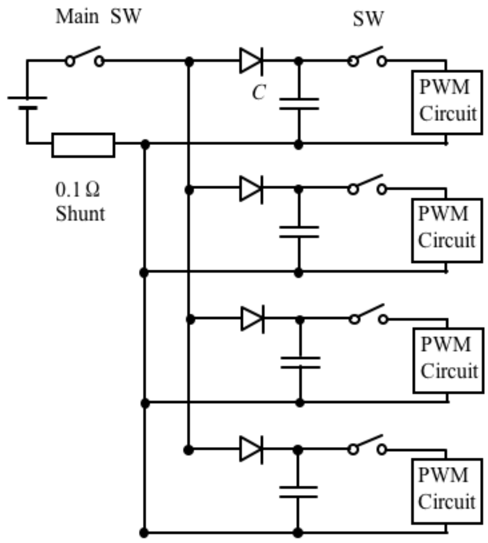

Fig.6. Circuit of battery power source

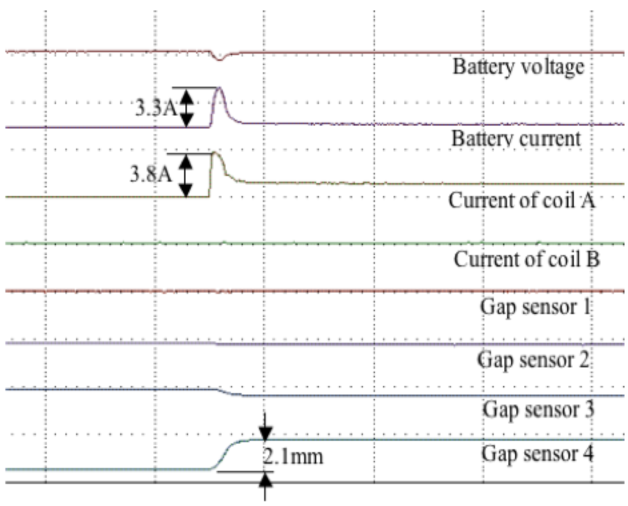

Fig.7. Variations at start up of levitation
(Capacitor was used. Initial gap length was 10mm)

capacitor covered the lack of the battery current.

To know the current needed for levitation, the magnet pole face was contacted with the magnetic rail and then the magnet was activated using a DC power source, where the gap length between the magnet and magnetic rail was selected as the parameter. The measured result is shown in Fig.8, where abscissa axis is the gap length and the vertical axis is the current. The smaller the contact gap length was, the larger current was needed for

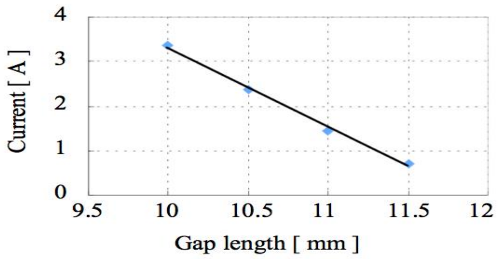

Fig.8. Relation between gap length and levitation

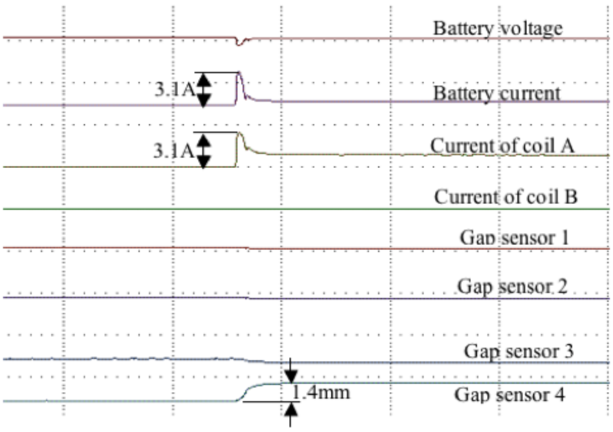

Fig.9. Variations at start up of levitation (Battery only used. Initial gap length was 10.5mm)

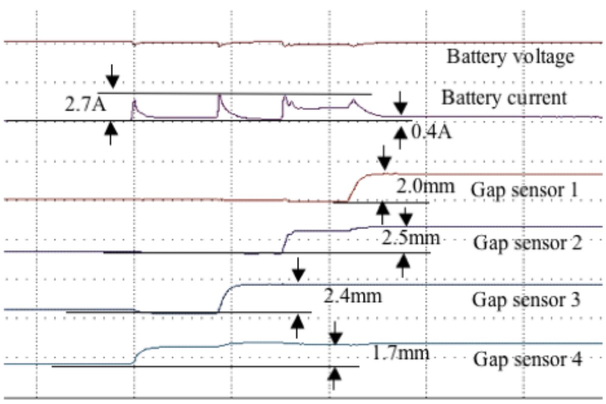

Fig.10. Variations at start up levitation (Capacitor was used. Initial gap length was 10.5mm)

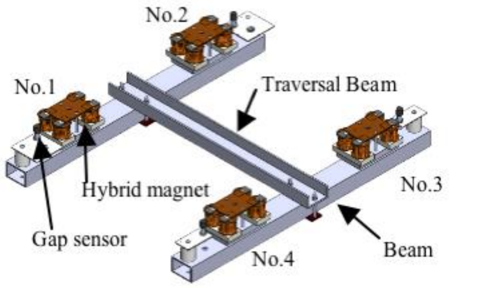

Fig.11. Structure of a Levitation part (Without magnetic rails)

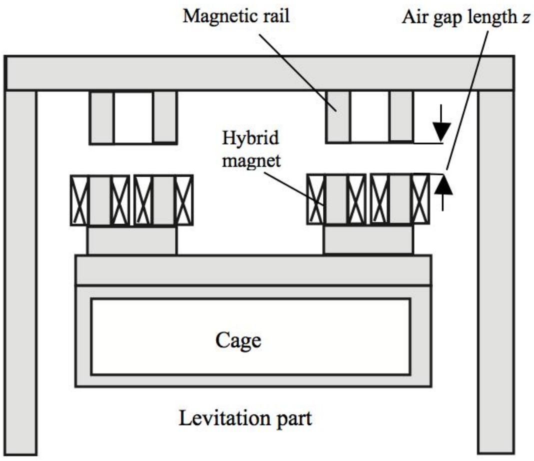

Fig.12. Outline of Equipment (Front view)

levitation in this figure. In the case that the gap length was 10 mm, a coil current of 3.4 A was required. Then the gap length of 10.5 mm was selected and the magnet was levitated using the batteries only, where the peak value of the battery current was 3.1 A as shown in Fig.9.

The battery current was 7.5A in the case that all of the magnets were locked and activated using the battery only simultaneously. The result indicated that it was impossible to levitate the truck simultaneously in the case of battery only.

At the beginning, all the magnets were contacted with the magnetic rail, and then the magnets were activated sequentially.

The gap length of No.4 magnet only was set at 10.5 mm, the gap lengths of the other magnets were 10mm. The experimental results are shown in Fig.10. The maximum battery current was 2.7 A, and after the truck was levitated, the battery current was 0.4 A. The gaps were different from each other. The main reason would be accidental error in fabrication and the twisting moment of the transversal beam that connected the two beams.

The gap length of No.4 magnet only was set at 10.5 mm, the gap lengths of the other magnets were 10 mm. The structure of a levitation part is shown in. Fig.11.

Figure 12 shows the outline of the equipment with magnetic rails. Positional relationship between the magnetic rails and the hybrid magnets is shown in Fig12. The magnetically levitated part can travel under the iron rails.

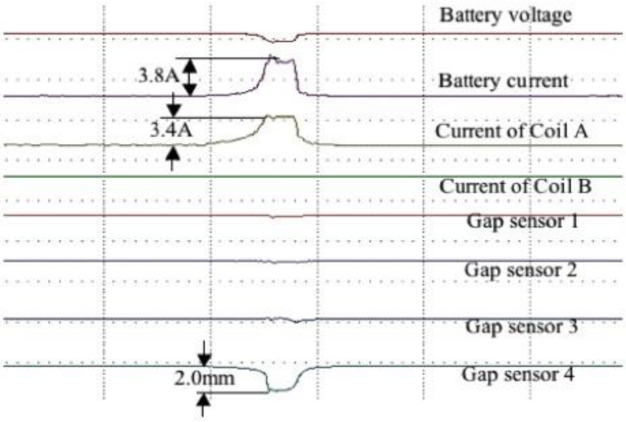

Fig.13. Variations after No.4 magnet was lifted up for a short time. (Battery only used.)

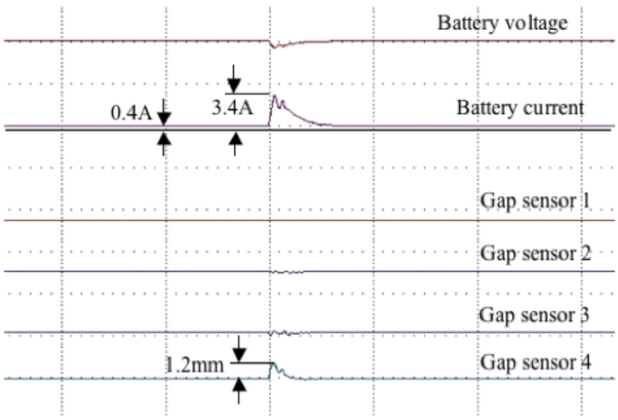

Fig.14. Variations after a mass was dropped near No.4 magnet (Capacitors were used.)

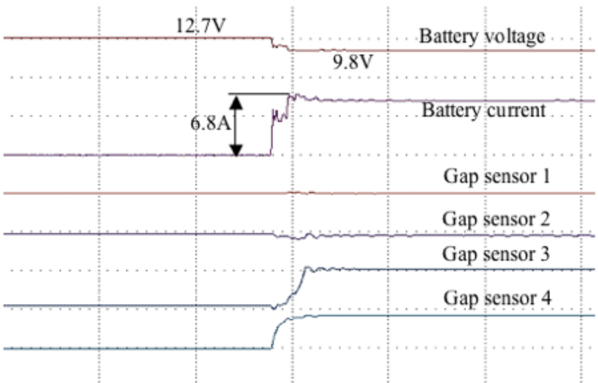

Fig.15. Variations after a mass was dropped near No.4 magnet (Capacitors were used.)

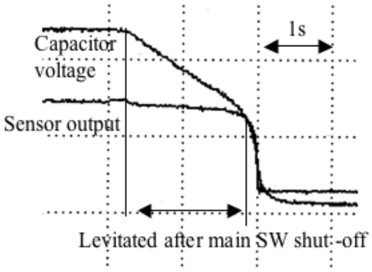

Fig.16. Transient characteristics of levitation After main SW shut-off

3.2 Stability of Levitation

After the truck was levitated, No.4 magnet was lifted by hand instantly to investigate the stability of levitation. The result is shown in Fig.13, where the gap length of No.4 magnet only changed in about 0.5 s and then the truck levitated automatically. The maximum battery current was 3.8 A. As the battery current needed to maintain the levitation was about 0.1 A per a coil, even in re-starting of No.4 magnet, the volt-age drop of the battery was small, then the other magnets maintain the levitation.

A mass of 174 g was dropped down near the No.4 magnet. The measured results are shown in Fig.14 and 15. In the case that parallel capacitors were connected with the battery, as shown in Fig.14, the truck was maintained in the levitated state, while the maximum battery current of 3.4 A flowed and only the gap length of No.4 magnet changed about 1.2 mm.

In the case that the truck was levitated using batteries only, as shown in Fig.15, the coil current flowed more than 6.8 A, nevertheless, the truck was not maintained in the levitated state after the mass was dropped. The gaps of No.3 and No.4 magnets were changed and the battery voltage dropped to 9.8V at the instance the mass hit the magnet.

4. Examinations

4.1 Levitation Time Using Capacitor

In the case that a parallel capacitor was connected with a set of batteries, the magnet was able to levitate using a small number of batteries, because the current from the capacitor compensated for the lack of the battery current. Also the capacitor improved the levitation stability against disturbance. Furthermore the levitation period of time was measured in the case that the voltage of the power source decreased to 0V.

Figure 16 shows the variation of the capacitor voltage and the gap sensor output after power switch off. The capacitor voltage decreased, after about 1.7 s, the capacitor voltage reached 7V, and then the gap sensor output dropped sharply. As the source current was about 0.1 A when the magnet was levitated, the stored energy in the capacitor was able to supply sufficient current to maintain the levitation of the magnet.

In the case that the battery has large internal resistance, the voltage drop in the battery is large. But by connecting an appropriate capacitor to the battery, the truck will be able to levitate and to maintain the levitation of the truck.

4.2 Levitation Time Using Capacitor

It is advantageous to use a small number of batteries for levitation because of the battery and maintenance costs.

The maximum battery current was calculated, changing the number of batteries in serially connection for this truck as shown in Table 2. The battery current of 4 A flows in the case of 10 batteries connected in series, while in the case of 8 batteries connected in series, the maximum current is estimated to be 2.9A. In the case that the truck takes off from the gap length of 10 mm to levitation, the minimum current is over 3.5 A. In this case, 10 batteries are required for levitation of the experimental truck.

Table 2. The Relation between Serial Number of Batteries and Maximum Battery Current (calculated)

Number of batteries	12	10	8
Voltage of batteries [V]	14.4	12	9.6
Battery current [A]	4.91	3.96	2.92

4.3 Comparison and Selection of Battery

Figure 17 shows an experimental result on internal resistance of batteries.

The authors chose Ni-MH AA size batteries to excite the coils and control the circuits. Because the Ni-MH AA size battery has low internal resistance than the alkaline battery as shown in Fig.17, it can flow a large current. A low internal resistance of battery is suitable for this system, since large current is required momentarily to levitate at the start up. The Ni-MH AA size battery also has the following merits: (1) easy to get, (2) reusable and (3) low cost.

5. Conclusions

An experimental truck of 20 kg was levitated using 10 nickel metal-hydride (Ni-MH) batteries in series by activating the magnets sequentially.

By connecting parallel capacitors with the batteries, the truck was able to levitate using a small number of batteries because the current from the capacitor compensated for the lack of the battery current needed at start-up. Also the capacitor improved the levitation stability against disturbance. The levitation part was kept levitating for about 2 hours and was stable against disturbance due to instantaneous external force. We found that the Ni-MH battery having a small internal resistance is suitable for this system. In the future, we will improve this experimental equipment and will conduct a driving experiment and a loading experiment.

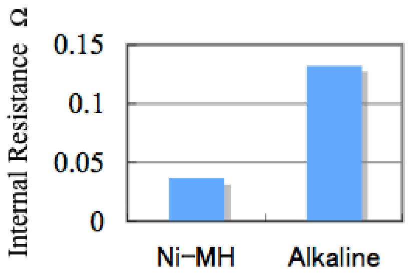

Fig. 17. Comparison of batteries
(Experimental result at load resistance 5 Ohm)

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