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Robust Zero Power Levitation Control of Quadruple Hybrid EMS System

Su-Yeon Cho*, Won-Ho Kim, Ik-Sang Jang***, Dong-Woo Kang† and Ju Lee***

Abstract – This paper presents the improved zero power levitation control algorithm for a quadruple hybrid EMS (Electromagnetic Suspension) system. Quadruple hybrid EMS system is a united form of four hybrid EMS systems one on each corner coupled with a metal plate. Technical issue in controlling a quadruple hybrid EMS system is the permanent magnet's equilibrium point deviation caused by design tolerance which eventually leads to a limited zero power levitation control that only satisfies the zero power levitation in one or two hybrid EMS system among the four hybrid EMS system. In order to satisfy a complete zero power levitation control of the quadruple hybrid EMS system, the proposed method presented in this paper adds a compensating algorithm which adjusts the gap reference of each individual axe. Later, this paper proves the stability and effectiveness of the proposed control algorithm via experiment and disturbance test.

Keywords: Magnetic levitation, Maglev, Hybrid EMS, Zero power, Control

1. Introduction

Suspending a system using the electromagnetic force has been the key technology in industries such as high speed transportation industries and semiconductor industries where they use wafer conveyor systems engineered with electromagnetic suspension systems. The main benefit of using the electromagnetic suspension system is that it is clean and energy saving. Its clean property is exploited in the wafer conveyor system in semiconductor manufacture line floating around the ceiling creating neither dust nor particles created from mechanical friction. Moreover, its frictionless property makes the high speed transportation easier to reach its desired speed [1]. However, the electromagnetic suspension system is limited in energy due to its limited power source. Usually the wafer conveyor system is loaded with a battery to sustain the suspension. Since a battery is not attached to a grid or other source of power, it is also called an individual power source. Throughout the history, engineers have endeavored to solve the issue and they ended up creating the hybrid EMS system. Hybrid EMS system is an evolved type of electromagnetic suspension which permanent magnet is additionally inserted in. Its unique property allows the system to maintain levitation without electrical power consumption. Although the hybrid EMS system consumes power in reality, its minute power consumption significantly extends battery duration.

Numerous research and investigations upon the zero power levitation control of hybrid EMS system had been conducted by engineers from around the world. The common ground found from these researches was that all of them had been conducted with a single hybrid EMS system [2-8].

This paper presents the zero power levitation of a quadruple hybrid EMS system, a system which has four hybrid EMS systems interconnected with one another. The major issue of this system is that it cannot reach zero power levitation with the conventional control algorithm [3, 7]. No matter how precisely the system is manufactured there is always design tolerance which deviates the position of the hybrid EMS, and as a result cause the limited zero power levitation control. This paper presents a new control algorithm which has modified control routine added with a gap reference compensator. Later, the paper proves its significance via experiment.

2. Hybrid EMS System

2.1 Basic specifications of hybrid EMS system

Zero power levitation is a control method which does not consume electric power to maintain levitation. This is realized by using a hybrid EMS system which is a combined form of an electromagnet and a permanent magnet as shown in Fig. 1. While the hybrid EMS system uses permanent magnet's attraction force as main levitation force, the electromagnets on each side consume a minimal amount of electric power to maintain the permanent magnet's equilibrium point.

† Corresponding Author : R&D Team, Digital Appliances, Samsung Electronics Co., Korea. (dwkang1222@gmail.com)
* Dept. of Electrical Engineering, Hanyang University, Korea. (julee @hanyang.ac.kr)
** Material & Device Research Center, Samsung Advanced Institute of Technology, Samsung Electronics Co., Korea. (wonho79@nate.com)
*** Mechatronics Group, Defence Program R&D Center, Samsung Techwin Co., Korea. (coldest81@gmail.com)
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Fig. 1. Picture of the hybrid EMS system

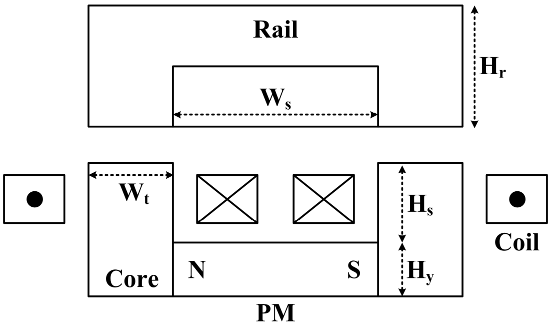

Fig. 2. Dimension of the hybrid EMS system

Table 1. Hybrid EMS system specifications

Core	Slot height(H_s)	33mm
	Teeth widths(W_t)	10mm
	Length(W_s)	40mm
	Stack length(L_{stack})	50mm
	Height(H_y)	14mm
Permanent Magnet (NdFeB)	Levitation force @rated gap(4.4mm)	120N
	Redisual flux density(B_r)	1.27T
Coil	Number of windings	660Turns
	Current density	4A/mm^2

Fig. 2 shows the dimension of the hybrid EMS system. The hybrid EMS system specifications had been determined based on the electromagnetic analysis results [9]. Table 1 shows specifications of the single hybrid EMS system. Nd-Fe-B permanent magnet, which is one of the rare earth materials, had been chosen as the permanent magnet to generate sufficient levitation particularly to generate force of 120N at 4.4mm gap distance.

2.2 Electromagnetic analysis result

The Hybrid EMS system had been gone under electromagnetic analysis to verify the system's dynamic characteristics and electromagnetic properties.

Fig. 3 illustrates the curve which shows the levitation force corresponding to the input current at different gap distances. The levitation force decreases exponentially as the gap increases and increases exponentially as current increases. Since the quadruple hybrid EMS system, which has four hybrid EMS systems, weighs approximately 40kg which is roughly 400N, the single hybrid EMS system

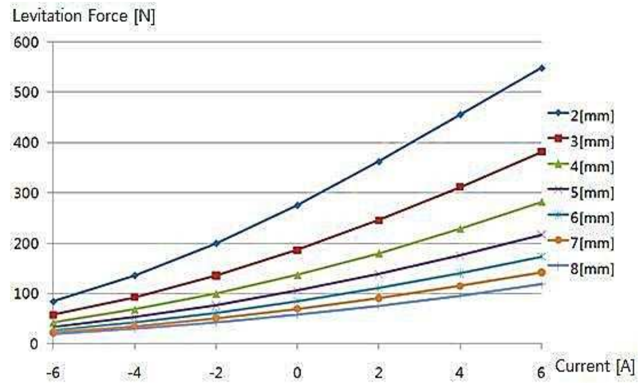

Fig. 3. Levitation force variation of hybrid EMS module corresponding to current and gap length

should at least generate 100N. Fig. 3 shows that the levitation force reaches approximately 120N with zero current at 4.4mm. This is where the zero power levitation is satisfied.

2.3 Quadruple hybrid EMS system

Fig. 4 is the picture of the quadruple hybrid EMS system set which had been built for experiment. There are four hybrid EMS systems on the bottom for levitation and four EMS systems (no permanent magnets used) on each side for guidance. Four EMS systems on each corner were not used in this experiment since it was designed to support the mover when moving through the curved rail.

The quadruple hybrid EMS system's specifications are shown in Table 2. The dimension of the quadruple hybrid EMS system is quite large that the design tolerance must be significant. Note that the design tolerance is the major cause of the limited zero power levitation.

Table 2. Dimension & weight of quadruple hybrid EMS system

Width	340mm
Depth	560mm
Height	165mm
Weight	40kg

Fig. 4. The picture of the quadruple hybrid EMS system which was actually used for experiment

3. Zero power levitation control

While there has been numerous researches from all around the world finding methods to satisfy zero power levitation control of a hybrid EMS system, zero power levitation control algorithm research dealing with four hybrid EMS systems all attached together is not common.

V : input voltage
i : input current
v : vertical velocity
z : gap distance
z_{ref} : gap reference
z^*_{ref} : gap reference compensation value
m : system's mass
g : gravitational acceleration
F_d : disturbance
R : wire resistance
L : wire inductance
K_{pi} : current P gain
K_{ii} : current I gain
K_{pv} : velocity P gain
K_{pz} : gap P gain
K_{rc} : reference compensation P gain
K_τ : torque coefficient
S : differentiator

3.1 Conventional control algorithm

Control algorithms used in most industrial applications are based on the PI control algorithm, because the PI control algorithm has easy and reliable property. The control algorithm used in the conventional zero power levitation control is also based on the PI control algorithm as shown in Fig. 5.

The conventional zero power levitation control is a state feed-back controller which basically uses the current information and the gap distance information. The velocity information is derived by differentiating the gap distance information. Sensed values are processed through the PI controller to generate the input voltage.

$$V(t) = K_{pz}\left(z(t) - z_{ref}\right) + K_{pv}v(t) + K_{pi}i(t) + \int K_{ii}i(t)dt \tag{1}$$

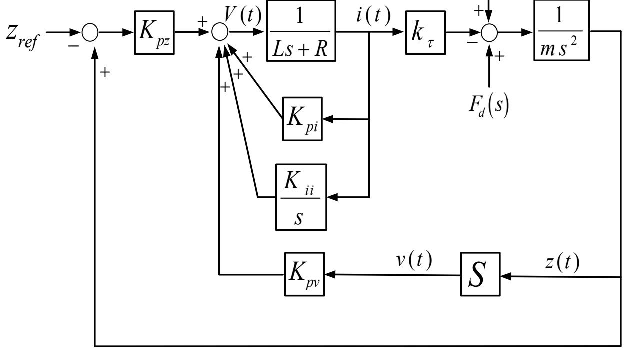

Fig. 5. Conventional zero power control algorithm based on the basic PI control

The conventional zero power levitation control algorithm shows a limited performance in quadruple hybrid EMS system due to its inevitable design tolerance. Design tolerance gives each hybrid EMS systems a different position where the zero power levitation is fulfilled. In other words, a certain hybrid EMS system goes to zero power only when a gap reference suitable for the specific hybrid EMS system is applied. When a gap reference is applied, except for some specific hybrid EMS system that is suitable for zero power levitation at the reference distance, others would not be able to reach zero power. Thus, under an identical gap reference input, not all four hybrid EMS systems could go zero power.

In order to fulfill a complete zero power levitation, each four hybrid EMS systems must respectively approach a different equilibrium point where the zero power levitation control is satisfied. Thus, controlling via identical gap reference makes it impossible for the quadruple hybrid EMS system to reach zero power levitation.

3.2 Proposed control algorithm

The proposed zero power control algorithm is an upgraded version of the conventional zero power control algorithm. As shown in Fig. 6, the proposed zero power control algorithm is composed of the regular PI controller and a newly added gap reference compensator. The newly added gap reference compensator generates an adjusting gap reference which eventually converges to the gap reference point where no input power is required to

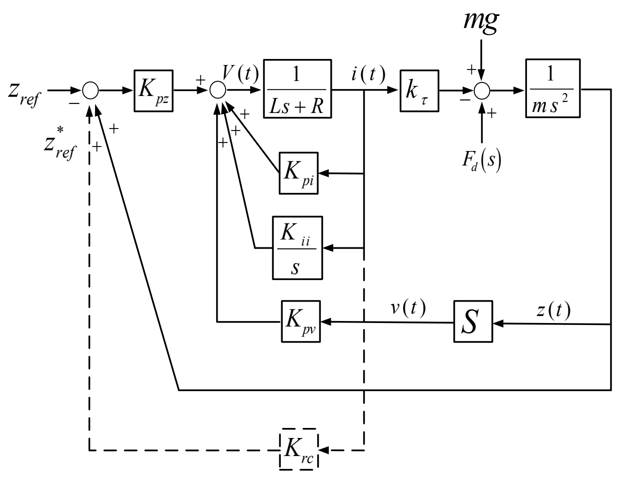

Fig. 6. Proposed zero power control algorithm which is a PI controller added with a gap reference compensation algorithm

maintain levitation.

$$V(t) = K_{pz}\left(z(t) - \left(z_{ref} - z_{ref}^{*}\right)\right) + K_{pv}v(t) + K_{pi}i(t) + \int K_{ii}i(t)dt \quad (2)$$

This simple but essential algorithm allows the quadruple hybrid EMS system to maintain a perfect zero power levitation control regardless of the design tolerance which creates a limited zero power levitation under conventional zero power levitation control algorithm. To be specific, the gap reference is changed according to the input current since the existence of the current value itself reflects the fact that the hybrid EMS has not yet reached the point where zero power levitation could be satisfied. It should be noted that this algorithm is aimed to realize a complete zero power levitation, not constant gap levitation which converges to the input gap reference. Its gap reference is adjusted based on the P control output of the current input.

4. Experimental results

The performance of the zero power levitation control of the quadruple hybrid EMS system has been verified through experiments. Experimental results compares the effectiveness of the conventional zero power levitation algorithm and the proposed zero power levitation algorithm. Later the stability of the system is proven by imposing additional mass to the system as a disturbance. Fig. 7 shows the experimental environment for the quadruple hybrid EMS system zero power levitation system.

4.1 Experimental result of the conventional zero power control algorithm

The first experiment was conducted with the conventional zero power levitation control algorithm which is composed of the state feed-back PI controllers. Fig. 8 shows the gap distance and three current values from three hybrid EMSs. The fourth hybrid EMS system's current

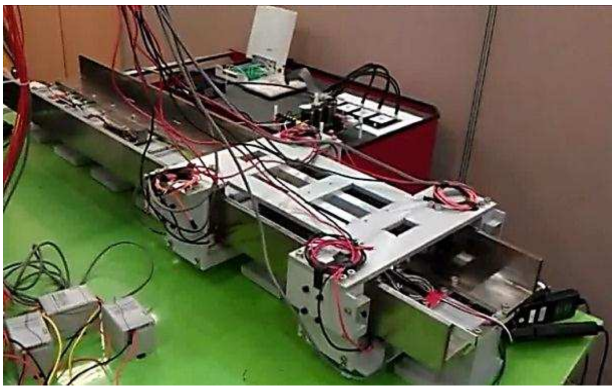

Fig. 7. picture of the experiment set

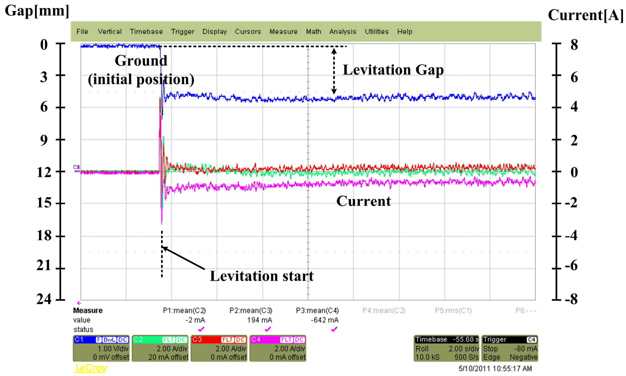

Fig. 8. Gap and current waveforms based on the conventional zero power levitation algorithm which exhibits incomplete zero power levitation

value was not measured due to the lack of number of probes; however, it should be noted that three is enough to prove the unsatisfying result. As shown in the current waveform, not all three hybrid EMS systems possess a zero steady state value. Only one hybrid EMS system exhibits a zero power levitation control, and the rest shows non-zero current values. This reflects the fact that the gap reference is suitable for zero power levitation only for one hybrid EMS system.

As mentioned in the previous section, the result of the experiment conducted under the conventional algorithm proves that a complete zero power levitation control cannot be achieved via conventional zero power control algorithm.

4.2 Experimental result of the proposed zero power control algorithm

The second experiment was conducted with the proposed zero power levitation control algorithm which is composed of the state feed-back PI controllers and the gap reference compensator algorithm. Fig. 9 shows the gap distance and three current values from three hybrid EMSs. As mentioned in the previous section, the result of the experiment conducted under the proposed algorithm proves

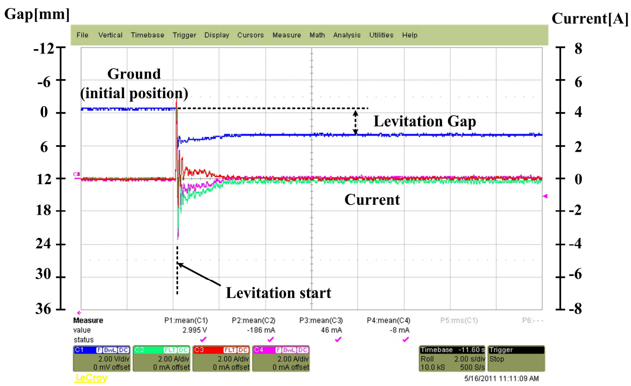

Fig. 9. Gap and current waveforms based on the proposed zero power levitation algorithm which exhibits complete zero power levitation

that a complete zero power levitation control can be achieved.

All four hybrid EMSs adjust its gap references independently. As a result, all of the current converges to zero. Eventually, while all four hybrid EMS systems possess different gap references and corresponding gap distances, all four hybrid EMS systems possess the same zero current input for levitation.

4.3 Experimental result of the proposed zero power control algorithm with disturbance

An extended experiment examining the stability of the quadruple hybrid EMS system had been carried out using an additional mass as a disturbance. The proposed zero power levitation control system must maintain zero power consumption even when there is disturbance such as the increase and decrease of mass. When there is an additional mass imposed onto the system, the quadruple hybrid EMS system instantly increase the input current to generate more attraction force so that the permanent magnet moves closer to the rail to stabilize at its new point of zero power levitation control.

Fig. 10 shows a current waveform maintaining the zero power levitation when additional load is imposed, and then removed. During the experiment, we burdened the quadruple hybrid EMS system with 3Kg mass and removed when the current converged to zero. The experiment proved that the zero power control system is stable when mass is applied as well as when it is removed. The proposed zero power levitation control allows each hybrid EMS to find its equilibrium point respectively.

The resulting gap distances are depicted in Fig. 11. All four hybrid EMSs do not share an exact identical gap because each hybrid EMS independently converges to a point where zero power levitation control is realized. When a disturbance is imposed on the system, gap distance adjusts responding to the intensity of the disturbance.

As mentioned earlier, additional mass was used as

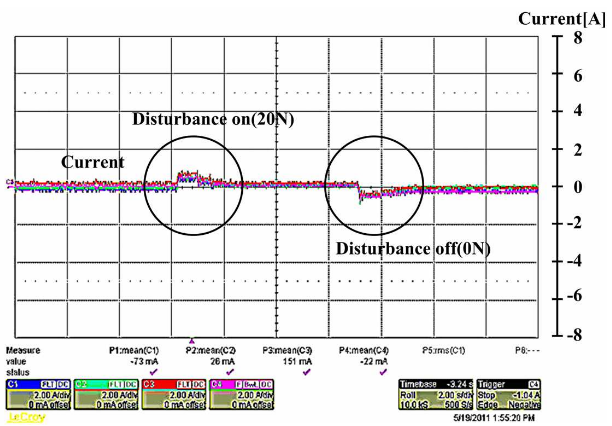

Fig. 10. Current waveform maintaining the zero power levitation under disturbance input for proving the stability of the system

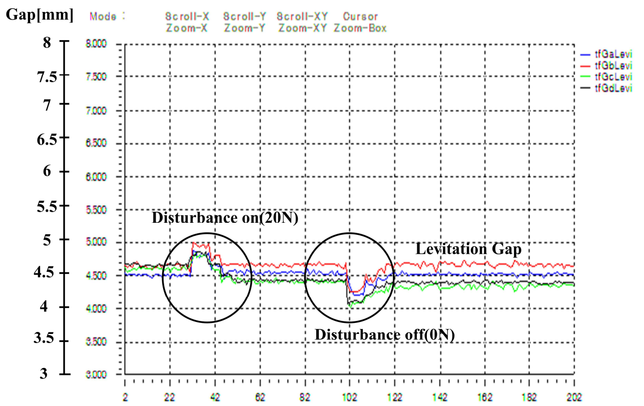

Fig. 11. Gap waveform maintaining the rated gap length under disturbance input

disturbance. Imposed mass makes the total weight of the quadruple hybrid EMS system heavier, and accordingly, gap reduces to attain more attraction force and vice versa.

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5. Conclusion

An algorithm which realizes a complete zero power levitation control in a quadruple hybrid EMS system had been proposed in this paper. Unlike single hybrid EMS systems, the quadruple hybrid EMS system is much more difficult to control and satisfy the zero power condition due to the design tolerance. A gap reference compensating algorithm was taken independently to adjust the gap reference of each hybrid EMS systems. This allows the respective hybrid EMS systems to converge to their own gap distances compatible with the point where zero power levitation control could be satisfied. The validity of the proposed zero power levitation control algorithm had been proven via experiments and the corresponding waveforms are included in the last section of the paper.

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Su-Yeon Cho He received his B.S. and M.S. degrees in Electrical Engineering from Hanyang University, Seoul, Korea in 2008 and 2010, respectively. Since 2010, he has been pursuing the Ph.D. degree at the Department of Electrical Engineering, Hanyang University. His research interests include design, analysis, testing and control of motor/generator; power conversion systems; and applications of motor drive, such as electric vehicles, high-speed maglev train and renewable energy systems.

Won-Ho Kim He received his B.S., M.S. and Ph.D. degrees in Electrical Engineering from Hanyang University, Seoul, Korea in 2005, 2007 and 2011 respectively. He is now working in Samsung Advanced Institute Of Technology. His research interests include motor design, analysis of motor/ generator; and applications of motor drive, such as electric vehicles, home appliances

Ik-Sang Jang He received his B.S., M.S. and Ph.D. degrees in Electrical Engineering from Hanyang University, Seoul, Korea in 2007, 2009 and 2012 respectively. He is now working in Samsung Techwin. His research interests include motor design, vibration & noise analysis of motor/generator; power conversion systems; and applications of motor drive, such as hybrid and electric vehicle.

Dong-Woo Kang He received his B.S., M.S. and Ph.D. degrees in Electrical Engineering from Hanyang University, Seoul, Korea in 2006, 2008 and 2011 respectively. He is now working in Samsung Electronics Co. His research interests include design, analysis, of motor/generator; power conversion systems; and applications of spherical motor for robots; home appliances.

Ju Lee He received his M.S. degree from Hanyang University, Seoul, South Korea, in 1988, and his Ph.D. from Kyusyu University, Japan in 1997, both in Electrical Engineering, He joined Hanyang University in September, 1997 and is currently a Professor of the Division of Electrical and Biomedical Engineering. His main research interests include electric machinery and its drives, electromagnetic field analysis, new transformation systems such as hybrid electric vehicles (HEV), and high-speed electric trains and standardization. He is a member of the IEEE Industry Applications Society, Magnetics Society, and Power Electronics Society.