Development of a mover having one nanometer precision and 4mm moving range

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In order to have an experience on movers having a nanometer precision, a mover has been fabricated and its performance is tested. In the ILC, range of about 1mm is required to cure the long term drift of the tunnel floor and precision of some nanometers is required during the beam operation in IR (Interaction Region). To achieve these range and precision, the mover has two stages, coarse mover stage and precision one. The coarse mover stage is a cam mover type which has a moving range of 4mm and a precision of 0.1 micrometers. The precision mover utilizes piezoelectric transducers which have a moving range of 0.4 micrometers and 1 nanometer precision. Results of performance test are presented.

1. INTRODUCTION

Since the beam size at the ILC IR is expected to be an order of a few nm, nanometer level stability of magnet position is required in the IR.

In order to achieve such stability, a mover with piezoelectric transducers is developed. But since the movement range of piezoelectric device is only about 0.4μm, a mover utilizing cam mechanism is attached to have a movement range as wide as 4.5mm. With such wide movement range, a long term drift of the tunnel floor can be cured remotely. Since the response time of piezoelectric device is quick, the ground vibration can be cured up to some tens of Hz by having a fast enough input from vibration or displacement sensors. This feature is important because the amplitude of ground vibration becomes smaller as frequency goes higher. It is reported that the amplitude is less than one nanometer around the frequency 20Hz in ILC site candidate areas [1]. Our destination is to cancel the vibration up to the frequency 30Hz.

2. SPECIFICATION

	CAM mover	Piezo mover
Movement range	> 3mm	> 0.4μm
Resolution	0.1μm	1nm
Speed	> 0.1 mm/sec at max.	> 0.5 μm/sec
Direction of Motion	X, Vand θy	X, Y, V and θx, θy, θv

(X and Y are horizontal directions, and V is vertical. X is perpendicular to the beam and Y along the beam.)

- The mass of the mover is about 350kg.
- The material is SUS303.
- The load limit is about 700kg.

3. MECHANICAL STRUCTURE

Fig.1 shows the picture of the mover. The structure of the mover is shown in Fig.2. The mover can be divided into two stages, cam mover part in bottom and piezo mover part on top. The cam mover is for rough adjustment in X direction (horizontal direction perpendicular to the beam axis) and vertical direction. The piezo mover can adjust the position in three directions and three angles around. High response speed of the piezo mover enables the mover to cancel the vibration caused by floor movement.

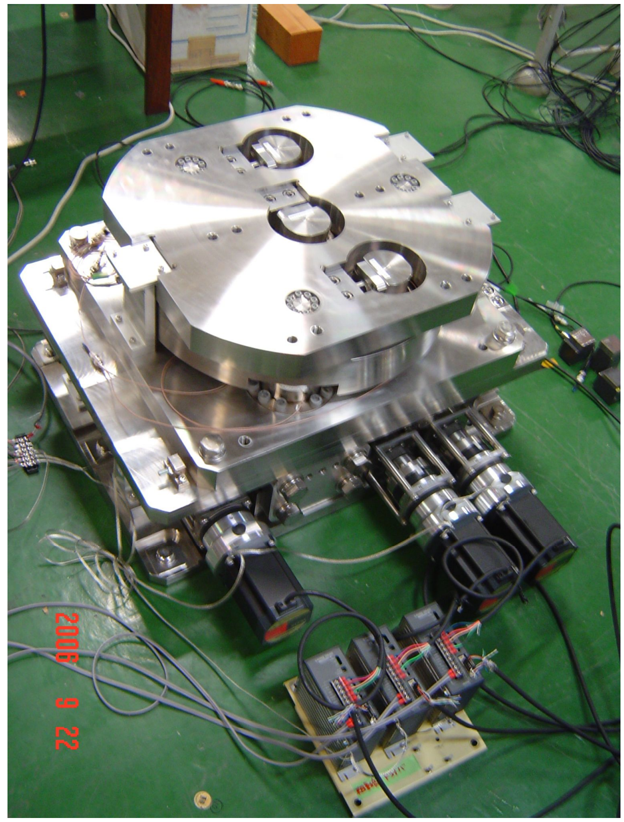


Figure 1: Picture of the mover

3.1. CAM mover stage

Three rotating shafts are driven by stepping motors. Another short shaft structures are inserted in each rotating shaft in two places with an offset by 1.6mm between each central axis in order to have a CAM structure. Two arms are connected to the CAM shafts at one end through bar bearings, and support the piezo-stage through bar bearings at the other end. Arms connected to the shaft (shaft-1) support one end of the piezo-stage, and arms connected to the shafts (shaft-2 and shaft-3) support the same another end of the stage as shown in Fig.2. With this structure people can move the piezo-stage in one horizontal direction and vertical direction as well by rotating three shafts.

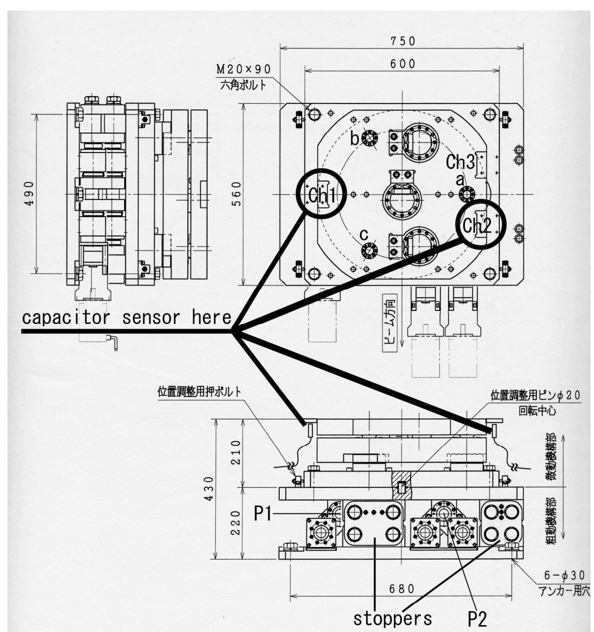


Figure 2: Structure of the mover

3.2. Piezoelectric mover stage

The schematic drawing for the piezo-mover stage is shown in Fig.3. The piezo-mover stage is divided into two parts, bottom part (A-part) and top part (B-part). The A-part adjusts the vertical position and the B-part horizontal position. Detailed structure is shown in Fig.4.

Vertically adjusting piezoelectric transducers in the A-part are placed in a, b and c points in Fig.3. Piezo-transducers push the B-part table according to applied voltages and the B-part table moves vertically owing to the spring structure in the piezo-holders as shown in Fig.4.

Horizontally adjusting piezoelectric transducers in the B-part are placed in d, e and f points in Fig.3. The transducer at d point pushes the top table in Y direction (beam direction), and those at e and f points in X direction. The top table moves horizontally owing to the horizontal springs as shown in Fig.4.

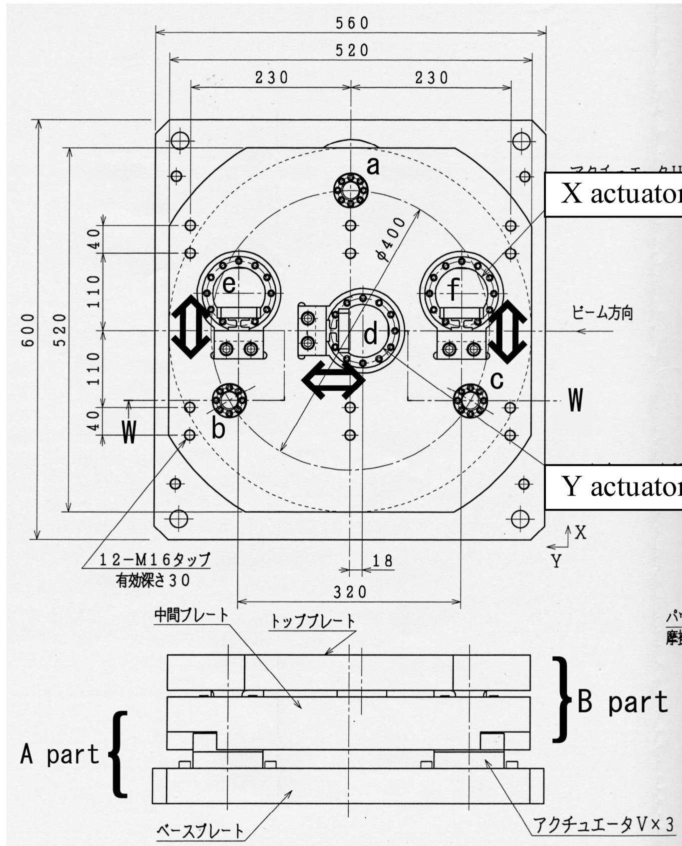


Figure 3: Structure for the piezo-stage

4. MEASUREMENTS

4.1. CAM motion

Fig.5 shows how the CAM stage moves schematically. The motion of points P1 and P2 are derived by solving the following equations, where (x1, y1) and (x2, y2) are the coordinates for P1 and P2.The definitions of other parameters are shown in Fig.5.

$$(x_1-r\cdot\cos\theta_1+D)^2+(y_1-r\cdot\sin\theta_1-h)^2=l^2 \quad (1)$$

$$(x_2-r\cdot\cos\theta_2-D)^2+(y_2-r\cdot\sin\theta_2-h)^2=l^2 \quad (2)$$

$$(x_2-r\cdot\cos\theta_3-D-d)^2+(y_2-r\cdot\sin\theta_3-h)^2=l^2 \quad (3)$$

$$(x_2-x_1)^2+(y_2-y_1)^2=4D^2 \quad (4)$$

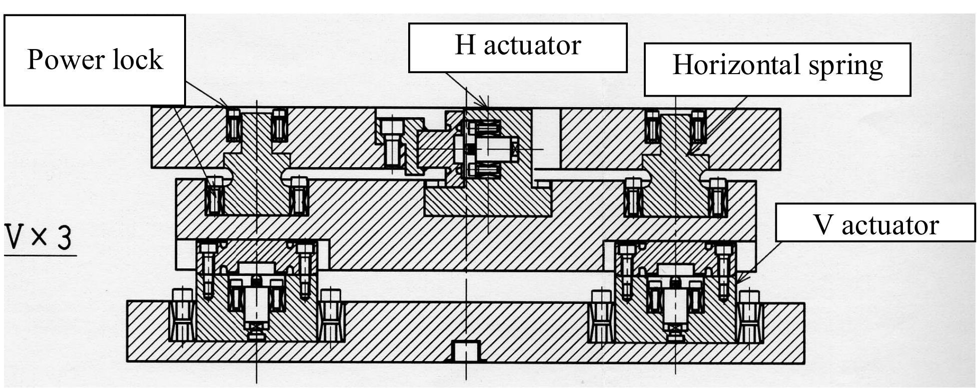


Figure 4: Cross section of the Piezo-stage along the line W in Fig.3

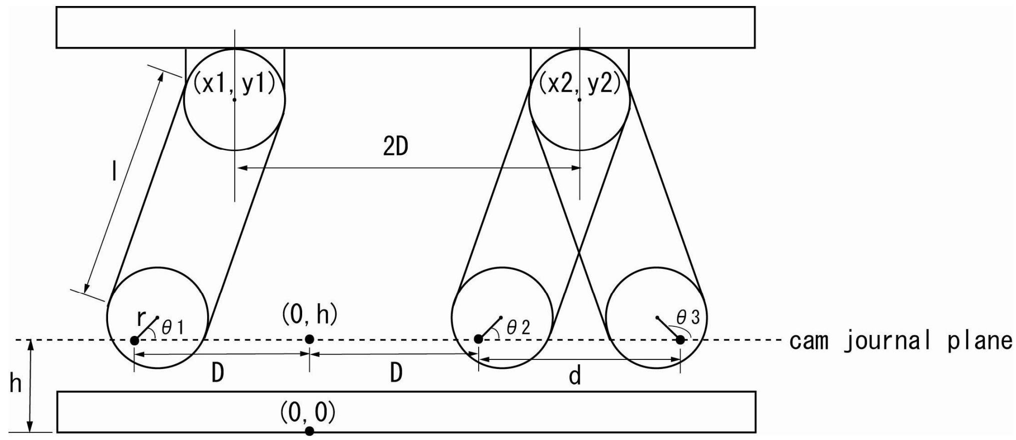


Figure 5: Structure for the CAM mover stage

Some samples of movement of the CAM stage are shown in Fig.6. Fig.6A shows the movement of P1 and P2 when θ1 is fixed to zero degree, θ2 is rotated anti-clockwise from 0 degree and θ3 clockwise from 180 degree at the same speed. In Fig.6B, θ1 and θ3 are fixed to zero degree and only θ2 is rotated. The slope of the table is measured and results are compared with the calculation in Fig. 7. Fig.7A and 7B show the results when the CAM shafts are rotated as in Fig.6A and 6B respectively. In these plots, measurement results are shown by "+" marks and the calculation by solid lines. Measurement and calculation show good agreement each other.

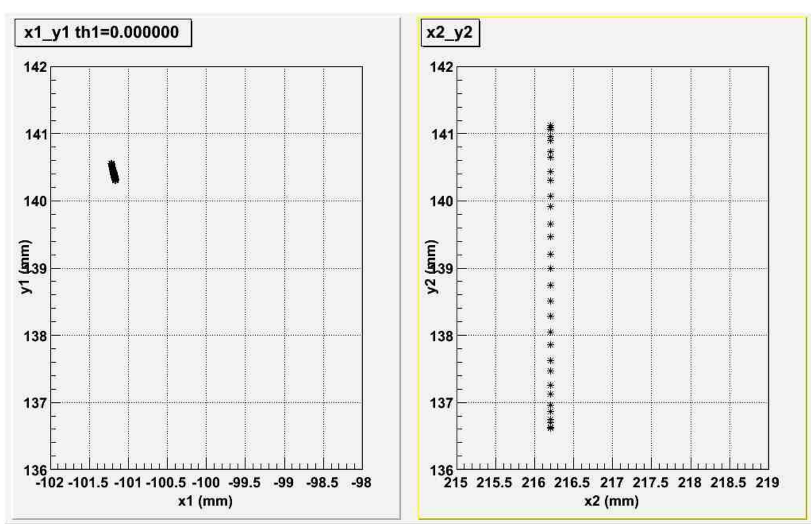


Figure 6A: Motion of P1 and P2 when θ1 is fixed to zero, θ2 is rotated anti-clock wise from 0 degree and θ3 clock wise from 180 degree at the same speed.

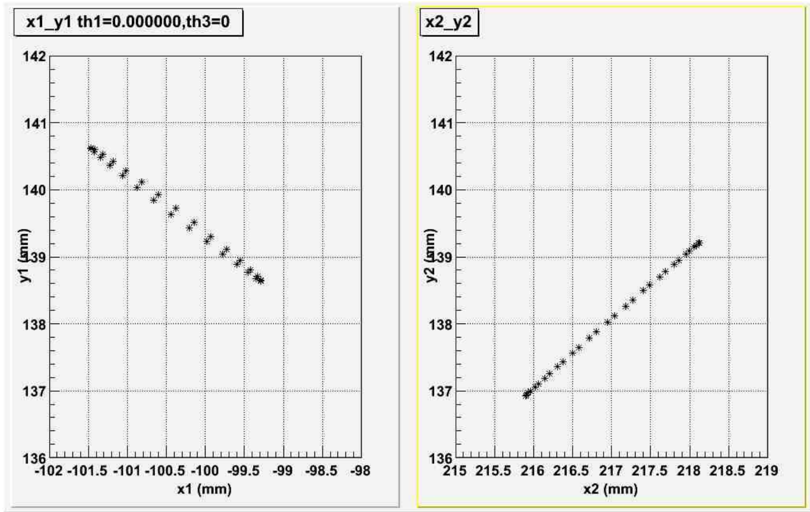
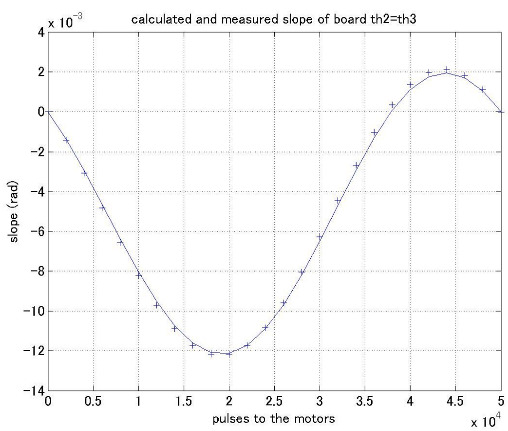


Figure 6B: Motion of P1 and P2 when θ1 and θ3 are fixed to zero degree and only θ2 is rotated



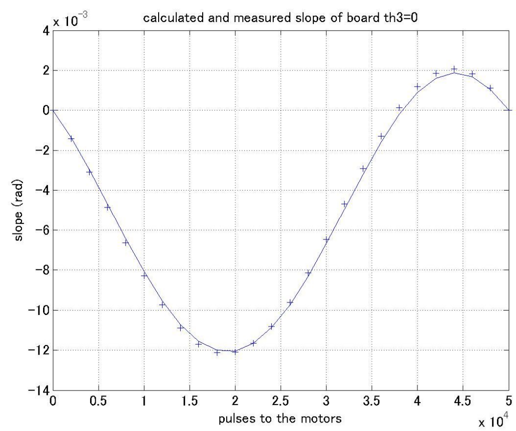
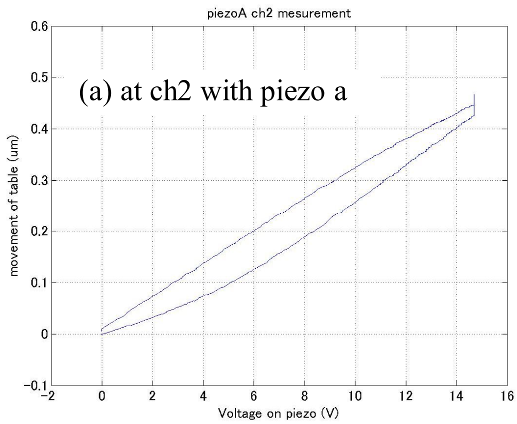


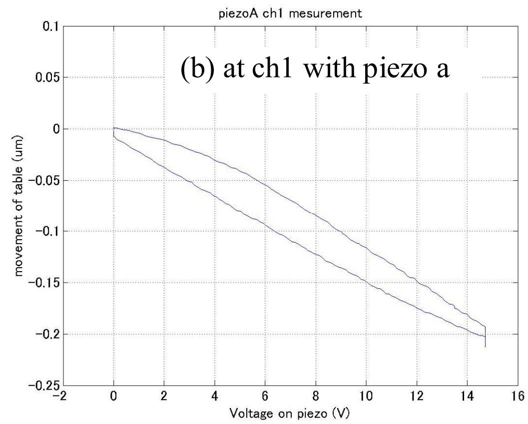
Figure 7A: Variation of the slope of the table for the CAM shaft rotation as in Fig.6A. Measurement results are shown by "+" marks and calculation by solid line.

Figure 7B: Variation of the slope of the table for the CAM shaft rotation as in Fig.6B.

4.2. Piezo motion

Vertical movement of the table was measured with a capacitance type displacement sensor as an excitation of one of the piezoelectric transducers was being changed. The displacement sensor was fixed on the CAM table and the electrode on the piezo table. Sensitivity of the sensor is 0.1V/μm. Results are shown in Fig.8. Movement was measured at the position "ch2" in Fig.8 (a) and in "ch1" in Fig.8 (b) and (c), where the positions "ch1" and "ch2" are shown in Fig.2. Excitation of piezo "a" was changed in Fig.8 (a) and (b), and that of piezo "b" was changed in Fig.8(c). The positions "a" and "b" are also shown in Fig.2. Hysteresis of the piezoelectric transducer can be seen in these plots. Because of this hysteresis, several iterations observing output from precision position sensors are necessary in order to adjust the table position with piezoelectric transducers.





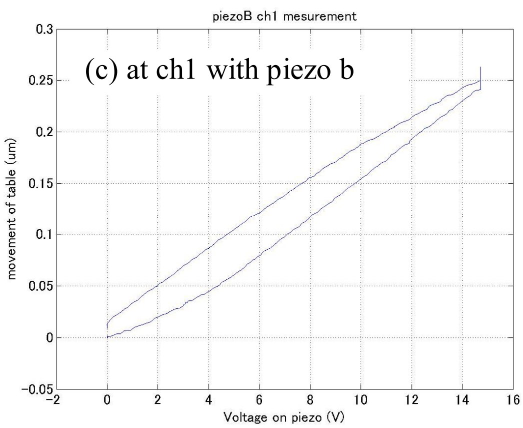


Figure 8: Vertical movement of the table. The displacement sensor is placed (a) at "ch2" and (b, c) at "ch1". Piezo "a" is excited in (a, b) and piezo "b" in (c).

4.3. Piezo resolution

Resolution of a piezoelectric transducer was measured with a capacitance type displacement sensor. The sensor is installed at the position ch2. The noise distribution of the displacement sensor is shown in Fig.9, where no voltage was applied to piezoelectric transducers. It can be seen from this distribution that the noise level of the sensor is about 2.4nm.

Changing the excitation of one of the piezoelectric transducers, data was recorded with the sampling rate 2.54 kHz. Results are shown in Fig. 10. Steps of about 12nm can be seen clearly. Resolution of one or two nm can be expected from this plot.

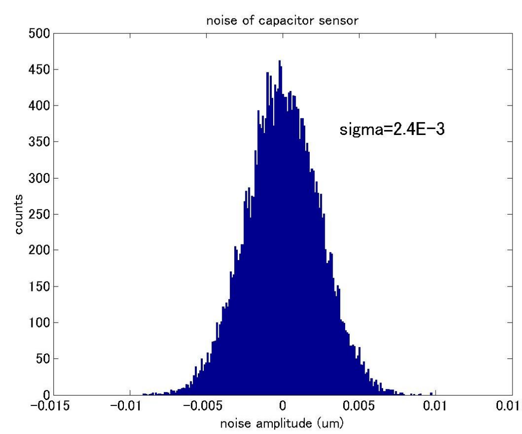


Figure 9: Noise distribution of the displacement sensor

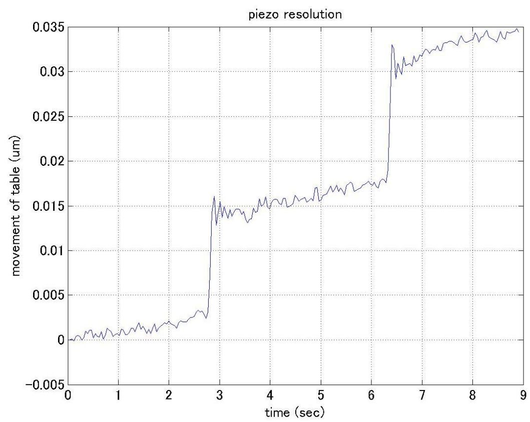


Figure 10: Vertical movement of the table when the applied voltage to the piezo-actuator is changed by 9V.

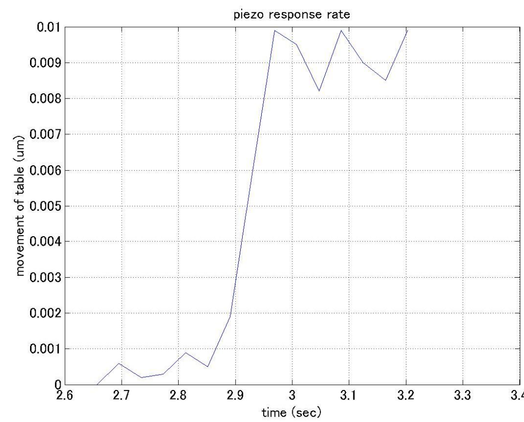


Figure 11: Extended plot of the step in Fig.10

4.4. Response speed of the piezoelectric transducer

Extended plot of the step in Fig.10 is shown in Fig.11. As the step corresponds to the variation of 9V in the voltage applied to the piezoelectric transducer, the response speed is 5.6 V/sec (about 56μm/sec).

4.5. Vibration of the table

In the designing stage, the natural frequency of the table was calculated. It was found that the CAM mover stage was rather soft in this study. The natural frequency was calculated as 45Hz which was close to 30Hz, the aiming speed of the table in the vibration cancellation scheme. So we have decided to install stoppers onto the CAM mover stage. We will release these stoppers only when we do the rough position adjustment. The natural frequency of the whole system was calculated as 84.5Hz. This value is high enough.

The vibration was measured with acceleration seismometers on the floor and on the table at the same time. The measurements were performed with and without stoppers. The place for stoppers is shown in Fig.2. PSD (Power Spectrum Density) is shown in Fig.12 for the case without stoppers and in Fig.13 for the case with stoppers. In these figures, (a) shows PSD for the movement in X direction (horizontal direction) and (b) for PSD for that in vertical direction, and blue curves stand for the movement on the floor and red ones for that on the table. It can be seen that the peaks around 30, 50 and 60Hz in Fig.12(a) shift to 65Hz or higher in Fig.13(a), and the peaks around 50 and 60Hz in Fig.12(b) shift to the frequency region higher than 100Hz in Fig.13(b). It is interesting that the vibration is damped on the table in the frequency region higher than 100Hz when the stoppers are released. This is thought to be caused by comparatively soft spring characteristics of the table without stoppers.

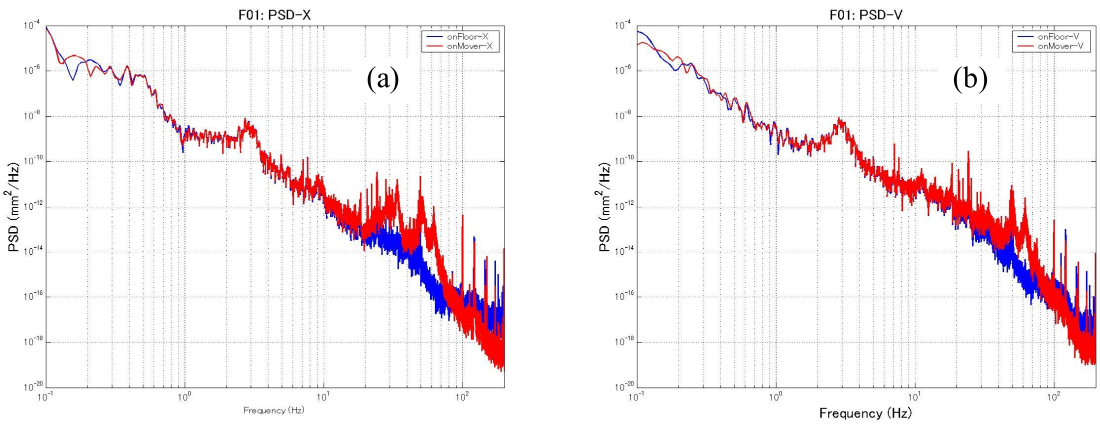


Figure 12: PSD for the vibration on the floor (blue curve) and on the table (red curve) without stoppers. (a) shows the PSD for the movement in X direction (horizontal direction) and (b) for that in vertical direction.

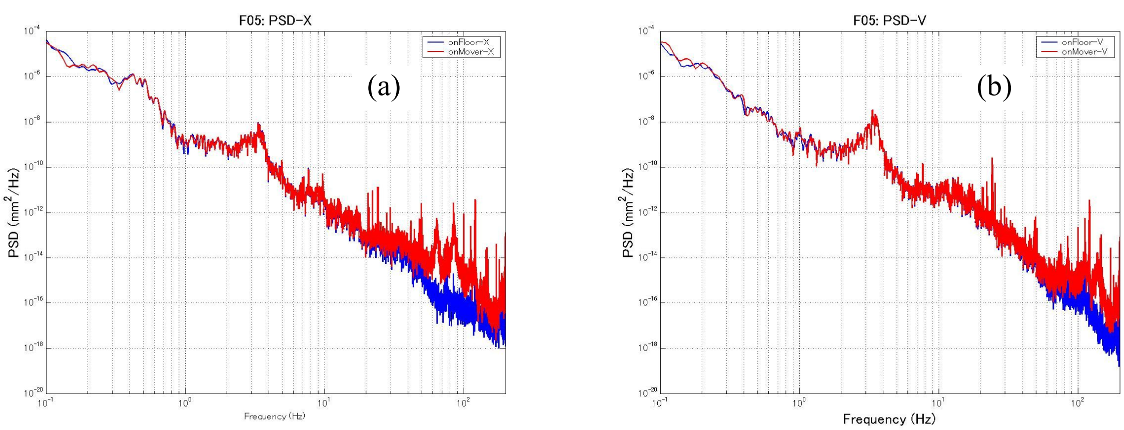


Figure 13: PSD for the vibration on the floor (blue curve) and on the table (red curve) with stoppers. (a) shows the PSD for the movement in X direction and (b) for that in vertical direction.

SUMMARY

Following results are derived.

- The movement range of 4.5mm was measured.
- As a step of 12nm was clearly observed, position resolution of about 1nm can be expected. Further study is needed.
- Response speed of a piezoelectric transducer was measured to be 5.6mV/sec (about 56μm/sec).
- Natural frequency of the mover system is 60Hz or higher with stoppers installed in CAM mover stage.

The performance of the mover was tested with capacitance type displacement sensors. But we could not measure the precision of the movement because these displacement sensors had rather big drift. We are developing a Michelson-Morley and Fabry-Perot laser interferometer system as a position sensor. Further study will be done with this new position sensor.

Also we are planning to develop a vibration cancellation system. Feedback or feedforward system will be developed to cancel the vibration transferred from the floor. Variation of the position of the magnet support table will be measured by Fabry-Perot laser interferometer system, and the displacement measured will be eliminated by piezo-actuators. In this way, we are planning to cancel the vibration of the mover table. As the response speed of piezo-actuators is high, the vibration cancellation can be expected up to about 30Hz, where the amplitude of the ground motion is less than 1nm in ILC candidate sites in Japan.

Acknowledgements

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References

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