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Robust Vibration Control using Superconductor as Levitation Device and Velocity Sensor

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ABSTRACT: *A new method of using a high Tc superconductor as two functions of levitation device and velocity sensor is introduced. The levitated object is controlled with an electromagnet using the measured velocity signal, that is the system involves a hybrid magnetic levitation of superconductor pinning effect and active magnetic bearing. The experimental setup of a single degree-of-freedom system is made using a cantilever beam. A coil is wound around a permanent magnet which is used as a velocity sensor. This coil produces electromotive voltage in proportion to relative velocity. A simple velocity feedback measured by the proposed technique well improves the damping property of the levitated object. However, the vibration isolation property from the base is decreased.*

In order to insulate against vibration from the base and to reduce vibration from external force an H_∞ optimum controller is designed. The accelerlation of the levitated object is also measured and used as well as the relative velocity. The H_∞ controller with two input signals is applied to the experimental setup. The results obtained are showing good vibration reduction and isolation property and indicating good robust stability.

1 Introduction

A high quality YBaCuO superconductor has been developed using a new production process, named Melt-Powder-Melt-Growth (MPMG). This superconductor has merits of big levitation force and high critical temperature (Tc). Hence it is expected for wide application of levitation such as energy storage flywheel and maglev carrier. However, the levitated object has poor damping and the dynamic behavior is very complicated [1].

Magnetically suspended isolation system is considered superior to the conventional spring-damper suspension because it has noncontact support capability. It is expected for clean room and high precision equipment applications [2][3].

This paper introduces a single degree-of-freedom (DOF) vibration isolation system using a high Tc superconductor. The fundamental levitation force is produced by the pinning effect between the superconductor and the permanent magnet. The levitated object, however has a high resonant peak [4]. Active magnetic levitation is incorporated to improve the dynamic property, that is, the system is hybrid levitation of superconductor pinning effect and attractive magnetic force.

A new velocity sensing technique is introduced to control the vibration [5]. The magnetic flux is produced by the permanent magnet and is pinned by the super conductor. This flux will be distorted by the motion of the levitated object. A sensing coil is wound around the permanent magnet. The back-electro-motive voltage is induced which is expected to be proportional to the relative velocity between the levitated object and the foundation. This signal is used to control the dynamic motion of the levitated object.

The relative velocity feedback improves the damping property of the levitated object. However, it affects adversely to the higher frequency isolation. H_∞ controller is designed to improve both damping and isolation properties using two input signals of the relative velocity and the acceleration. The system is simulated on a com-

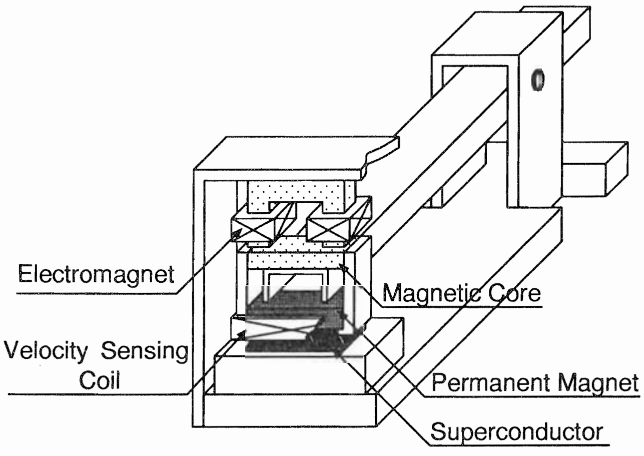

Figure 1: Schematic of Experimental Setup

puter to evaluate the proposed technique. A simple experiment is performed and the results are showing high performance of this technique.

2 Hybrid Magnetic Levitation System

To confirm the fundamental property of the hybrid levitation system, a single DOF vibrating system is made using a canti-lever beam.

2.1 Experimental isolation system

Schematic of the experimental setup is shown in Fig. 1. A permanent magnet is attached under the free end of the beam and the other end is supported by a ball bearing. The length of the beam is 600 mm and the equivalent weight of the levitated part is 2.02 kg. The permanent magnet (Sumitomo NEOMAX-32H) has the size of 70 × 50 × 16 mm and the surface flux density of 1.168 T in free space.

Four MPMG type superconductors are placed under the permanent magnet which has high Tc of 100 K and the size of 40 × 40 × 15 mm. They are put in the cooling chamber which is filled with liquid nitrogen (77 K).

The velocity sensing coil (0.3 mm diameter) is wound 85 turns around the permanent magnet as shown in Fig. 1. Upper the beam, an electro-magnet is installed to produce the control force. The magnet core has the cross-sectional area of 15 cm^2 and the length of 24 cm. The control coil is wound 840 turns with 1 mm copper wire.

2.2 Velocity sensing test

High Tc superconductor pinning points restrict the motion of magnetic flux. Hence the magnetic flux is distorted according to the vibration of the levitated permanent magnet. The sensing coil is wound around the permanent magnet which is expected to produce the relative velocity signal between the levitated object and the foundation. An experiment is performed using the setup shown in Fig. 1. First, the superconductor is cooled by liquid nitrogen without flux. Then the levitated object with permanent magnet is closed and the average airgap is set at 7.1 mm above the superconductor. The impulse response is measured by hammering the levitated object and recording the decaying response, which is shown in Fig. 2. The upper curve is the displacement of the levitated object measured by the eddy-current sensor. The lower one is the voltage in the sensing coil which is proportional to the velocity. The sensitivity of this signal is evaluated as 0.01 Vs/m.

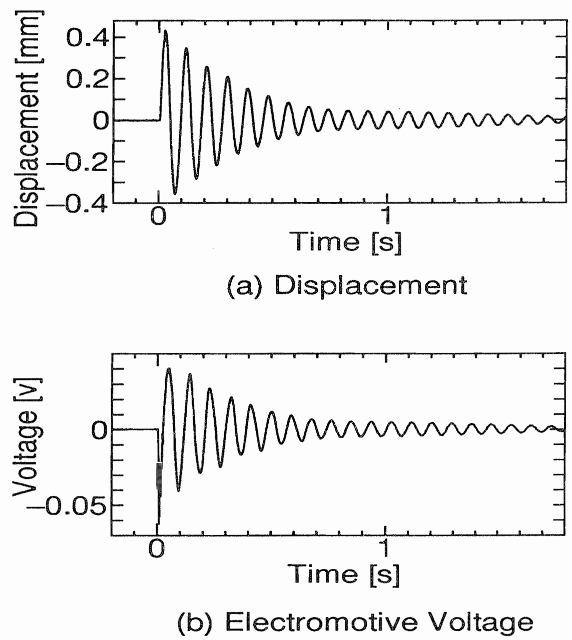

Figure 2: Comparison of Velocity Sensing Signal and Measured Displacement Signal

2.3 Direct velocity feedback control

An electromagnet is installed over the levitated object to control vibration. Control capability of the selfsensing velocity feedback is tested using this electromagnet. The average airgap between the electromagnet and the attractive surface is set at 1.4 mm and the steady-state current is 0.2 A.

The selfsensing velocity is fedback directly to the electromagnet though power amplifier. The impulse response is measured as shown in Fig. 3. The upper curve is the displacement while the lower one is the control current. The feedback gain used is 0.8 As/m in this case.

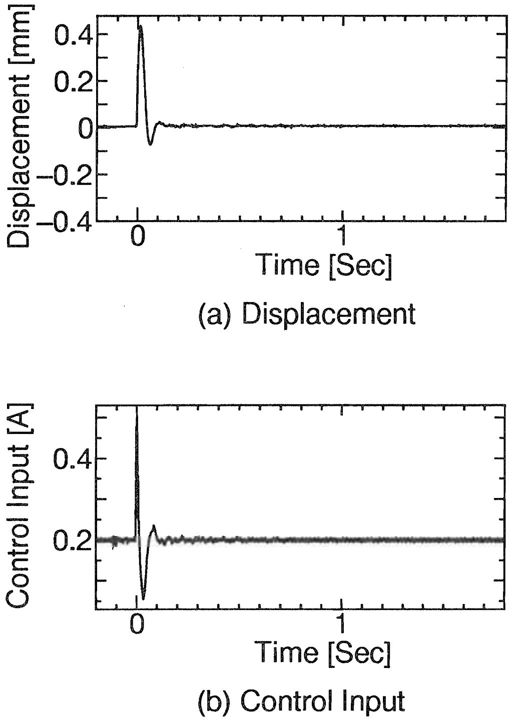

Figure 3: Impulse Response of Displacement and Control Input

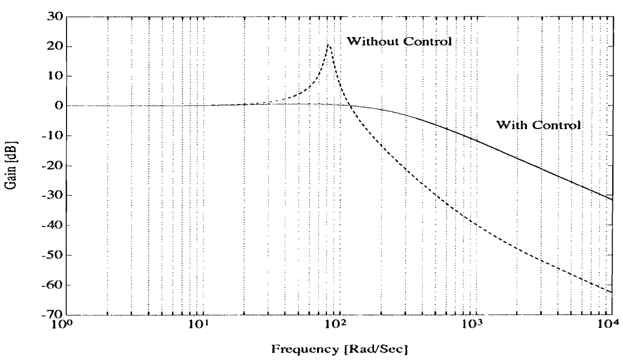

Figure 4: Simulated Transmissibility from Base to Levitated Object

The transient vibration is well reduced by the direct velocity feedback.

The main defect of this technique is the decay in isolation property. The relative velocity feedback is equivalent to increase the damping coefficient between the levitated object and the base. Hence higher frequency transmissibility is increased by increasing the feedback gain. The simulated transmissibility is shown in Fig. 4. A large feedback gain of 14 As/m is used in this case in order to clarify the effect of velocity feedback on higher frequency transmissibility.

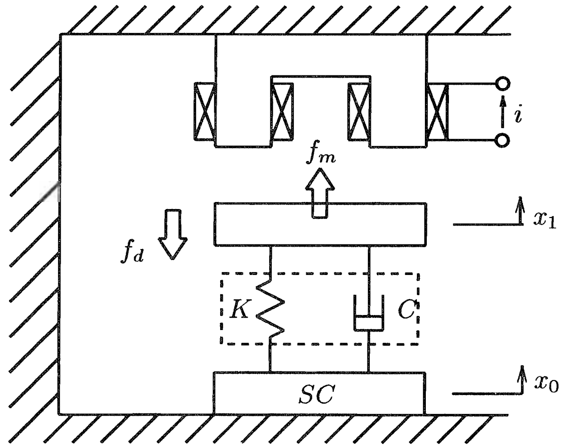

Figure 5: Single Dgree-of-Freedom Model

Table 1: Parameters and Variables

equivalent mass	:	M
control current	:	i
displacement of levitated object	:	x_1
displacement of base	:	x_0
magnetic force	:	f_m
external force	:	f_d
stiffness of magnet	:	Φ
force factor of magnet	:	Ψ

3 Robust Control

The selfsensing velocity feedback improves damping property, but it decreases the higher frequency isolation. Hence a robust controller is designed using two input signals; the selfsensing relative velocity and the acceleration of the levitated object. The H_∞ robust controller is designed using MATLAB robust control toolbox.

3.1 Modeling of the control system

The hybrid superconductor levitation system is modeled as a single DOF vibrating system as shown in Fig. 5. The superconductor pinning effect is approximated by a stiffness K and damping C. The parameters and variables used are shown in Table 1.

The state equation and the control law are written as the following.

$$\begin{aligned} \dot{\boldsymbol{x}} &= \boldsymbol{A}_p \boldsymbol{x} + \boldsymbol{B}_{p1} \boldsymbol{w} - \boldsymbol{B}_{p2} u \\ \boldsymbol{z} &= \boldsymbol{C}_{p1} \boldsymbol{x} + \boldsymbol{D}_{p11} \boldsymbol{w} - \boldsymbol{D}_{p12} u \\ \boldsymbol{y} &= \boldsymbol{C}_{p2} \boldsymbol{x} + \boldsymbol{D}_{p21} \boldsymbol{w} - \boldsymbol{D}_{p22} u \\ u &= \boldsymbol{K}(s)\, \boldsymbol{y} \end{aligned} \qquad (1)$$

where $\boldsymbol{z}$ is the controlled variable, $\boldsymbol{y}$ is the measured variable and u is the actuating signal. The variables and the coefficient matrices are selected as

Table 2: Equivalent Constants of Levitated Dynamics

resonant frequency	:	ω_n	11.2 [Hz]
stiffness	:	K	9.96×10^3 [N/m]
damping factor	:	C	14.8 [N·sec/m]

$$\boldsymbol{x} = \begin{bmatrix} x_1 - x_0 \\ \dot{x}_1 \end{bmatrix} , \quad \boldsymbol{z} = [\dot{x}_1]$$

$$\boldsymbol{y} = \begin{bmatrix} \dot{x}_1 - \dot{x}_0 \\ \ddot{x}_1 \end{bmatrix} , \quad \boldsymbol{w} = \begin{bmatrix} \dot{x}_0 \\ f_d \end{bmatrix} , \quad u = [i]$$

$$\boldsymbol{A}_p = \begin{bmatrix} 0 & 1 \\ -\frac{K+\Phi}{M} & -\frac{C}{M} \end{bmatrix} , \quad \boldsymbol{B}_{p1} = \begin{bmatrix} -1 & 0 \\ \frac{C}{M} & -\frac{1}{M} \end{bmatrix}$$

$$\boldsymbol{B}_{p2} = \begin{bmatrix} 0 \\ \frac{\Psi}{M} \end{bmatrix} , \quad \boldsymbol{C}_{p1} = \begin{bmatrix} 0 & 1 \end{bmatrix}$$

$$\boldsymbol{D}_{p11} = \begin{bmatrix} 0 & 0 \end{bmatrix} , \quad \boldsymbol{D}_{p12} = [0]$$

$$\boldsymbol{C}_{p2} = \begin{bmatrix} 0 & 1 \\ -\frac{K+\Phi}{M} & -\frac{C}{M} \end{bmatrix} , \quad \boldsymbol{D}_{p21} = \begin{bmatrix} 1 & 0 \\ \frac{C}{M} & -\frac{1}{M} \end{bmatrix}$$

$$\boldsymbol{D}_{p22} = \begin{bmatrix} 0 \\ \frac{\Psi}{M} \end{bmatrix}$$

The equivalent mass is determined M=2.02 kg by the measurement. The other vibrating parameters are estimated from the transient response shown in Fig. 2. They are shown in Table 2. The electromagnet has the force factor $\Psi = 4.95$ and the negative stiffness $\Phi = -5.23 \times 10^3$.

3.2 Design specifications

The velocity of the levitated object $\dot{x}_1$ is selected as the controlled variable because it should be small. Then the weight for the control variable is determined as

$$\boldsymbol{W}_P(s) = \frac{10}{\frac{s}{40\pi} + 1} \tag{2}$$

The plant has uncertainty such as flux creep and the parameter change. This is considered as a multiplicable uncertainty for higher frequency. Hence the weight for the uncertainty is selected as

$$\boldsymbol{W}_T(s) = \frac{\frac{s}{2\times10^4\pi} + 1}{\frac{s}{10\pi} + 1} \begin{bmatrix} 1.7\times10^{-2} & 0 \\ 0 & 1.7\times10^{-2} \end{bmatrix} \tag{3}$$

The power amplifier has the current saturation. Considering this effect, the weight for actuating signal is determined by trial and error as

$$\boldsymbol{W}_u = 8.5 \times 10^{-2} \tag{4}$$

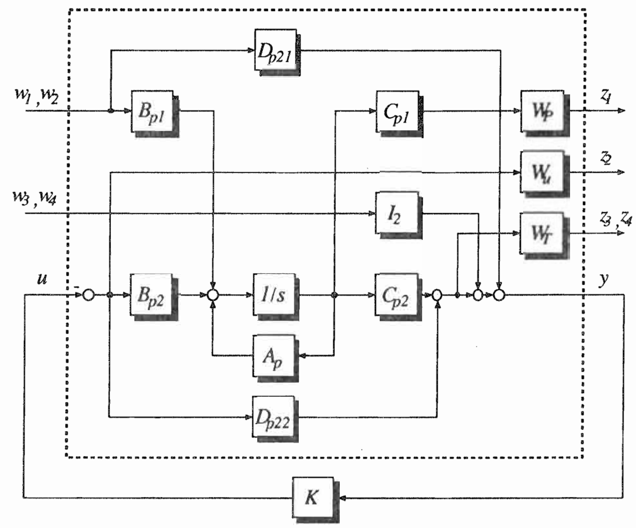

Figure 6: Block Diagram of Closed Loop System with H_∞ Controller

3.3 Generalized plant

The mathematical model of the system is augmented including the weighting functions as shown in Fig. 6. The weights are expressed using the Doyle's notation as

$$\boldsymbol{W}_P(s) = \left[\begin{array}{c|c} A_{wp} & B_{wp} \\ \hline C_{wp} & D_{wp} \end{array}\right]$$

$$\boldsymbol{W}_T(s) = \left[\begin{array}{c|c} A_{wt} & B_{wt} \\ \hline C_{wt} & D_{wt} \end{array}\right]$$

Then, the generalized plant G is written by

$$G = \left[\begin{array}{c|c|c} A & B_1 & B_2 \\ \hline C_1 & D_{11} & D_{12} \\ \hline C_2 & D_{21} & D_{22} \end{array}\right] =$$

$$\left[\begin{array}{ccc|cc|c} A_p & 0 & 0 & B_{p1} & 0 & -B_{p2} \\ B_{wp}C_{p1} & A_{wp} & 0 & B_{wp}D_{p11} & 0 & -B_{wp}D_{p12} \\ B_{wt}C_{p2} & 0 & A_{wt} & 0 & 0 & -B_{wt}D_{p22} \\ \hline D_{wp}C_{p1} & C_{wp} & 0 & D_{wp}D_{p11} & 0 & -B_{wp}D_{p12} \\ 0 & 0 & 0 & 0 & 0 & W_u \\ D_{wt}C_{p2} & 0 & C_{wt} & 0 & 0 & D_{wt}D_{p22} \\ \hline C_{p2} & 0 & 0 & D_{p21} & I_2 & -D_{p22} \end{array}\right]$$

4 H_∞ Controller Design and Experimental Results

4.1 Controller design

The controller is designed using MATLAB robust control toolbox. The weights $\boldsymbol{W}_T(s)$ and W_u are fixed as indicated by eqns. (3) and (4). The weight $\boldsymbol{W}_P(s)$ is multiplied by $1/\gamma$ and the calculation iteration is carried

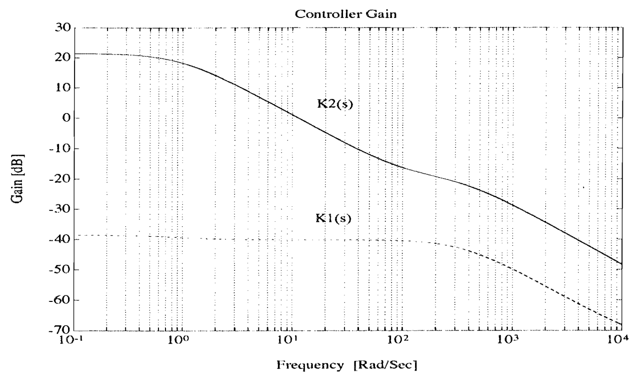

Figure 7: Gain Plot of H_∞ Controller

out. The controller is solved when $\gamma = 176$ as

$$K_1(s) = \frac{3.6204 \times 10^{-11}s^4 - 7.6618s^3}{s^4 + 5.8916 \times 10^3 s^3}$$
$$\frac{-2.2684 \times 10^4 s^2 - 2.7542 \times 10^6 s - 3.0934 \times 10^6}{+2.6504 \times 10^6 s^2 + 2.4385 \times 10^8 s + 2.3194 \times 10^8}$$

$$K_2(s) = \frac{-3.3357 \times 10^{-10}s^4 + 4.7470 \times 10 s^3}{s^4 + 5.8916 \times 10^3 s^3}$$
$$\frac{+2.2318 \times 10^5 s^2 + 4.9011 \times 10^7 s + 2.7287 \times 10^9}{+2.6504 \times 10^6 s^2 + 2.4385 \times 10^8 s + 2.3194 \times 10^8}$$

The gains of them are shown in Fig. 7.

4.2 Simulation

The system is simulated on a computer to evaluate the proposed robust controller. The simulated responses are shown in Figs. 8 to 11. First, the impulsive force is applied to the levitated object and the decaying velocity response is calculated as shown in Fig. 8. The upper curve is the response with the designed controller, while the lower one indicates the response without the controller. Figure 9 shows the response from the base motion; that is, the foundation is assumed to move impulsively and the velocity response of the levitated object is calculated. The upper and the lower curves are the responses with and without the designed controller, respectively. The vibration is well reduced by the proposed controller.

The frequency responses from the external force and from the base vibration are calculated as shown in Figs. 10 and 11, respectively. The peak resonances are well reduced with the proposed controller. The transmissibility from the base is also well reduced by this controller. This effect is due to the use of two input signals of acceleration and the relative velocity and to the use of designed H_∞ controller.

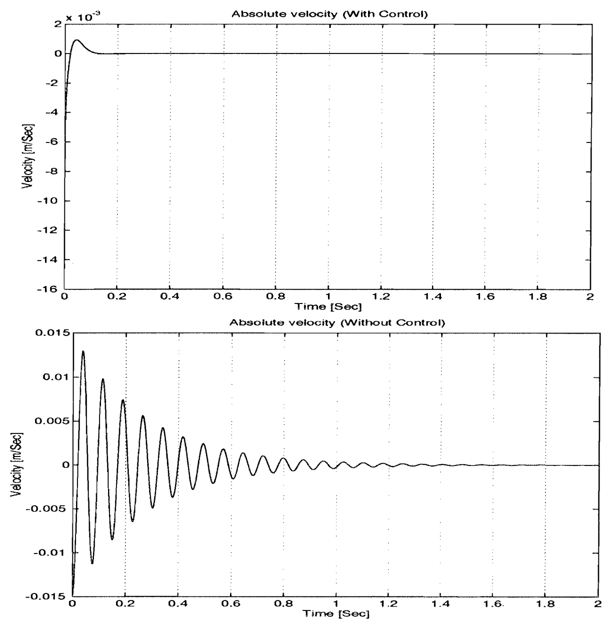

Figure 8: Impulse Response from the External Force

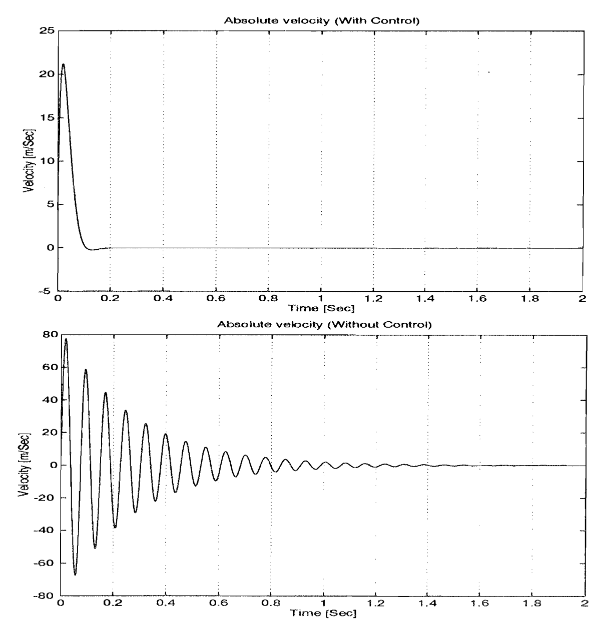

Figure 9: Impulse Response from the Base Vibration

4.3 Experimental results and considerations

A simple experiment is carried out using PC based digital controller and the experimental setup shown in Fig. 1. The designed analog H_∞ controller is transformed into z-domain using the bilinear transformation. The sampling interval used is 0.5 ms. The controller is programmed using Borland-C.

Only the impulse response test is carried out by hammering the levitated object and recording the decaying

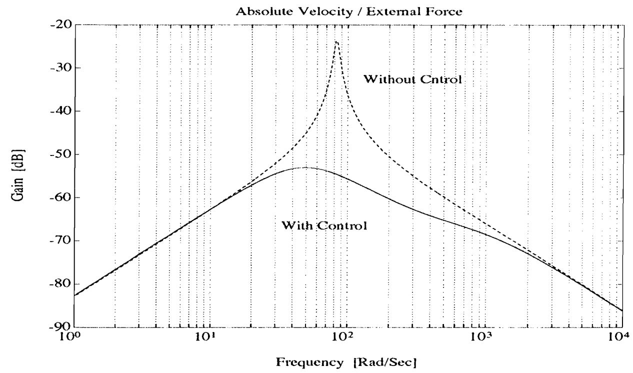

Figure 10: Frequency Response from the External Force

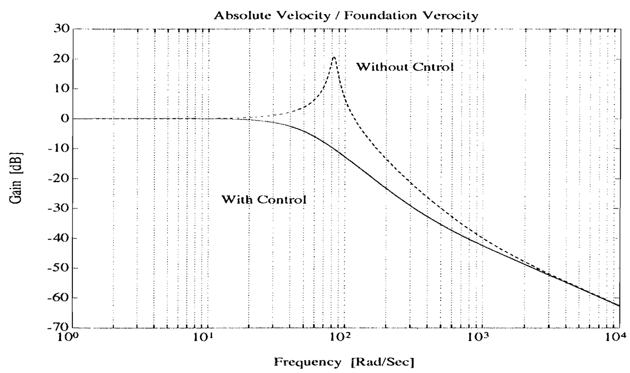

Figure 11: Frequency Response from the Base Vibration

response as shown in Fig. 12. The upper response is the velocity of the levitated object, while the lower one is the control current. Compared with the simulated response, the damping is slightly worse. However, the vibration is well controlled by the proposed technique. Low frequency motion is recognized which is due to poor characteristics in low frequency range of the power amplifier. The proposed H_∞ controller well reduces peak vibration and also improves vibration isolation property. This is due to the use of two input signals. The H_∞ control theory is adequate for the design of such a multiple-input control system.

5 Conclusions

A hybrid levitation system is designed for precision vibration isolation system using high Tc superconductor pinning effect and active magnetic bearings. Superconductor is used as both levitation and the velocity sensing device. The coil is wound around the levitated magnet which produces the relative velocity signal. The measured acceleration is also used to control the system. To design two input robust controller, H_∞ theory is used

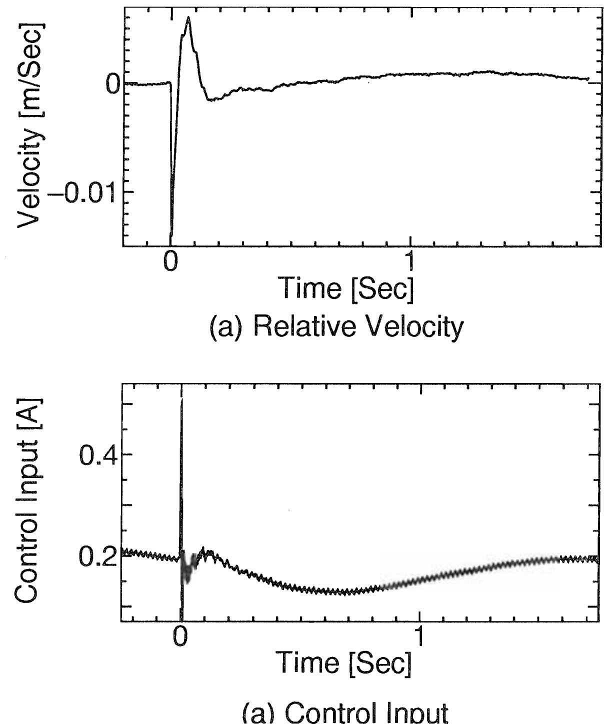

Figure 12: Experimental Impulse Responce

and the system is simulated on a computer. The vibration property as well as the isolation capability is well improved by the proposed controller. A simple experimental setup is made and the results are showing the good damping and isolation capability.

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