Discussion on vibration isolation and suppression performance of pneumatic and piezoelectric active vibration isolators

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Abstract

Pneumatic vibration isolator has a soft spring, and by combining with active vibration isolation control technology, precision equipment can be isolated from floor vibration in a wide frequency range. Although there is argument to point out the deterioration of the vibration isolation performance by the effect of the coupling of the natural mode, when two pneumatic vibration isolators are placed in a stack, the deterioration can be appropriately eliminated by the control technology, and as a result, the vibration isolation performance can be further strengthened. In addition, there are advantages such as superiority in position and attitude maintenance performance with respect to the unbalanced load on the isolator compared with the piezoelectric vibration isolator. Therefore the pneumatic active vibration isolator is a useful device for a variety of installation conditions. This paper describes the characteristic of pneumatic and piezoelectric vibration isolator, which are typical active vibration isolators, together with simulation results.

1. Introduction

Pneumatic active vibration isolator is widely used as a device for isolating precision equipment from floor vibration. The vibration transmission through the pneumatic mounts is quite small in a high frequency range and vibration in a low frequency range is isolated by active control. As a result, pneumatic active vibration isolator can remove floor vibration in wide frequency range.

If the pneumatic active vibration isolator is installed under a pneumatic passive vibration isolator, its vibration isolation performance is further strengthened. There exists an argument to point out the deterioration of vibration isolation performance due to the coupling of natural modes when two pneumatic vibration isolators with close natural frequencies are placed in a stack. However, the deterioration can be reduced to negligible level by Tokkyokiki control technology.

Moreover, this paper deals with the vibration suppressing performance against direct disturbances, which are sound noise, air flow and stage moving, etc., applied on active vibration isolator. Pneumatic active vibration isolator can quickly suppress its vibration by its active control. The piezoelectric active vibration isolator, which is listed as another typical active vibration isolator, has superior suppression performance to pneumatic type for the disturbances below its natural frequency, while the suppression performance near the natural frequency is significantly deteriorated. In addition, the piezoelectric active vibration isolator cannot correct the tilt by the unbalanced load on the isolator.

Let’s consider the vibration isolation control in a high frequency range. Since the pneumatic active vibration isolator can utilize the physical property of its soft spring, the control force for the vibration isolation is almost unneeded in a high frequency range. On the other hand, since the piezoelectric active vibration isolator has harder spring than that of pneumatic type, much more control force is required in comparison with the pneumatic type in order to obtain the comparable vibration isolation performance to the pneumatic type. In a high frequency range, there exist plural elastic modes in both installation floor and mounted equipment, and the elastic modes are easily excited by active control force. Therefore, the piezoelectric active vibration isolator, whose vibration isolation performance in the high frequency range depends largely on the active control force, is affected by the elastic mode of the installation floor and the mounted equipment, and the vibration isolation performance can easily be deteriorated.

As described above, the pneumatic active vibration isolator of Tokkyokiki has many excellent advantages compared with the piezoelectric active vibration isolator by its active control method, and the isolator is widely applied in various installation condition. In this paper, the differences between pneumatic and piezoelectric vibration isolator, based on its structure and the control system, are described in detail with simulation results.

2. Tokkyokiki's concept of pneumatic active vibration isolation system

2.1. Structure and control method of pneumatic active vibration isolator

Fig. 1 shows a schematic diagram of the pneumatic active vibration isolator of Tokkyokiki. The vibration isolation control is performed while keeping the position and attitude of the load constant by acceleration and displacement sensors embedded inside the vibration isolator. In addition, the coordinate control system is introduced by Tokkyokiki. As shown in Fig. 2, this is a system in which the sensor measurement values of each vibration isolation unit are converted into the translation and rotation movement on the whole load on the vibration isolator, and the control is carried out for each degree of freedom. By this technique, it becomes possible to control translation and rotation direction separately. As shown in Fig. 3, it is possible to control to improve the vibration isolation performance by softening the vertical and horizontal directions while keeping the tilt constant by hardening the rotation direction, even if the loading object has at a higher center of gravity.

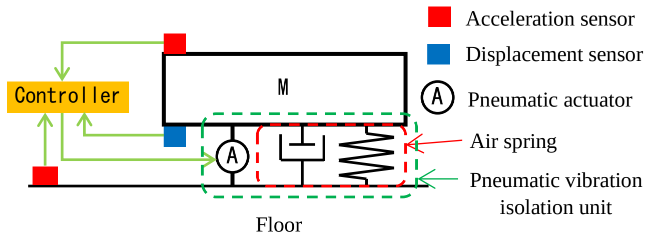

Fig. 1 Tokkyokiki's control method of pneumatic active vibration isolator

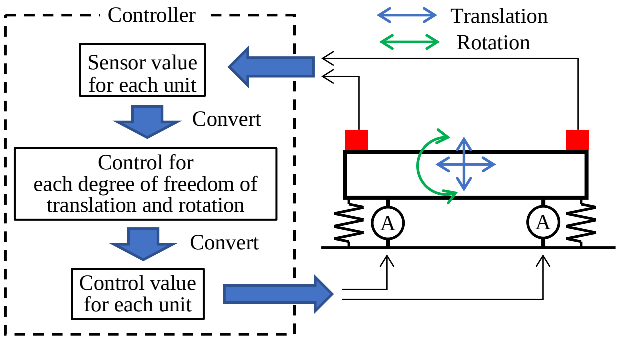

Fig. 2 Control method of Tokkyokiki's pneumatic active vibration isolation system

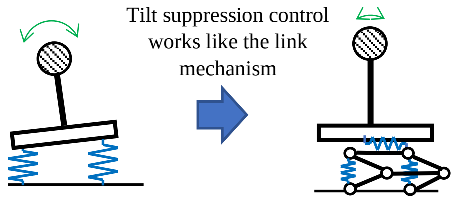

Fig. 3 Image view of tilt suppression control

2.2. Vibration isolation performance for the two pneumatic vibration isolators are stacked (passive and active type).

In this section, it is shown by using a simple one-dimensional simulation that the active control can obtain high vibration isolation performance in wide frequency range even when the pneumatic active vibration isolator is installed under a pneumatic passive isolator whose natural frequency is near value.

Fig. 4 shows a simulation model of the two-stage vibration isolation system. “M1” represents a load supported by the passive vibration isolator built into the mounted equipment, and “M2” represents a frame of the equipment and installation plate (floating table) supported by the lower active vibration isolator. While the pneumatic vibration isolator is controlled by multiple types of sensors as shown in Fig. 1, we will consider only the feedback control from the acceleration signal on the isolator to the actuator for simple consideration of the phenomenon for this case. As the simulation condition, the mass ratio: MR = M2 / M1 is 1.0, the natural frequency of the upper isolator is 1.8 Hz, and the natural frequency of the lower isolator is 2.0 Hz.

Fig. 5 shows the simulation results. The upper side of the figure represents the vibration transfer characteristics from the slab to the upper isolator, and the lower side represents the vibration transfer characteristics from the slab to the lower vibration isolator. According to the figure, while the vibration isolation performance from 1 to 4 Hz is deteriorated due to the coupling of the two natural modes that are close to the two vibration isolators in the passive state where acceleration control is not performed, the deterioration can be avoided appropriately by the active control. As a result, high vibration isolation performance can be achieved in a wide frequency range.

Fig. 6 shows the vibration transfer characteristics from the floor to the upper vibration isolation table when the mass ratio (MR) is changed. When the active vibration isolator is in the passive state, the vibration isolation performance near the natural mode deteriorates with increasing mass ratio, but when the control state is active, the vibration isolation performance does not deteriorate even if the mass ratio increases.

When the simulation model is extended to two or more dimensions, the coupling exists in the degree of freedom of translation and rotation. Therefore, it is difficult to improve the vibration isolation performance by such simple control method alone. However, Tokkyokiki solves this coupling problem by individually controlling the degree of freedom of translation and rotation as described in the previous section.

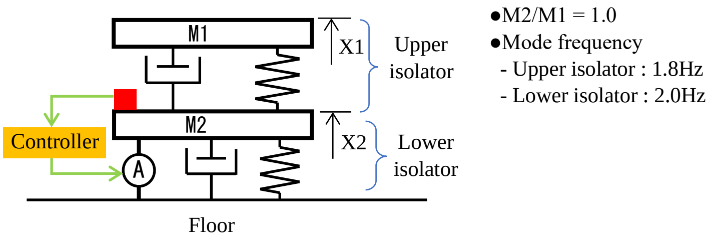

Fig. 4 1D model of two-stage pneumatic vibration isolation system

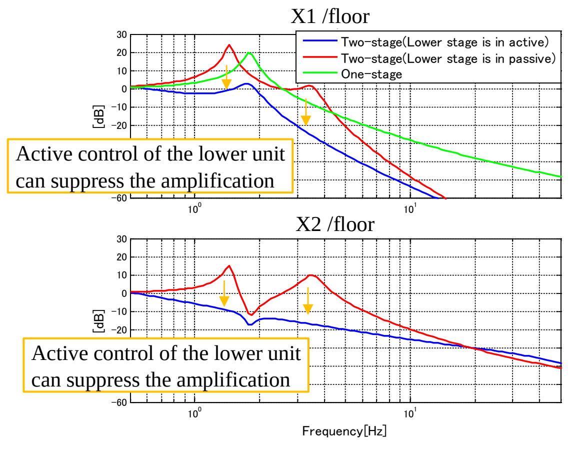

Fig. 5 Vibration isolation performance of two-stage pneumatic vibration isolation system

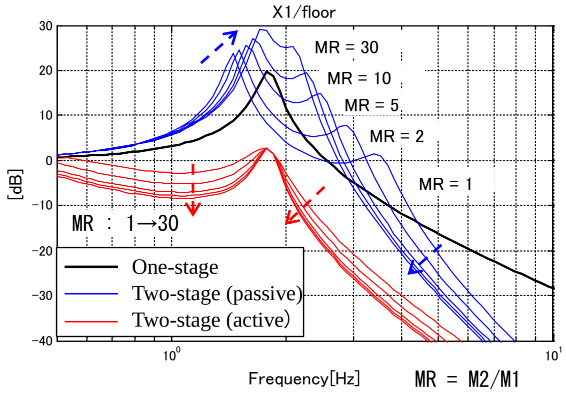

Fig. 6 Vibration isolation performance from floor to X1 when the mass ratio is changed

2.3. Vibration isolation control under 1 Hz

Though vibration isolation control under 1Hz is generally considered to be difficult, one experimental example shows that Tokkyokiki's active vibration isolator can overcome the difficulty, even if the mounted equipment has higher center of gravity, by its control technology.
Fig. 8 shows the vibration isolation performance when an object with high center of gravity is mounted on the pneumatic active vibration isolator which shows in Fig. 7. It can be seen that the natural mode in the passive state exists at 1Hz due to the effect of the high center of gravity, and the vibration around the frequency is amplified, but the active vibration isolation control is possible from 0.4Hz in both horizontal and vertical directions.

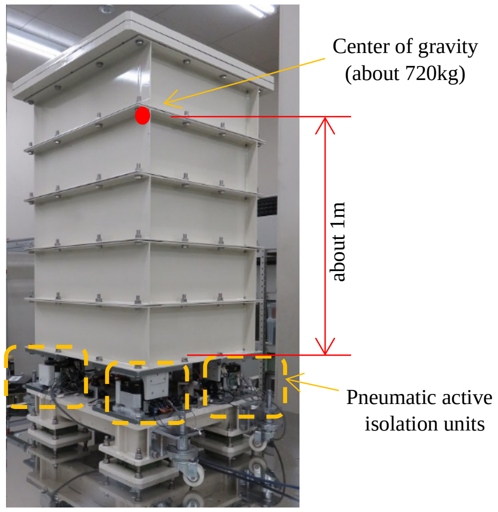

Fig. 7 Vibration isolation control experiment under 1Hz

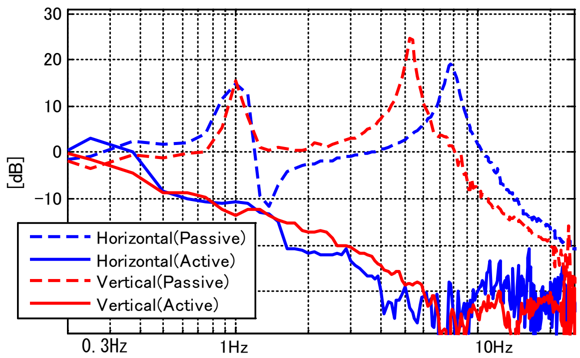

Fig. 8 Vibration isolation performance

3. Overview of piezoelectric active vibration isolator

Fig. 9 shows a schematic diagram of a typical piezoelectric active vibration isolator. In the figure, “M” is the mounted object on the vibration isolator, and “m” is the intermediate mass built in the isolator, which is about several kilograms. An elastomer disposed on “m” and a surface plate and an equipment is installed on the upper part of the elastomer. The natural frequency of the piezoelectric active vibration isolator is several times higher than that of the pneumatic vibration isolator. As an advantage of the high natural frequency, the mounted equipment on the isolator is difficult to tilt even in the case of passive state, as a result, the attitude is easily stabilized. On the other hand, as shown in Fig. 10, strong control force is necessary in high frequency range to achieve the same level of vibration isolation performance as the pneumatic type.
Regarding the control system, feedback control from acceleration or absolute velocity sensor signals on “M” and “m” to piezoelectric actuators can be considered. Since feedback control by the sensor signal on “M” is significantly affected by the elastic mode of the mounted equipment, control becomes difficult and practical application will also be difficult with piezoelectric active vibration isolator in which strong control force is required in high frequency range. On the other hand, the feedback control by the sensor signal on “m” is less susceptible to the elastic mode of the mounted device due to the vibration isolation effect of the elastomer. Actually, feedback control by only the sensor signal on “m” is common as a control system of commercial piezoelectric vibration isolator.

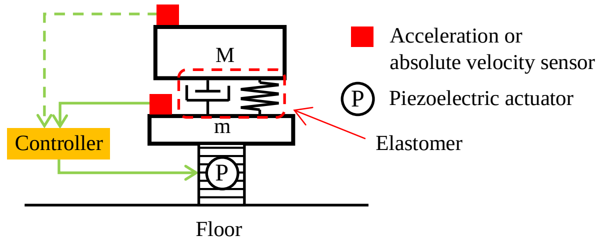

Fig. 9 Schematic diagram of a piezoelectric active vibration isolator

a

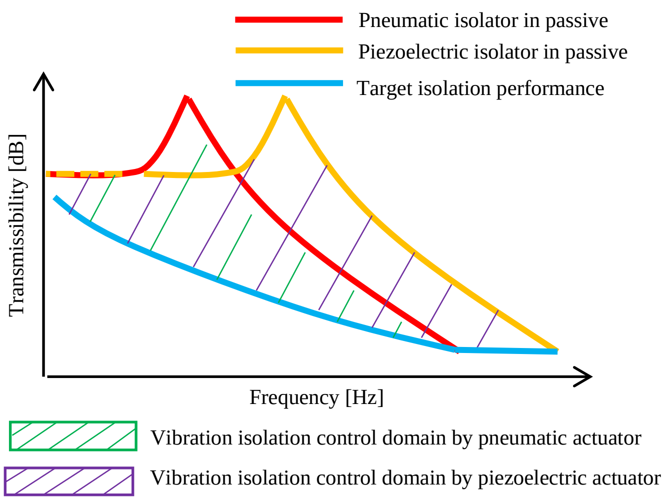

Fig. 10 Frequency domain required for vibration isolation control in each vibration isolator

In addition to the difficulty of control in the high frequency range, the following demerits are pointed out for the general piezoelectric active vibration isolator.

- The suppression performance by the direct disturbance on the isolator largely depends on the physical property of the internal elastomer. In such environment where the disturbance has a frequency element near the natural mode of the vibration isolator, the vibration can easily be amplified.
- The tilt of the mounted equipment due to an unbalanced load on the isolator cannot be corrected by the piezoelectric actuator as shown in Fig. 11. Furthermore, the general elastomer used for the vibration isolation creeps several millimeters in the initial load and several tens to hundred micrometers during several tens to hundred hours usage. When such degree of tilt becomes important, the attention should be paid to the installation of the vibration isolator.

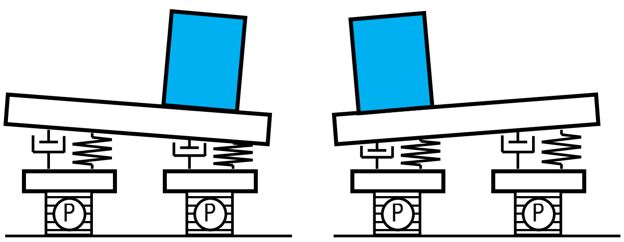

Fig. 11 Equipment tilt on the piezoelectric active vibration isolation system due to an unbalanced load

3.1. Difficulty of high-frequency range vibration isolation control by the active vibration isolator with hard spring

Pneumatic active vibration isolator has high performance of vibration isolation in high frequency range thanks to the physical characteristics of their soft spring. Therefore, no strong control force is required in this frequency range. When the spring is hardened like a piezoelectric active vibration isolator, strong control force is required to obtain the vibration isolation performance comparable to the pneumatic type in the high frequency range.

The strong control force be applied without any problem even in the high frequency range, if the mounted object on the vibration isolator and the installation floor have rigid body. However, in the micro vibration field, both of the mounted object and the floor should be regarded as elastic bodies, and they have many natural vibration modes in the high frequency range. Furthermore, in the view of micro-meter order, there are many gaps between the vibration isolator and the floor, therefore so many elastic modes exist as shown in Fig. 12. It should be noted that those elastic modes caused by the gaps of installation can be reduced or moved to a higher frequency range by improving the floor flatness or fixing the vibration isolator by anchor bolts.

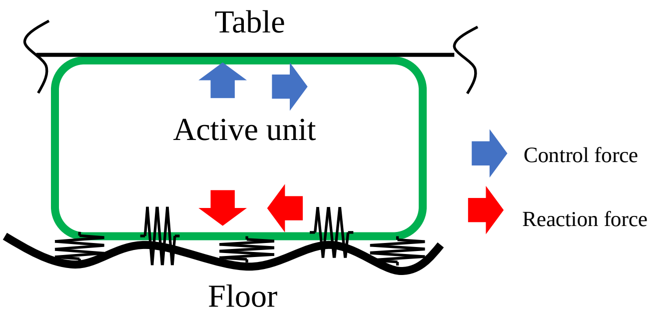

Fig. 12 Installation condition of active vibration isolator and floor in view of the micro-meter order

Fig. 13 shows examples of rigid and elastic modes that are controlled by the vibration isolator. The rigid mode represented by Fig. 13 (a) is the vibration mode when an object on the actuator is regarded as a rigid body, and its shape is simple. The elastic mode represented by Fig. 13 (b), that is the vibration mode when the object on the actuator and the installation floor, etc. are deformed, becomes a complicated shape, and there are many elastic modes in the higher frequency range than the rigid mode.

Because of its simple shape, the rigid mode is observable and vibration is controllable with a limited number of sensors and actuators. Both of the pneumatic and piezoelectric active vibration isolator can control this rigid mode. On the other hand, the elastic mode cannot be observed accurately with a limited number of sensors and actuators, and in many cases, the elastic mode is easily excited by the vibration isolation control as its reverse effect. Therefore, in the high frequency range where multiple elastic modes exist, passive system that does not require control by sensors and actuators but rely only on the physical properties of the springs are easier to obtain high vibration isolation performance. Fig. 14 shows the effect of the elastic mode on the vibration isolation performance. When there is no effect of elastic mode, high vibration isolation performance can be achieved by active control up to high frequency range regardless of eigenvalue of vibration isolator. However, if the effect of the elastic mode is large, the vibration isolation performance deteriorates because the appropriate control is not possible in that frequency range. Especially, the vibration isolator that has hard spring, represented by the piezoelectric active vibration isolator, is greatly affected by the elastic mode, because the strong control force is necessary in the high frequency range.

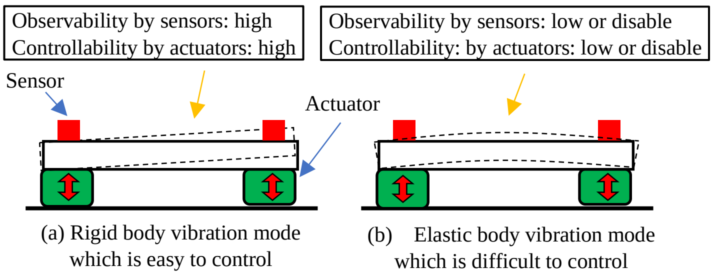

Fig. 13 Differences in the difficulty of control depending on the shape of vibration mode

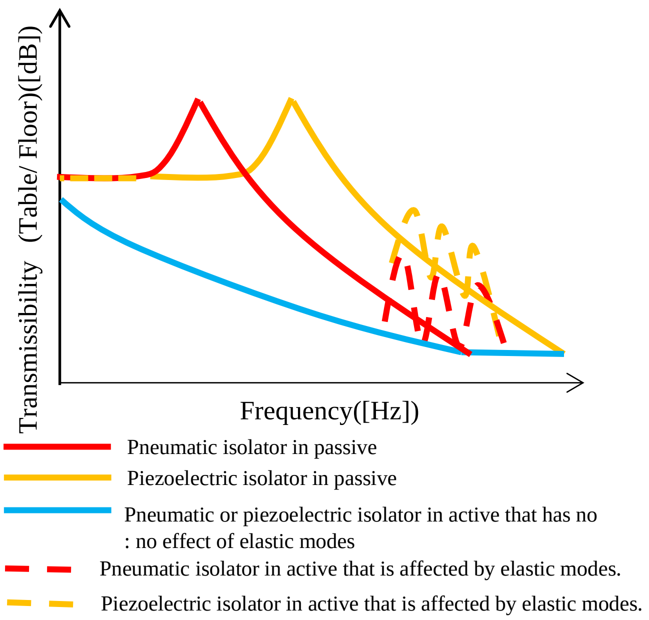

Fig. 14 Effect of elastic mode on vibration isolation performance

4. 2D-simulation of two-stage vibration isolation system

In this section, it is shown by simulation that the two-stage active isolation system, where a high center of gravity equipment with a built-in pneumatic vibration isolation unit is mounted on the pneumatic active vibration isolator, has excellent vibration isolation and vibration suppression performance. The simulation model is extended to two dimensions with degrees of freedom of translation and rotation in order to consider the effect of the high center of gravity load which can be tilted easily. The equipment is assumed to be an object of high center of gravity with built-in pneumatic vibration isolation unit, such as electron microscope. Fig. 15 shows a schematic diagram of the simulation model, and the parameters used in the simulation are in Table 1. The natural frequency of the pneumatic active vibration isolator is 5Hz, assuming a standard unit in Tokkyokiki. Then, the natural frequency of the piezoelectric active vibration isolator used as a comparison object is 15Hz.

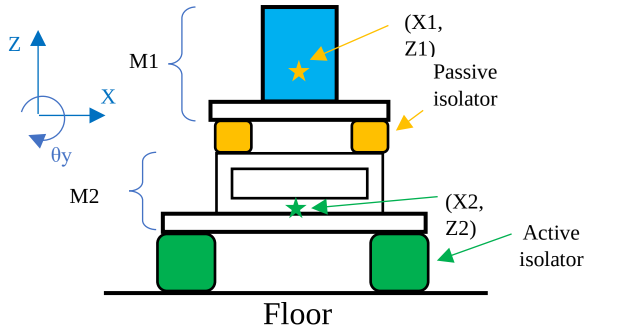

Fig. 15 2D simulation mode of two-stage vibration isolation system

Table 1 Simulation parameter of Fig. 15

		Pneumatic active	Piezoelectric active
Active isolator	Natural frequency*1	5 [Hz]	15 [Hz]
	Damping ratio	0.05	0.15
	Coordinate of each unit	(x, z): (-0.5, -0.1), (-0.5, -0.1) [m]	
Passive isolator	Natural frequency	2 [Hz]	
	Damping ratio	0.1	
	Coordinate of each unit	(x, z): (-0.5, 0.8), (+0.5, 0.8) [m]	
M1	Weight	1000 [kg]	
	Center of gravity	(x, z): (0, +1.0) [m]	
M2	Weight	1000 [kg]	
	Center of gravity	(x, z): (0, -0.05) [m]	
Measurement point (X1, Z1)		(0.0, +1.0) [m]	
Measurement point (X2, Z2)		(0.0, 0.0) [m]	

*1 : Value when assuming that the load on the vibration isolator is a rigid body.

4.1. Vibration isolation performance

Fig. 16 and Fig. 17 show the vibration transfer characteristics from the floor to the load on the passive vibration isolation (X1, Z1) and the table on the active vibration isolator (X2, Z2). Fig. 16 is a result by the pneumatic active vibration isolator and Fig. 17 is a result by the piezoelectric active vibration isolator. The control parameters are tuned to a realistic level so that both of transfer characteristics from the floor to the table on active vibration isolator become comparable.

The reason why the natural frequency of the active vibration isolator for the passive mode (active off) in these figures shows larger values than that of Table 1 is that it is affected by the spring element of passive isolator in the equipment.

From this result, it can be seen that vibration isolator can achieve excellent vibration isolation performance both horizontal (X) and vertical (Z) directions regardless of pneumatic type or piezoelectric type, even if the mounted object on the active vibration isolator has high center of gravity with a built-in pneumatic vibration isolator.

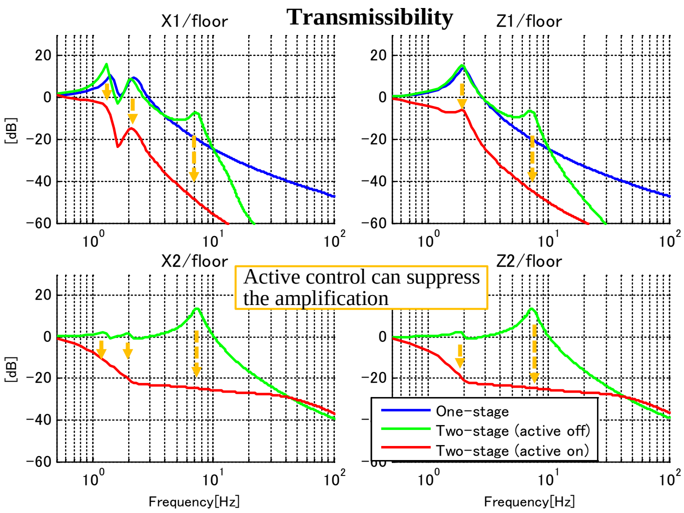

Fig. 16 Vibration isolation performance by two-stage vibration isolation system in the case of the pneumatic active vibration isolator

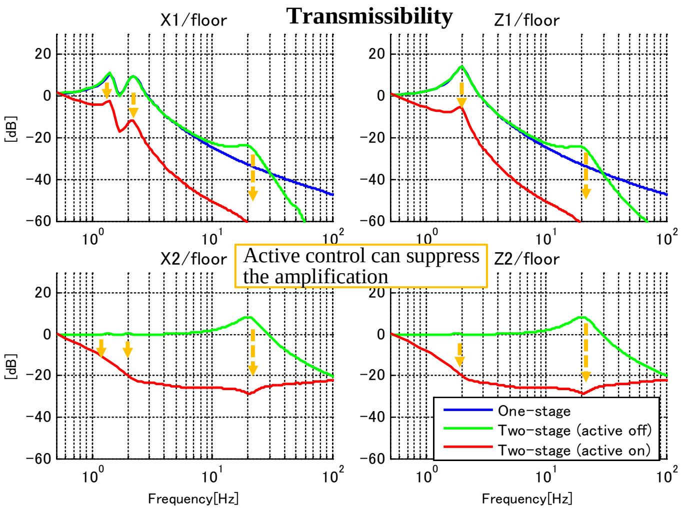

Fig. 17 Vibration isolation performance by two-stage vibration isolation system in the case of the piezoelectric active vibration isolator

4.2. Vibration suppression performance against direct disturbance on the isolator

In the same control status as the previous section, as shown in Fig. 18, the vibration suppression performance when the direct disturbance is input on either the passive vibration isolator or the active vibration isolation table is evaluated by simulation. Rectangular wave with excitation times of 0.1[s] and maximum force of 1[N] is used for the direct disturbance.
The simulation results are shown from Fig. 19 to Fig. 22. Table 2 shows the combination of the positions of direct disturbance and the active vibration isolators in each figure. From Fig. 19 and Fig. 21, it can be seen that the pneumatic active vibration isolator can suppress the effect of direct disturbance promptly by active control. From Fig. 20 and Fig. 22, it can be seen that the suppression performance of the piezoelectric active vibration isolator is almost constant with or without active control. As described in previous section 3, the suppression performance of piezoelectric active isolator against direct disturbance on the isolator depends largely on the physical property of the internal elastomer.

Table 2 Figure number table of simulation result

Direct disturbance	Active vibration isolation system	
	Pneumatic	Piezoelectric
f1	Fig. 19	Fig. 20
f2	Fig. 21	Fig. 22

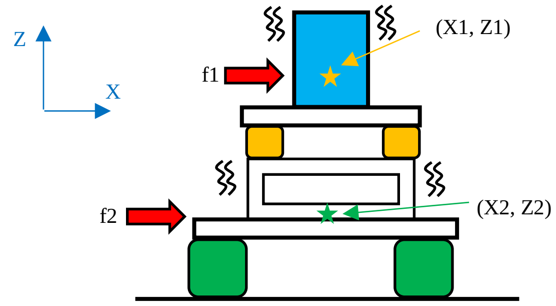

Fig. 18 two-stage vibration isolation system affected by the direct disturbance

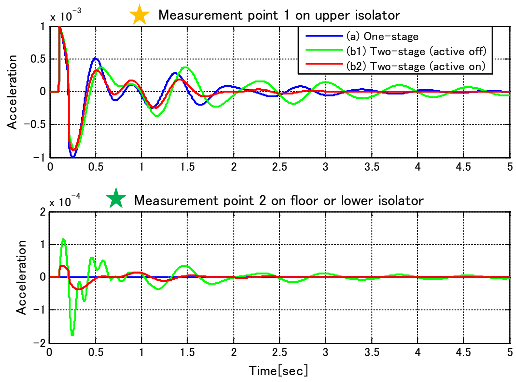

Fig. 19 X direction acceleration when external force f1 is input on the passive isolator in the case of the pneumatic active vibration isolator

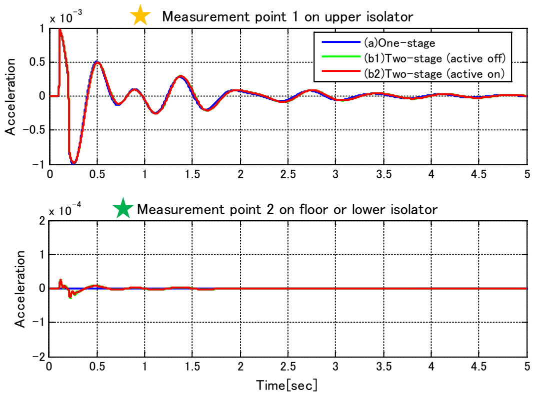

Fig. 20 X direction acceleration when external force f1 is input on the passive isolator in the case of the piezoelectric active vibration isolator

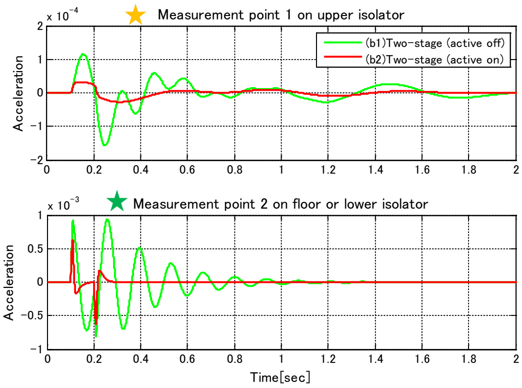

Fig. 21 X direction acceleration when external force f2 is input on the active isolator in the case of the pneumatic active vibration isolator

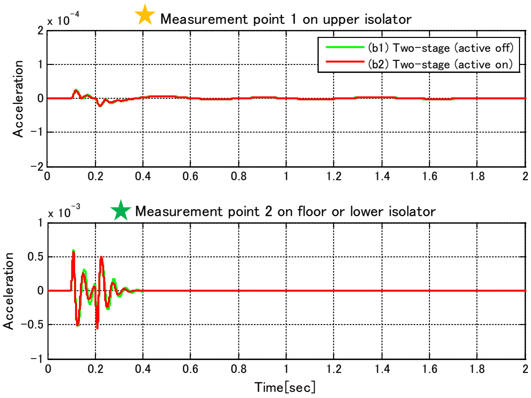

Fig. 22 X direction acceleration when external force f2 is input on the active isolator in the case of the piezoelectric active vibration isolator

5. Vibration Suppression performance when stage moves

In this section, the effect of stage movement on pneumatic and piezoelectric active vibration isolators is compared and evaluated by the two-dimension simulation model. Semiconductor lithography equipment is assumed as mounted equipment. Fig. 23 is a schematic diagram of the simulation model, and Table 3 shows the parameters used in the simulation. In this table, the parameters of the active vibration isolator are same as described in the previous section 4. In addition, the gravity acceleration of the stage is also considered in the modeling to evaluate the amount of tilt caused by the center of gravity change of the loading equipment on the vibration isolator when the stage moves.

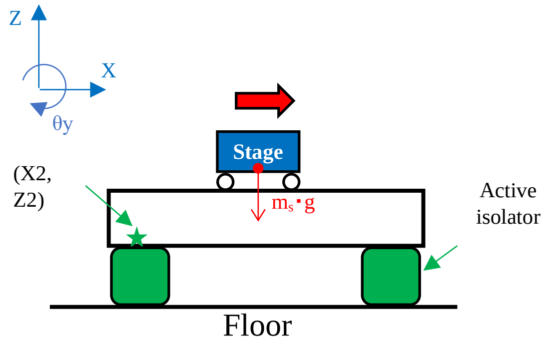

Fig. 23 2D-simulation model of active vibration isolation system when stage moves

Table 3 Simulation parameter of Fig. 23

		Pneumatic active	Piezoelectric active
Active isolator	Natural frequency	5 [Hz]	15 [Hz]
	Damping ratio	0.05	0.15
	Coordinate of each unit	(x, z): (-0.5, -0.1), (-0.5, -0.1) [m]	
Stage	Weight	100 [kg]	
	Center of gravity	z: (0, +0.2) [m]	
	Moving distance	x: +0.5[m] (-0.25 → +0.25 [m])	
	Other conditions	Max. acceleration: 1.96[m/s^2] Max. velocity: 0.2[m/s], Max. jerk: 50[m/s]	
M2	Weight	2000 [kg]	
	Center of gravity	(x, z): (0.0, 0.0) [m]	
Measurement point (X2, Z2)		(-0.5, 0.0) [m]	

Fig. 24 and Fig. 25 show the vibration transfer characteristics from the floor to the table on the active vibration isolator (X2, Z2). Fig. 24 is a result by the pneumatic active isolator, and Fig. 25 is a result by the piezoelectric active isolator. The control parameters are tuned to the realistic level so that the transfer characteristics from the floor to the load on the active vibration isolator are comparable as in section 4.

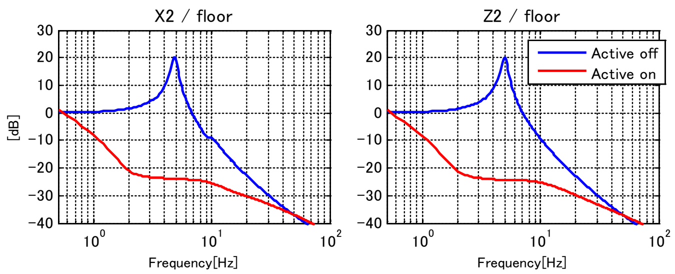

Fig. 24 Vibration isolation performance of stage moving model in the case of the pneumatic active isolator

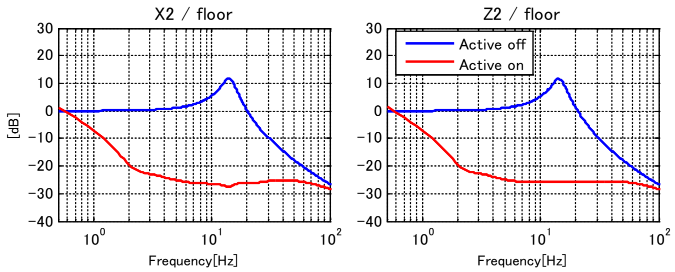

Fig. 25 Vibration isolation performance of stage moving model in the case of the piezoelectric active isolator

The simulation results are shown in **Fig. 26** and **Fig. 27**. **Fig. 26** is by the pneumatic isolator, and **Fig. 27** is a result by the piezoelectric isolator. In these figures, the upper side shows the horizontal acceleration on the vibration isolator, and the lower side shows the vertical displacement. The upper side is used for evaluation of suppression performance, and the lower side is used for evaluation of attitude maintenance performance when the center of gravity of the load changes. From **Fig. 26**, it can be seen that the vibration of the pneumatic vibration isolator when stage moves is quickly suppressed by the control, and the displacement of the load is also quickly restored by the displacement control. Tokkyokiki has the technology of stage feedforward control which uses the velocity and displacement signals of the stage for vibration suppression control, and it is possible to further improve the suppression and the attitude maintenance performance by the stage feedforward control than the result of **Fig. 26**.

From **Fig. 27**, it can be seen that the suppression performance of the piezoelectric active vibration isolator is almost constant with or without active control, and the performance is greatly affected by the natural frequency of the isolator. Moreover, it can be seen that the displacement after the stage movement does not return to before. These reasons are as follows which are described in Section 3.

・The suppression performance against the direct disturbance on the isolator depends largely on the physical property of the internal elastomer.

・The tilt of the mounting equipment due to the unbalanced load on the isolator cannot be returned by the control of the isolator.

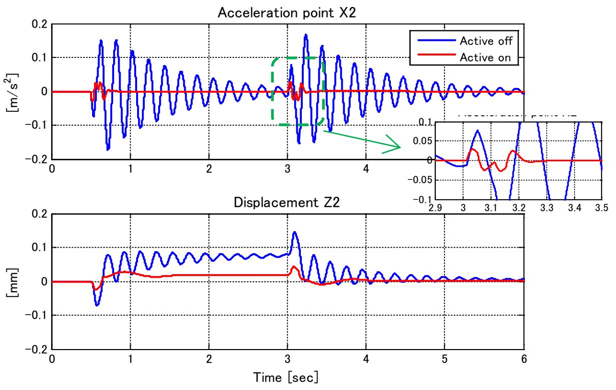

Fig. 26 Acceleration in X direction and displacement in Z direction time response when the stage moves in the case of the pneumatic active vibration isolator

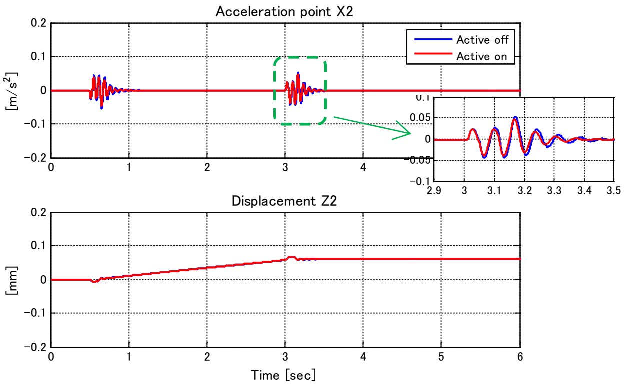

Fig. 27 Acceleration in X direction and displacement in Z direction time response when the stage moves in the case of the piezoelectric active vibration isolator

6. Conclusion

The piezoelectric active vibration isolator has the following restrictions due to structural reasons.

・This isolator specializes in vibration isolation for low to middle frequency range (approximately 2 to 30Hz). Since the elastic mode in the high frequency range is easily excited, it needs to be installed together with a pneumatic vibration isolator which has soft spring.

・It is necessary to consider that the equipment on the isolator may tilt in the order of tens to hundreds of micrometer caused by the creep of the internal elastomer.

・The suppression performance against direct disturbance on the isolator depends largely on the physical property of the internal elastomer. Since the performance is not improved by active control, the vibration caused by the disturbance which has frequency element near the eigenvalue of the isolator will be amplified.

Since the pneumatic active vibration isolator has a soft spring, it has a disadvantage that it is unbalanced without control, but the control technology of Tokkyokiki can sufficiently overcome this disadvantage. Even if the mounted equipment is a passive vibration isolator which has high center of gravity and low eigenvalue, the active isolator is stable and can obtain high vibration isolation performance in wide frequency range without deterioration of vibration isolation performance. It can be said that the pneumatic active vibration isolator is a versatile vibration isolator having wider application range than the piezoelectric active vibration isolator.