A Laser Guided Magnetic Suspension System

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ABSTRACT

Control of magnetic suspension of linear moving objects brings out problems related to measurement of suspension gaps. Placing probe type gap sensors such as eddy current type sensors on the suspended object or the stator are conventional configurations. However, such configurations result in such problems as: either (i) necessity of wiring or wireless signal transmission from the suspended object; or (ii) calibration of many sensors situated on the stator; or (iii) accuracy of suspension being limited by the machining accuracy of the sensor targets. To solve the above problems, and to seek new control possibilities, we have developed methods of using laser beams as a plane-reference for magnetic suspension. Because the laser beam propagates along a straight line, the line or plane defined by the laser can be used as a reference against which control of suspension is executed. We have so far developed three optical systems each consisting of a semiconductor laser and light detectors such as single cell lateral effect photodiodes or multi-segment photodiodes. Two of the three optical systems have reflectors such as prisms or corner cubes attached to the slider to eliminate wiring to the suspended object. By applying the developed optical systems to a one d.o.f. magnetic suspension apparatus, we have so far confirmed suspension accuracy of 0.3 μm (p-p) (in air), and suspension stiffness of 5 N/μm. Also, though not a quantitative experiment, robustness of suspension in smoke filled containers has been observed. The paper will focus on the optical designs, experiment results, and expected field of applications.

INTRODUCTION

With a few exceptions [1,2], gap sensors are generally used for active control of magnetic bearings. In the case of rotary type magnetic bearings, the gap sensors used for detection of air gaps are situated in a radial formation on the stator side. This configuration does not necessitate wiring to the rotor. However, in the case of linear magnetic suspension systems, measurement of air gaps with gap sensors brings out various problems related to wiring or accuracy of suspension. Placing probe type gap sensors such as eddy current type sensors on the slider or the stator are conventional configurations [3,4]. **Figure** 1 (a) and (b) are schematic of the possible configurations. However, such designs result in such problems as: either (i) the need of wiring or wireless signal transmission from the moving body [5], if the sensors are situated on the slider; or, (ii) suspension accuracy being limited by the machining

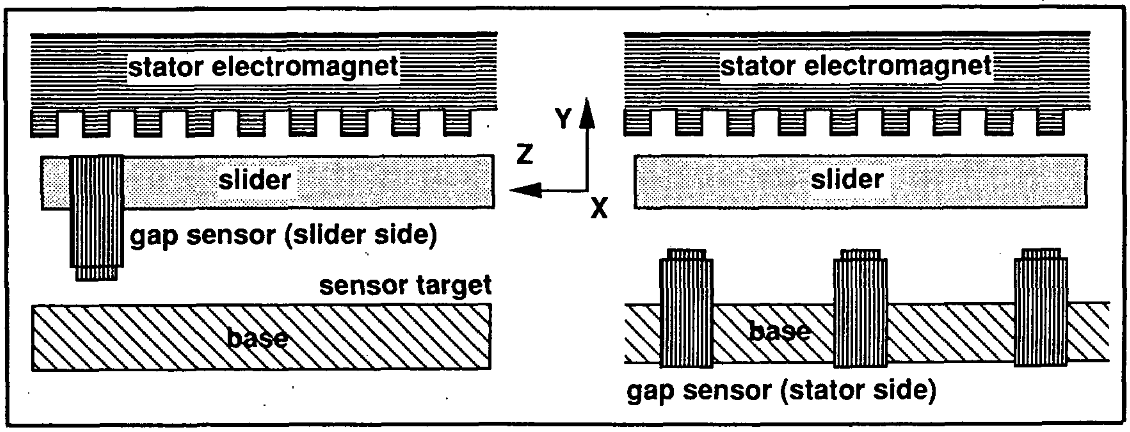

Figure 1. Schematic drawings of linear magnetic suspension systems with probe type gap sensors. (a) gap sensor situated on the slider necessitate wiring or wireless signal transmission from the slider to the stator, (b) gap sensors situated on the stator necessitates calibration of many sensors.

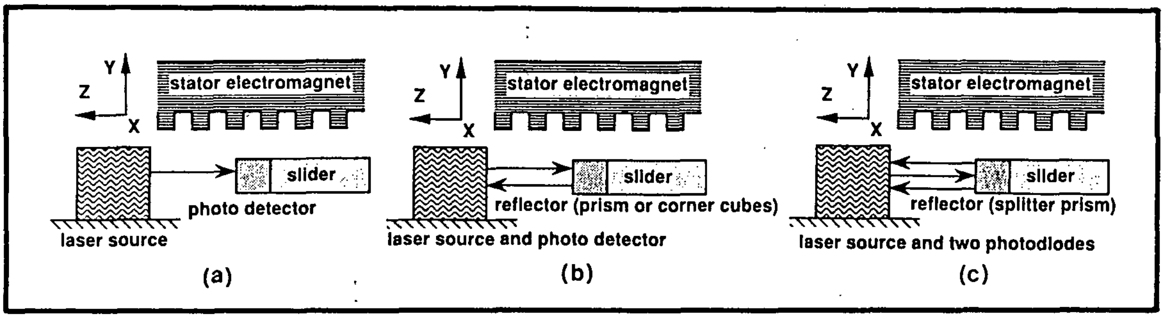

Figure 2. Schematic drawings of three types of optical designs for measurement of air gap of a linear moving slider. (a)Type I, with photodetector on the slider,(b)Type II, with reflector on the slider to eliminate wiring to the moving body, and (c) beam splitting prisms on the slider to transform displacement of the slider to differing magnitudes of the returning beams.

accuracy of the sensor target on the stator side if the sensors are placed on the slider; or (iii) the need for calibration of many gap sensors if the sensors are situated on the stator side.

To solve the above problems, and to seek new control possibilities, we have developed three methods of using laser beams as a plane reference for magnetic suspension. Because the laser beam propagates along a straight line, the line or plane defined by the laser can be used as a reference against which air gaps are measured and used for control of suspension. **Figures** 2 (a),(b) and (c) are schematic views of the three optical systems designed for detection of air gap of a linear moving slider. The Figures are simplified to one degree of freedom. Each system consists of a laser diode and light detectors such as single cell lateral effect photodiodes or multi-segment photodiodes. Two of the three optical systems have reflectors such as prisms or corner cubes attached to the slider to eliminate wiring to the suspended object. Details of each optical system will be discussed in the next Chapter.

An existing technique of using laser beams and photodetectors for sensing of fine displacements can be found in the field of atomic force microscopy [6,7,8]. Hollis, Allan and

Salcudean has used light emitting diodes and two dimensional lateral effect photodiodes for sensing six degrees of freedom of a magnetically suspended object or "flotor" [9,10]. The areas of applications where the merits of a laser guided suspension system can be fully appreciated are: (i) transportation of samples in vacuum chambers [11,12,13]; (ii) semiconductor processing and lithography in vacuum [14,15,16], where high cleanliness and accuracy of guidance is required; (iii) measurement of large air gaps for suspension control of flotors [9,10,17,18], where measurement of large air gaps with high resolution is relatively difficult to achieve with probe type sensors.

The following will be discussed: (i) configuration of the three optical systems; (ii) evaluation of photodetectors suitable for magnetic suspension, (iii) experiment with the three optical systems; (iv) merits and demerits of each optical system; and (v) design of a linear conveyor system.

INSTRUMENT

Figure 3 is a schematic diagram of an apparatus used to compare the displacement outputs of various types of photodetectors and a conventional capacitance type gap sensor. A photodetector is attached to the end of a piezoelectric actuator for actuation perpendicular to the axis of the laser. Effects of such factors as laser path length, actuation amplitude, actuation frequency, air turbulence, disturbance of other light sources are evaluated with the apparatus.

Figure 4 depict configurations of three types of optical systems, each corresponding to the schematics of **Figure** 2. In the following text, the optical systems are named **Types** I, II and III for simplicity. X,Y, and Z axes are defined as **Figure** 4, where the Z axis is defined as the axis of the laser beam, and the X and/or Y axes are defined as the direction of magnetic suspension. **Type** I depicted in **Figure** 4(a) has a laser diode light source on the stator side, and a photodetector on the slider. The photodetectors used in Type I are single cell lateral effect photodiodes or multi-segment photodiodes. The photodetectors can detect the position of the incident laser spot with a resolution better than 0.1 μm, and have bandwidths from 0 Hz to frequencies higher than few 100 kHz [19,20,21]. Since the photodetector mounted on the slider recieves the laser beam directly from its source, **Type** I is expected to enable

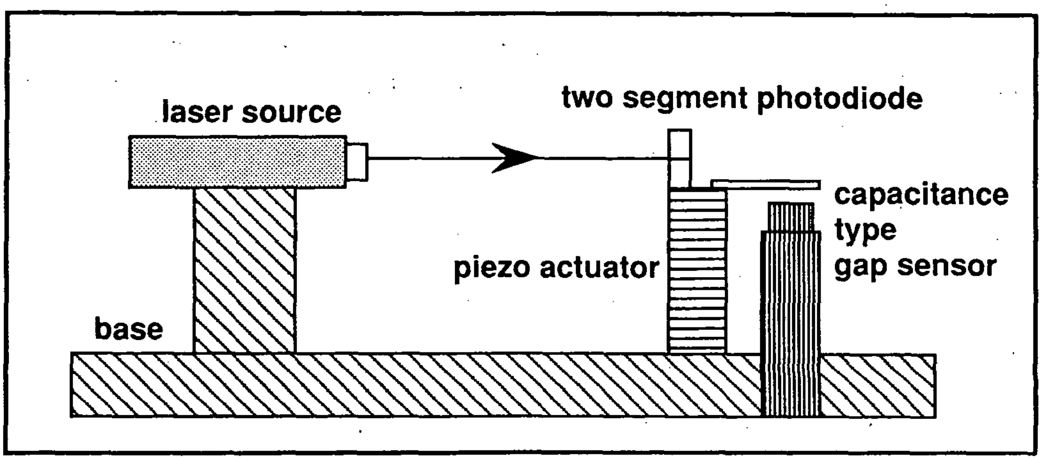

Figure 3. Schematic of the apparatus used to compare the displacement outputs of conventional capacitance type gap sensors and photodetector sensors. Piezoelectric actuators were used to actuate the photodetector.

detection of displacement with resolution around 0.1μm, and with the accuracy determined by the straight propagation of the laser.

Type II depicted in **Figure** 4(b) has a laser light source and a photodetector situated on the stator side, and a reflector such as a right angle prism or a corner cube attached to the slider. The photodetector used in this design are the same as those of **Type** I. **Type** II was designed to eliminate wiring from the slider. Light emitted from the laser source in the Z direction enters the reflector and is then reflected parallel to the incident beam. The prism or the corner cube is placed in such a way that the axis of the reflected beam moves in relation to the movement of the slider in the X and/or Y directions. By detecting the translational movement of the axis of the reflected beam in the X and/or Y directions with a position sensitive photodetector, it is possible to measure the displacement of the slider perpendicular to the axis of the laser. The design has such merits as simplicity, compactness, and elimination of wiring from the slider. The use of corner cubes as the reflectors has additional advantages such as: detection of displacement in the X and Y directions from a single laser beam; and detection of translational displacements of the slider without interference from the rotational motions of the slider. This means that all degrees of freedom of the slider except the Z coordinate can be measured by placing more than three corner cubes on the slider. As a demerit of Type II, it should be noted that the parallelism of the reflected beam to the incident beam is a limiting factor of suspension accuracy. The error of suspension will increase as the slider moves farther away from the photodetector in the Z direction.

Type III depicted in **Figure** 4(c) has a laser source and two photodiodes on the stator side and two right angle prisms on the slider. **Type** III was designed, so that the accuracy of suspension is least affected by the precision of the reflector. As depicted in **Figure** 4(c), two right angle prisms situated on the slider have their ridge in contact with one another. The laser spot is split into two beams by the ridge of the prism. Then, the two split beams are each reflected parallel to the incident beam. The magnitude of the two reflected beams change as the relative position of the ridge change to the spot of the incident beam. Therefore, it is

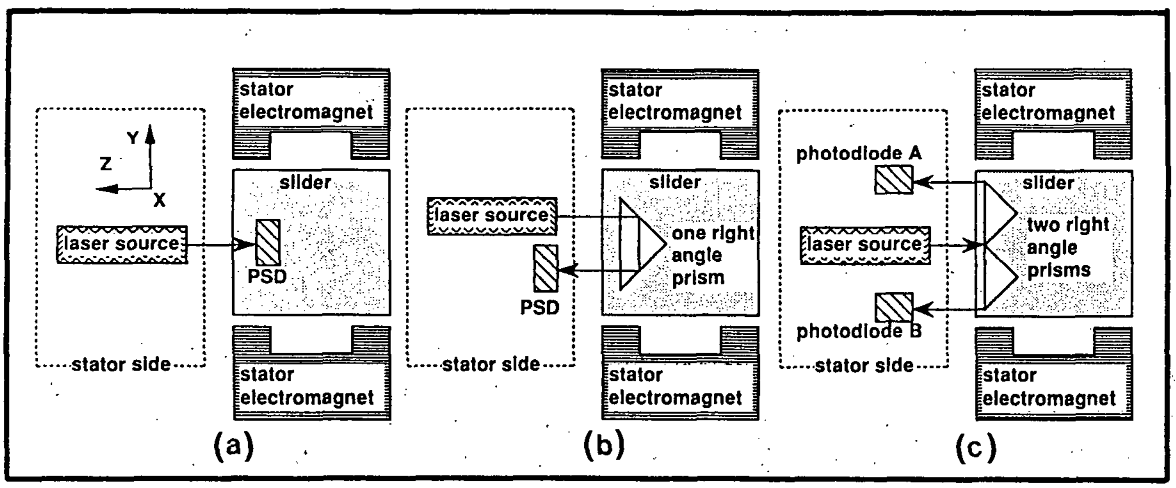

Figure 4. Schematic of the three optical designs. Each figure correspond to the figures of Figure 2. (a) laser source on the stator side, and photodetector on the slider. Requires wiring or wireless transmission of the displacement signal to the stator side. (b) laser source and photodetector on the stator side, and reflector such as right angle prisms or corner cubes on the slider. Eliminates wiring to the slider. Suspension accuracy limited by the accuracy of the prisms. (c) laser source and two single cell photodiodes on the stator side, and two beam-splitting right angle prisms on the slider. Suspension accuracy is not affected by the accuracy of the prisms.

possible to detect the displacement of the slider by measuring the difference of magnitude of the two reflected beams with photodiodes. This method of measuring displacements as the difference of magnitude of the returning beams frees the accuracy of the system from being limited by the optical machining accuracy of the prisms. By placing focusing lenses in front of photodiodes, the system will become more robust to tilting of the returning laser beams due to rotational movements of the slider. The technique of using the ridge of a prism to split a laser beam is common in laser optics [22].

EXPERIMENT

Basic experiments by actuating photodiodes with piezoelectric actuators

The apparatus depicted in **Figure** 3 was used to compare the displacement outputs of photodetector sensors and conventional capacitance type sensors. **Table** I is a list of merits and demerits confirmed with the apparatus. **Figure** 5 are sensor outputs for a two segment type photodiode. It can be seen that for both triangular and sinusoidal actuation with the piezoelectric actuator, displacements are detected with reasonable clarity at an amplitude of 0.1 μm, and a frequency of 3 kHz. Other data depict the order of stability of the photodetector outputs. Note that time scales are different for **Figures** 5 (a), (b) and (c), (d).

Table I. Comparison of photodetectors.

Type	multisegment photodiode / single chip photodiode	single cell lateral effect photodiode
measurable span of laser spot displacement	small (up to 5 mm)	large (up to 50 mm)
resolution	better than 0.1 μm	better than 0.1 μm
output fluctuation (in insulated box)	small (approx. 0.1 μm)	large (approx. 1 μm)
output fluctuation (when beam path disturbed by heat)	small (approx. 5 μm)	large (approx. 10 μm)
frequency range	0 Hz to 10 MHz or higher	0 Hz to a few 100 kHz

One degree of freedom suspension experiments for three types of optical designs

A one degree of freedom apparatus was used to measure the suspension properties of the three optical systems. An iron block guided by a roller bearing in the direction of the air gap (Y direction) was used as an object to be suspended. Proportional differential feedback was used. A capacitance type gap sensor with a resolution of 0.1μm and a bandwidth of 0 Hz to 20 kHz was used to monitor the displacement of the suspended object. The three optical systems depicted in **Figure** 4 were adjusted so that the displacement signals become zero when the suspended object is at the center of the two stator magnets. By setting a suitable feedback gain, stable suspension was confirmed for all of the optical systems. The performance of magnetic suspension are listed in **Table** II.

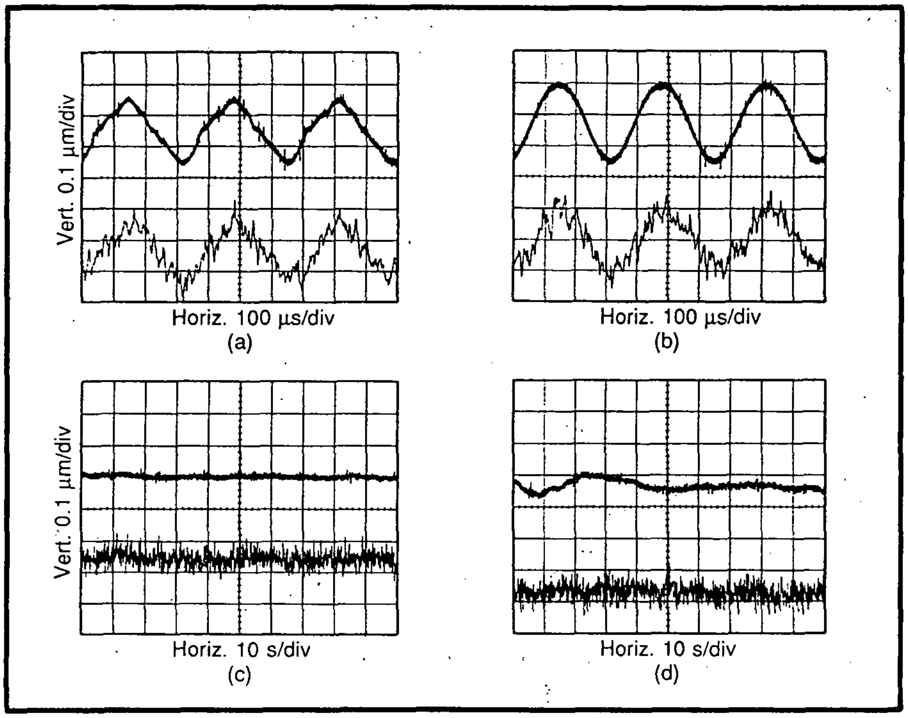

Figure 5. Outputs of a capacitance type gap sensor and a two segment photodiode. Actuation amplitude was 0.1 μm, and the frequency was 3 kHz. (a) triangular wave, beam path 200 mm, in thermally insulated box, (b) sine wave, ligth path 200 mm, in insulated box, (c) no actuation, beam path 200 mm, in insulated box, (d) no actuation, ligth path 1500 mm, insulation of light path with a cardboard tube.

Table II. Performance of one degree of freedom magnetic suspension apparatus for three types of optical designs. Suspension accuracy was measured in air, in a thermally insulated box. Gap fluctuation was measured by placing a hand as a heat source near the laser path. Mass of the suspended object was 0.4 kg, and mean air gap was 0.3 mm. The distance between the laser source and the reflector or detector was 200 mm.

	Type I	Type II		Type III
photodetector	Lateral effect photodiode	Lateral effect photodiode	Multi-segment photodiode	single cell photodiode
suspension accuracy (p-p)	2 μm	2 μm	0.3 μm	0.3 μm
gap fluctuation (p-p) (when disturbed by heat)	10 μm	10 μm	5 μm	5 μm
suspension stiffness	1 N/μm	1 N/μm	5 N/μm	3 N/μm

Suspension accuracy was measured by placing the apparatus in a thermally insulated box to decrease the effect of air turbulence. Fluctuation of air gap was measured by placing a hand as a heat source near the laser path. It was observed that the systems using lateral effect photodiodes were more susceptible to air turbulence. The suspension performance of **Types** I and II using the same photodetector are equal, implying that suspension performance is mainly determined by the performance of the photodetector. The following can be concluded from the experiment:(i) Multi-segment photodiode is a better choice over the lateral effect photodiode from the viewpoint of stability and suspension stiffness; and, (ii) suspension performances were comparable or better than those using conventional gap sensors.

DESIGN OF A LINEAR CONVEYOR SYSTEM

In this Chapter, an example of an optical system for magnetic suspension of a linear conveyor system is introduced. First, the merits and demerits of the three optical designs are discussed, and then, the optical system for control of a linear conveyor is introduced. The apparatus is currently under preparation.

Comparison of three optical systems

The merits and demerits of the three optical systems are listed in **Table** III and **Table** IV. From **Table** III and **Table** IV, a simple guideline for choice of optical systems can be drawn as follows:

(i) For stable suspension accuracy throughout the guiding span of the linear conveyor, **Type** I and **Type** III is the better choice.

(ii) For elimination of wiring to the slider, **Type** II and **Type** III should be used.

(iii) The use of corner cubes in **Type** II ensures return of the reflected beam to the photodetectors.

(iv) For simplicity of structure, the use of corner cubes for **Type** II is a good choice.

Table III. Merits of the three types of optical systems.

	Merits
Type I	**High suspension accuracy determined by the straight propagation of the laser beam can be expected.**
Type II	**Requires no wiring to the moving slider.**
	Use of corner cubes for reflectors enables detection of displacements in two directions from a single laser beam.
	Use of corner cubes for reflectors makes possible measurement of translational movements of the slider without interference from rotational motions.
	Simple in structure.
Type III	**Requires no wiring to the moving slider.**
	High suspension accuracy throughout the moveable span of the slider can be expected.

Table IV. Demerits of the three types of optical systems.

	Demerits
Type I	Requires wiring or wireless transmission of the gap signal to the stator side.
Type II	Suspension accuracy is limited by the parallelism of the incident and the reflected beams, which is determined by the precision of the prisms.
Type III	When right angle prisms are used, translational displacement in only one direction is measureable from one laser beam.

Optical design for a linear conveyor system

An example of an optical system based on **Type** II for magnetic suspension of a linear conveyor system is introduced. Experiments have not yet been made with the apparatus.

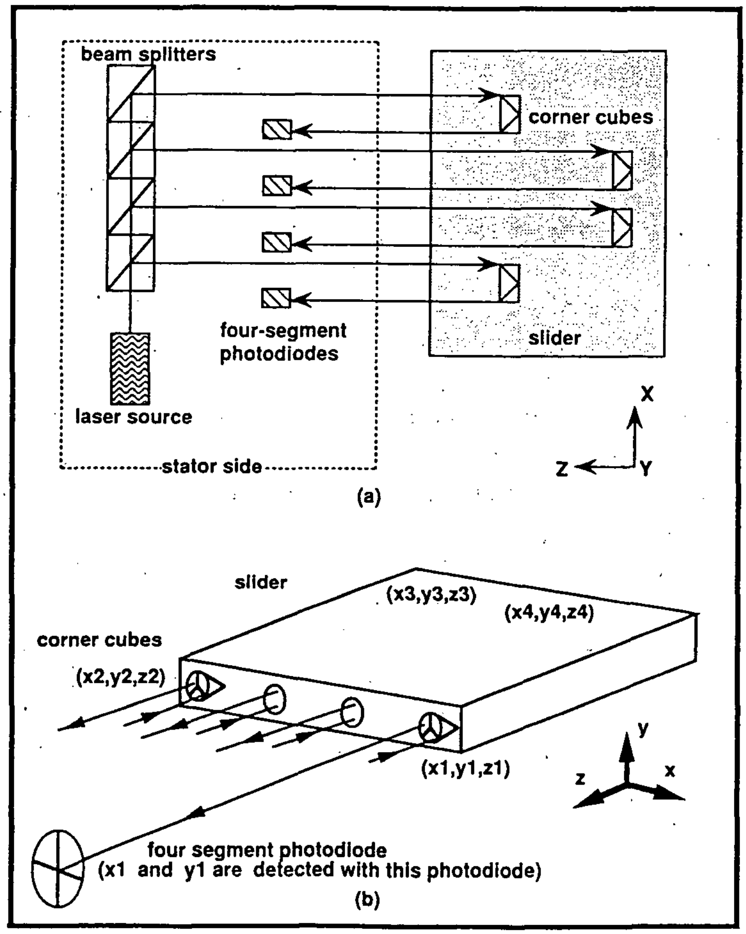

Figure 6. (a) Top view of the optical design for measurement of air gaps of a linear conveyor system. (b) schematic view of the optical design. Parallel translation of the returning beams correspond to the displacement of the corner cubes in the X and Y directions. Therefore, by placing more than three corner cubes on the slider, it is possible to calculate all freedom of motions of the slider except the Z coordinate.

Figure 6 depict the configurations of the optical system. A beam from a laser source is split into four parallel beams by beam splitters. The parallel beams are each reflected by four corner cubes attached to the corners of a slider. The reflected beam is parallel to the incident beam. Translational movement of the corner cubes in the X and Y directions result in parallel displacement of the reflected laser. Therefore, by placing four-segment photodiodes on the axes of the returning laser beams, it is possible to measure all degrees of freedom of the slider except the Z coordinate. As mentioned before, the displacement signals in the X and Y directions are not affected by the rotational movements of the slider, which means that attitudes of the slider can easily be calculated from addition and subtraction of the sensor outputs.

The design depicted in **Figure** 6 is simple and space saving. However, the accuracy of suspension is limited by the parallelism of the incident and the reflected beams. Suspension error will increase as the slider moves away from the photodetectors in the Z direction. If high suspension accuracy is required throughout the movable span of the slider, such as in the case of XY positioning table for semiconductor processing, an optical design based on **Type** III should be adopted.

CONCLUSIONS

A basic idea of using laser beams as a plane reference for measurement of air gaps of linear magnetic suspension systems was introduced. Three optical systems for measurement of slider displacements were designed. By using a one degree of freedom apparatus, it was confirmed that magnetic suspension control is possible for all three optical designs. Magnetic suspension control using single cell lateral effect photodiodes were found to be susceptible to air turbulence compared to multi-segment photodiodes. The best suspension data confirmed with the one degree of freedom apparatus was suspension accuracy of 0.3 μm (in air, in thermally insulated box), suspension stiffness 5 N/μm, and gap fluctuation of about 5 μm (in air, when disturbed by placing a hand near the laser path). Merits and demerits of the three optical systems were discussed, and then, an example of an optical system for control of a linear conveyor system was introduced. The merits of magnetic suspension using laser beams are : (i) high accuracy of magnetic suspension throughout the movable span of a linear conveyor system; (ii) super clean to be used in ultrahigh vacuum and clean chambers; (iii) simple and compact design both for stator and slider; (iv) elimination of wiring to the moving slider; (v) simple wiring of the stator side; and (vi) robustness against electromagnetic noise.

The use of laser beams need not be limited to control of linear magnetic suspension mechanisms. Its merits can also be applied to such examples as: air gap measurement for rotary magnetic bearings with large air gaps; remote control of actuators by moving the laser; and, magnetic bearing with high electrical isolation. We expect the technique to be used in wide field of applications.

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