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Advances in Magnetic Suspension Technology
--- Towards Smart Mechatronics ---

Takeshi MIZUNO
Saitama University
E-mail: mizar@mech.saitama-u.ac.jp

Abstract

Several recent advances in magnetic suspension technology leading to smart mechatronics are reported. The magnetic suspension system using the attractive force of an electromagnet needs servo action to achieve stable suspension. It gives advantages and drawbacks to such magnetic suspension systems. Recent works making the use of the advantages and/or overcoming the drawbacks are presented.

Keywords: magnetic suspension, magnetic bearing, mechatronics

1. Introduction

Magnetic suspension generates force for suspension through magnetic fields. There is no contact between stator and floator so that no mechanical friction and wear are expected in operation even without lubrication. This advantage has already given rise to a lot of industrial applications such as Maglev system [1, 2], and active magnetic bearing (AMB) for complete contact-free suspension of a rotating object [3-6]. The most successful application is turbomolcular pump. In this application, AMB-based instruments are dominant.

However, the full potential of industrial applications has not been acheived yet. To fully utilize this unique technology, technical innovations and advances are still necessary althogh some people may consider this technology to be rather mature.

This report presents several recent innovations and advances in magnetic suspension technology. Because it is far beyond the author's ability to cover the whole aspects of magnetic suspension technology, an overview of technological fundamentals is presented first, which is followed by reports on the recent works of the author and a comment on *"toward smart mechatronics"*.

2. Fundamentals

There are various combinations of material in supporting magnet and suspended body to achieve magnetic suspension [1, 6]. The method mostly used in industrial applications utilizes the attractive force of an electromagnet. Figure 1 shows a basic actively controlled magnetic suspension system that consists of the following components:

- object to be suspended (floator)
- electromagnet to produce suspension force
- sensor to detect the displacement of the floator
- electronic analog or digital controller
- power amplifier to feed current to the windings of the electromgnet

This system is inherently unstable in the normal direction. Stable action can be achieved by sensing the position of the rotor and controlling the force fields to prevent the floator from departing from its desired position with sufficient rapidity; increase the current when the air gap is too large, decrease the current when the air gap is too small. The necessity of such servo action gives advantages and drawbacks to active magnetic suspension system.

One of the advantages is the capability of achieving various functions that are impossible for conventional mechanical suspension. For example, unbalance compensation is one of the unique characteristics of magnetic bearings; harmonic forces due to the imbalance are effectively compensated by the magnetic forces [7, 8]. Applicability to measurement systems is another advantage; when the integral-like action is implemented, the force acting on the floator can be estimated from the control input. This function is utilized in the identification of rotor dynamics and wind tunnels (see Section 3) [9, 10]. It is also possible to combine other functions with

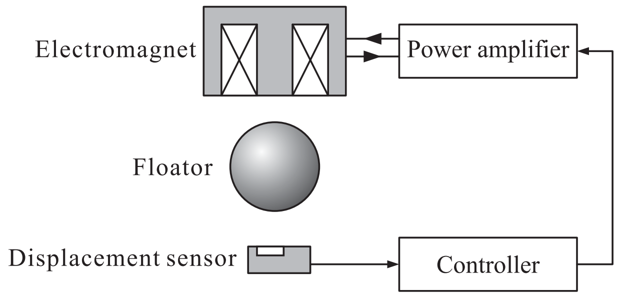


Fig.1. Basic structure of active magnetic suspension system

suspension. One of them is to combine motor function, which is called as self-bearing motor or bearingless motor [6]. We apply such system to wind tunnel suspension that is treated in Section 3.

One of the drawbacks is high cost as compared to conventional mechanical suspensions. To achieve hardware savings for cost reduction, *self-sensing* or *sensorless* magnetic suspension been proposed [11]. It is based on the property that voltage-controlled magnetic suspension system is controllable and observable even if only the coil current is the output (variable to be measured). Because the displacement and velocity of the floator can be estimated by an observer, the hardware of displacement sensing can be removed. It has been studied extensively as one of the most promising methods of reducing the cost of hardware [11-14]. Nevertheless, the reduction of cost is still insuffient. The authors have proposed quite a different approach of hardware reduction with an attention to another key component: *power amplifier*. This component is indispensable for the operation of a *single* suspension system so that it is impossible to omit the amplifier itself. The key point of the proposal is to reduce the *number* of power amplifier to float *multiple* floators, for example, with a *single* power amplifier [15]. It will give another promising method of reducing the hardware. Such magnetic supension is named as *multiple magnetic suspension* that is treated in Section 4.

Another drawback is the necessity of external energy to operate servomechanism. When the suspension force is supplied only by an electromagnet, a steady current flowing the electromagnet is necessary to counterbalance the gravitational force. It causes energy consumption and heating up of the electromagnet. An effective way of solving such a problem is zero-power magnetic suspension using hybrid magnet [16-18]. Recently, a energy harvesting technique such as solar power generation has been introduced and combined with magnetic suspension technology [19], which is treated in Section 5.

3. Wind Tunnel

Magnetic suspension provides an ideal way of supporting a model for wind tunnel tests because there is no support interference problem arising with mechanical model-support [21, 21]. The forces and moments to support the model are generated by electromagnets arranged outside the test section. In addition, aerodynamic forces acting on the model are estimated from the control current of the electromagnets.

Aerodynamics around a spinning body such as golf ball is still an intriguing topic in both academic and industrial fields. Although simulation-based analysis has been making very rapid progress, the details of the dynamics have not been clarified sufficiently. The main difficulty is that the target phenomenon is a complex mix of macro-scale and micro-scale dynamics. Therefore, ideal wind tunnel tests are still required for more precise and reproducible observation. However, conventional wind tunnels using magnetic suspension were not designed to test a spinning body so that they lacked the function of rotating the body [20, 21].

We have proposed a wind-tunnel system for spinning body to measure hydrodynamic forces acting on the body [9]. In the proposed system, the body is suspended and rotated by electromagnets. The forces acting on the body are measured from the control signal for suspension. An apparatus with a 60×60 mm wind tunnel has been developed [10]. It uses a 3-axis optical sensor operating in a fully-differential mode. This apparatus achieves stable suspension and rotation. The hydrodynamic forces acting on the spinning body are measured actually.

Figure 2 shows a photograph of the fabricated apparatus. The size of the total system is $360 \times 1200 \times 440$ mm, approximately. It consists of a magnetic suspension mechanism, a three-axis displacement sensor, a controller and a wind-tunnel. The outline of Each component will be explained in the following. A schematic drawing of the mechanism for magnetic suspension is shown in Fig.3 where the nearest electromagnet is removed for a better view of the inside poles. The size is $244 \times 244 \times 296$ mm. The suspension system has eight electromagnets for controlling the three-dimensional position of a sphere body made of ferromagnetic material. Each electromagnet has five 300-turn coils. The impedance of the electromagnet can be adjusted by the connections of the coils. The distance of the poles are kept long enough for a 60×60 mm wind tunnel to be inserted.

The operation of the fabricated 3-axis optical sensor is illustrated in Fig.4. It combines a pair of unit with a LED (light source), four collecting lens and four phototransistors. It can detect the three-dimensional positions of the body in the full-differential mode.

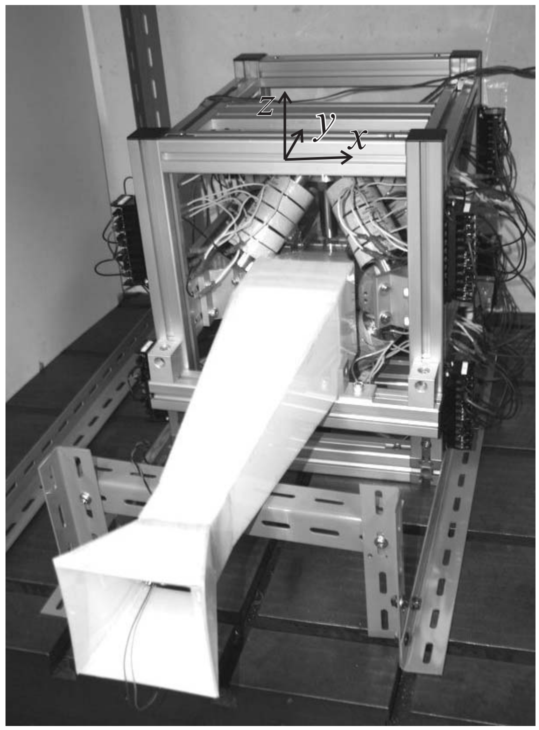


Fig.2. Fabricated wind tunnel with a magnetic suspension mechanism

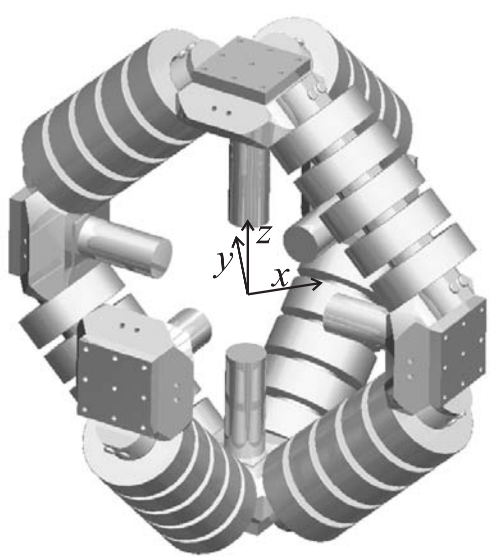


Fig.3. Schematic drawing of the magnetic suspension mechanism

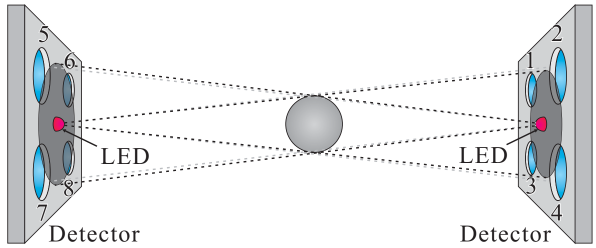


Fig.4. Three-dimensional differential optical displacement sensor

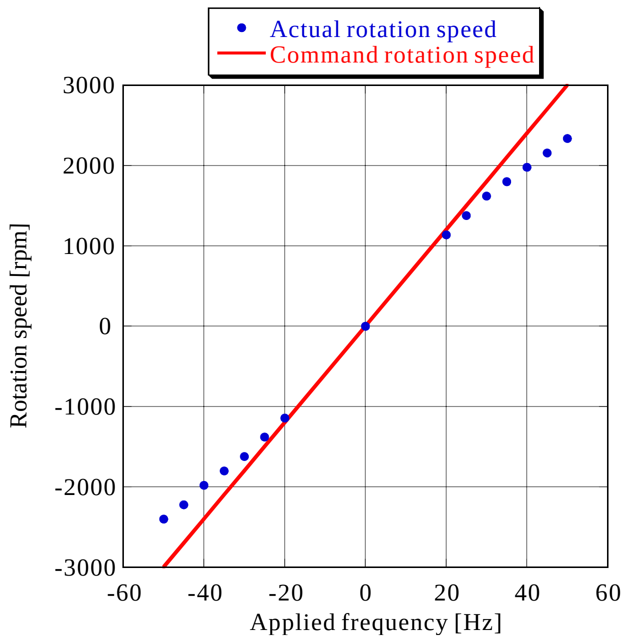


Fig.5. Relation between driving frequency and rotation Speed

Because the suspension system is inherently unstable, stabilization using active control is required. The outputs of the sensors are inputted into a DSP-based digital controller. The controller calculates control signals and send them together with excitation signal for rotation to eight power amplifiers for the electromagnets through D/A converters. The aerodynamics forces acting on the body are estimated from the control signals for maintaining the position of the body.

Stable suspension was achieved by applying PID control. The rotation of the body was realized by superimposing two-phase AC signals on the control signals for the *x*- and. *y*-directions. The rotation about the vertical axis (*z*-axis) was achieved. The relation between the excitation frequency and the rotational speed was studied experimentally. The results are summarized in Fig.5. The body is driven up to 3000rpm. Since the principle of rotation is same as that of induction motor, the slip is observed in higher frequency regions.

Several wind tunnel tests were successfully carried out. The fluid drag and lift forces were measured from the control input. It was observed from the measurement results that the drag force was proportional to the square of the wind speed approximately and the lift force also increased as the wind speed increased [10].

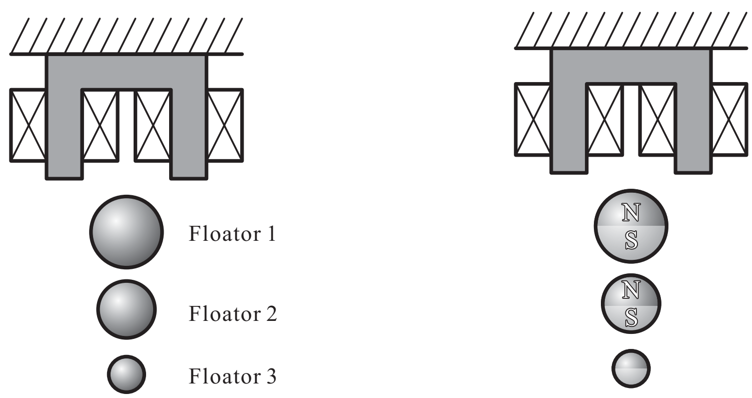
4. Multiple Magnetic Suspension

A basic magnetic suspension system has a single floator (object to be suspended) and electromagnet that is controlled with a single power amplifie as shown in Fig.1. Multiple magnetic suspension is a unique approach of hardware reduction with an attention to *power amplifier* [15]. In multiple magnetic suspension, multiple floators are controlled with a single power amplifier. Multiple magnetis suspensions are classified into series and parallel.

Series magnetic suspension

The basic concept of *series* multiple magnetic suspension is illustrated by Fig.6(a) in which three floators are suspended with a single electromagnet. In the following, a series-type multiple magnetic suspension system with n floators is referred to as n-series magnetic suspension system. The floator 1 is suspended by the electromagnet and magnetized. Then, the floator 2 is also magnetized through the floator 1. In the same manner, all the floators are magnetized. Therefore, they can be suspended by the single electromagnet. However, the attractive forces between the floators obtained by the magnetization are frequently insufficient to suspend the successive floator(s). To obtain sufficient attractive force, permanent magnetic (pre-magnetized) floators are used instead of ferromagnetic floators as shown by Fig.6(b). Yamamoto *et al.* [22] has proposed *indirect suspension*, which corresponds to 2-series magnetic suspension, and achieved stable noncontact suspension.

It can be shown analytically that both current-controlled and voltage-controlled n-series magnetic suspension systems are controllable [23]. It can be shown analytically that both current-controlled and voltage-controlled n-series magnetic suspension systems are observable when one of the displacements is detected. It is obvious that the systems are observable when multiple displacements are detected. The voltage-controlled n-series magnetic suspension system is also observable even if only the current of the electromagnet is detected. It indicates that the self-sensing control of series multiple magnetic suspension systems is feasible theoretically.



(a) Ferromagnetic floators (b) Pre-magnetized floators

Fig.6. Series multiple magnetic suspension system with three floators

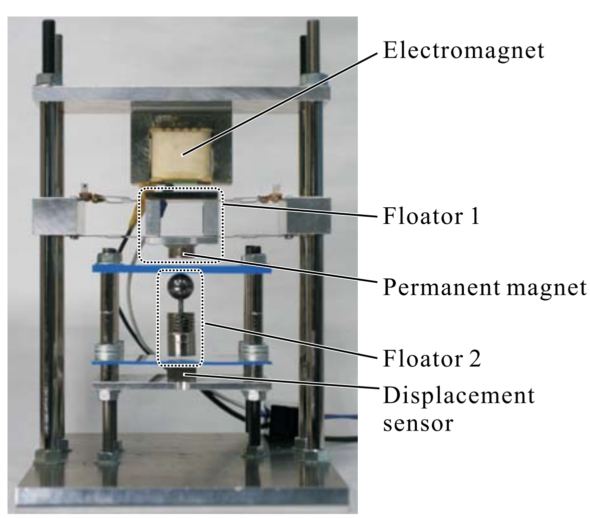


Fig.7. Photo of force measurement apparatus using double series magnetic suspension

One application of *2*-series magnetic suspension is force measurement; the proposed system can measure force without any displacement of the point of force actuation [24]. When PID control is applied to the displacement of the floator 2, the floator 1 displaces in proportion to the force applied to the floator 2 whereas the position of the floator 2 is maintained at the original position. Therefore, the force can be estimated for the displacement of the floator 1.

The proposed method has an advantage over conventional methods that the distance between the operating point of force (second floator) and the source of force is kept invariant. In addition, when the stiffness between the first and second floators is low, even small force leads to large displacement. Therefore, the proposed measurement method is suitable for the noncontact measurement of micro force. Figure 7 shows an apparatus fabricated based on this concept and the effectiveness of the proposed method has been studied experimentally [24]. The measurement results suggest that the proposed force measurement method will achieve higher resolution than conventional servo-type force measurement method.

Parallel magnetic suspension

A schematic drawing of a parallel magnetic suspension system is shown by Fig.8 in which *three* floators and electromagnets controlled with a *single* power amplifier. Based on this principle, the number of floators and

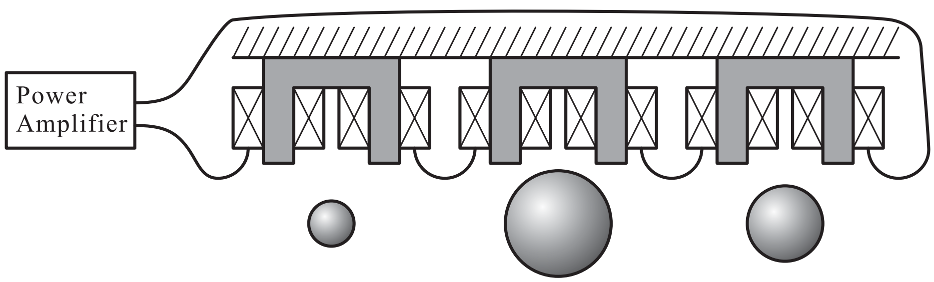


Fig.8. Parallel multiple magnetic suspension system with three floators and series-connected coils

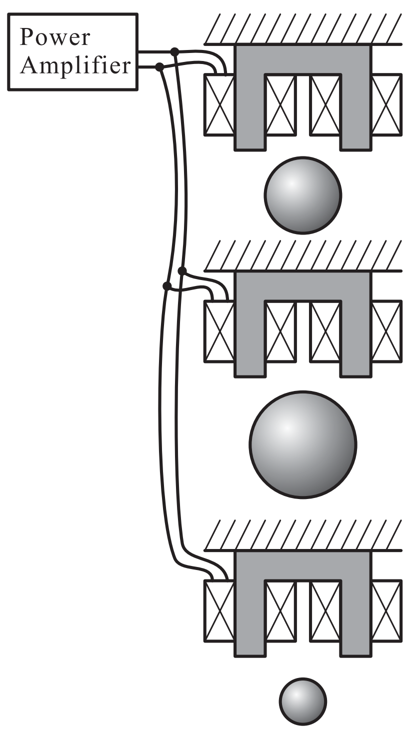


Fig.9. Parallel multiple magnetic suspension system with three floators and parallel-connected coils

electromagnets controlled by a single electromagnet can be set two or more arbitrarily. When the number is n and the connection of the coils is series as shown in Fig.4, we call it as n-parallel magnetic suspension system with *series connection*. Another connection of the coils is parallel as shown in Fig.9. Such system is referred to as n-parallel magnetic suspension system with *parallel connection* [15].

The controllability and observability of parallel magnetic suspension systems have been studied and the conditions under which the parallel magnetic suspension system are controllable and observable are clarified [15]. For example, The state equation of a current-controlled double parallel suspension system with series connection is given by

$$\dot{\boldsymbol{x}}_{cpt2}(t) = \boldsymbol{A}_{cpt2}\boldsymbol{x}_{cpt2}(t) + \boldsymbol{b}_{cpt2}i(t) , \tag{1}$$

where

$$\boldsymbol{x}_{cpt2} = \begin{bmatrix} x^{(1)} \\ \dot{x}^{(1)} \\ x^{(2)} \\ \dot{x}^{(2)} \end{bmatrix}, \quad \boldsymbol{A}_{cpt2} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ a_{21}^{(1)} & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & a_{21}^{(2)} & 0 \end{bmatrix}, \quad \boldsymbol{b}_{cpt2} = \begin{bmatrix} 0 \\ b^{(1)} \\ 0 \\ b^{(2)} \end{bmatrix}, \quad a_{21}^{(k)} = \frac{k_s^{(k)}}{m^{(k)}}, \quad b^{(k)} = \frac{k_i^{(k)}}{m^{(k)}}$$

x : displacement of the floator, i : control current (common), m : mass of the floator, k_s : force to displacement factor, k_i : force to current factor, and a parenthetic superscript "(k)" indicates that the quantity is related to the kth subsystem consisting of a floator and the corresponding electromagnet (k=1 or 2). The factors k_s and k_i are usually nonzero. The controllability matrix of this system is given by

$$\boldsymbol{M}_C^{cpt2} = \begin{bmatrix} 0 & b^{(1)} & 0 & a_{21}^{(1)}b^{(1)} \\ b^{(1)} & 0 & a_{21}^{(1)}b^{(1)} & 0 \\ 0 & b^{(2)} & 0 & a_{21}^{(2)}b^{(2)} \\ b^{(2)} & 0 & a_{21}^{(2)}b^{(2)} & 0 \end{bmatrix} \tag{2}$$

Calculating the determinant gives

$$\det \boldsymbol{M}_C^{cpt2} = \left\{(a_{21}^{(1)} - a_{21}^{(2)})b^{(1)}b^{(2)}\right\}^2 \tag{3}$$

Therefore, the system (1) is controllable if and only if

$$a_{21}^{(1)} \neq a_{21}^{(2)} \tag{4}$$

This implies that the open-loop *mechanical* dynamics must be different among the subsystems for controllability [15].

The feasibility of parallel magnetic suspension has already been demonstrated experimentally in the case of $n = 2$ (double parallel suspension system) [25]. The zero-power control has also been achieved in the same system [26]. In addition, the concept of *multiple suspension* has been extended to *electrostatic* suspension [27].

5. Solar Magnetic Suspension

The necessity of external energy is one of the critical problems of active magnetic suspension system in widening its application fields. Recently, a energy harvesting technique such as solar power generation has been introduced and combined with magnetic suspension technology [19].

Figure 10 shows a photograph of a fabricated solar magnetic suspension appratus. 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. The floator is made of soft iron and a hollow sphere having an outer diameter of 43 mm. A disk-shaped ferrite magnet is attached to the top of the floator for the zero-power suspension. In this apparatus, the single-degree-of-freedom vertical translational motion of the floator is actively controlled while the other motions are passively stabilized by the edge effects.

Figure 11 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. The fabricated solar magnetic suspension system has 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 luminance and instantaneous power consumption just after a disturbance acts in the floator.

To maintain levitation for a long time by solar energy solely, significantly dedicated low-power peripheral devices are developed. Figure 12 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.

The average power consumption of the fabricated magnetic suspension system is 33 mW in stable suspension.

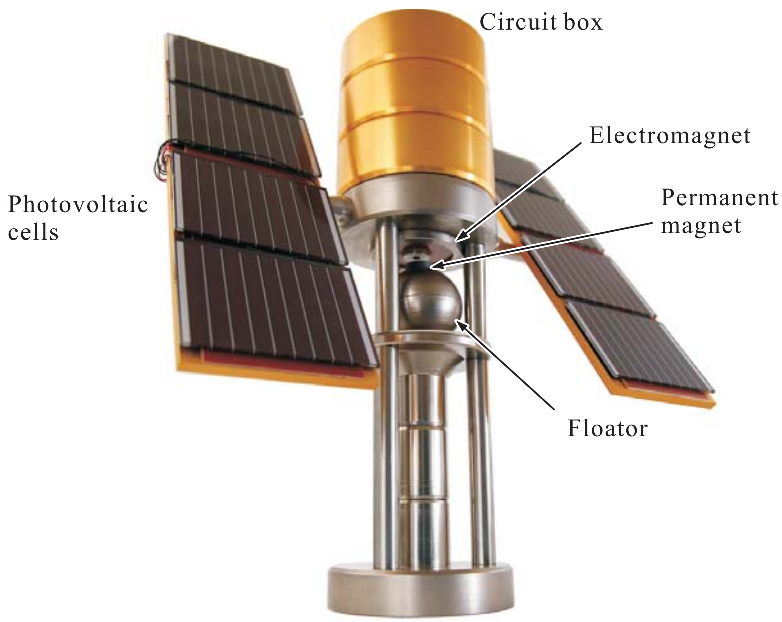


Fig.10. Photo of the fabricated solar magnetic suspension apparatus

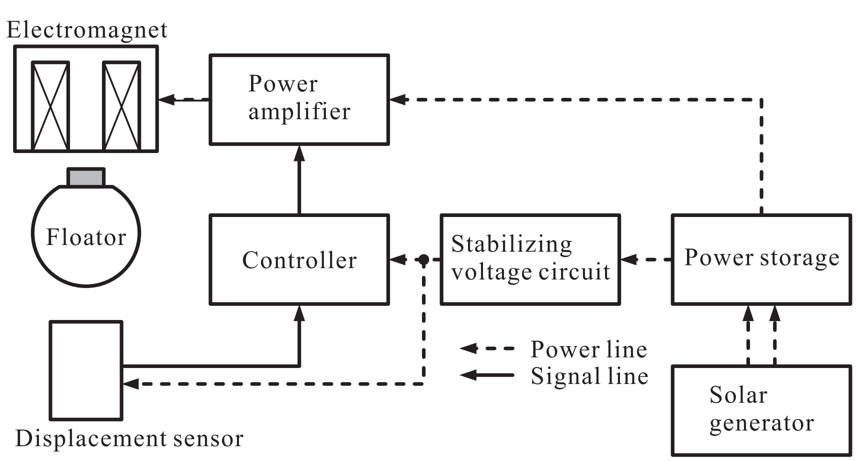


Fig.11. Outline of the solar magnetic suspension system

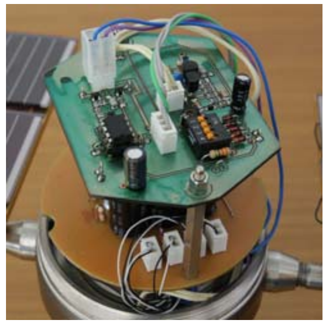


Fig.12. Photo of the circuits for peripheral devices (inside the circuit box).

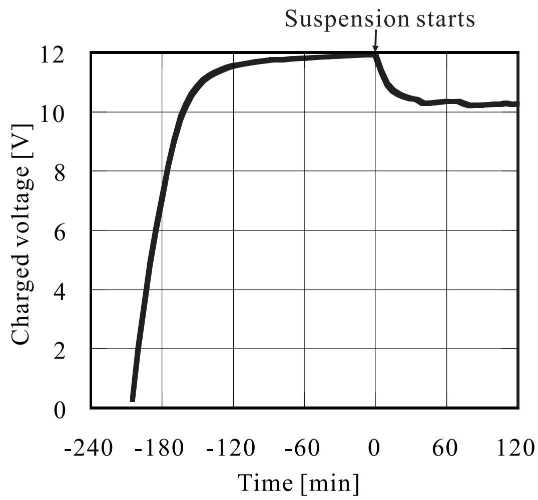


Fig.13. Time-history of the charging voltage under a low luminance.

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 5klx-illuminance of a fluorescent lamp.

Figure 13 shows a time history of the charged suspension voltage under such low luminance. 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 until the supply and demand power were balanced (after 60 min).

6. Toward Smart Mechatronics

Mechatronics is an interdisciplinary area of engineering based on classical fields of mechanical and electrical engineering and on information technology [6]. A typical mechatronic system takes in signals, process them and puts out signals to produce forces and/or motions. Such a system detects changes in environment and reacts to them according to a suitable strategy through information processing. Therefore, mechatronic systems are more or less *smart*. For innovations in mechatronics, however, qualitative changes or evolutions will be necessary. One of the candidates is the introduction of energy harvesting technology to mechatronic systems because it will lead to clean and tidy (another sense of smart) machines. I hope that the advances described above will be clues to future *smart mechatronics*.

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