CONTROLLER DESIGN OF AN ELECTROMAGNETICALLY LEVITATED VIBRATION ISOLATION SYSTEM

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ABSTRACT

In this paper, a system identification is applied to an electromagnetically levitated vibration isolation system to obtain a precise model for controller design. To identify a model of the system, a multivariable ARX model is chosen and the coefficients of the polynomials are identified by the prediction error method. After that a H_∞ controller is designed for stable levitation without contact. Experimental results reveal that the designed controller achieves better performance than that of the PID controller.

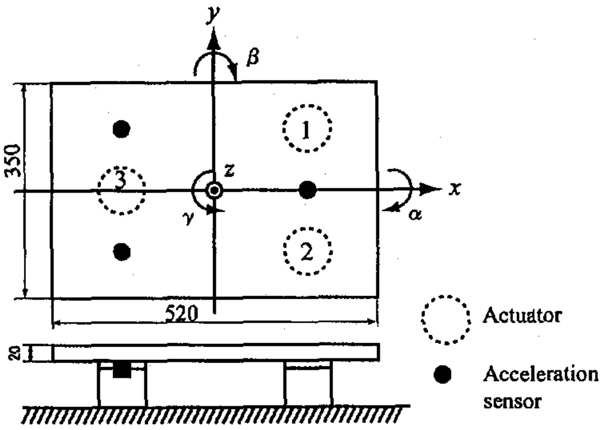

Figure 1. Magnetically levitated isolator

INTRODUCTION

Recently, vibration isolation is an important topic especially for the semiconductor manufacturing and micro-scale observation using an electron microscope. Any disturbances from an installed floor will have negative effects on manufacturing and observation accuracy. There are two ways for vibration isolations: active and passive methods. A vibration-proof rubber, a coil spring, or an air bearing is used for a passive vibration isolation method. These passive methods cannot isolate in low frequency range, and vibration level become bigger under the natural frequency of the passive isolation system. On the other hand, an active vibration isolation method using an electromagnetic actuator, an air pressure actuator, and a piezoelectric element enables transmissibility even at a natural frequency less than unity.

The electromagnetically levitated vibration isolation system features no mechanical contact between the isolation table and installation floor, therefore this system may have advantages such as, high-precise positioning accuracy and semipermanent life, and can be used in a special environment such as high and clean vacuum. However a magnetic levitation system is unstable by nature, therefore the system has to be controlled. The controller needs to have capability of simultaneous levitation control and vibration isolation.

A mixed H_∞ and *PI* controller based on physical model was designed for the system by K.Watanabe et al.[1] in 1996. They succeeded in reducing the transmissibility from the floor to the table more than 90%. To achieve lower transmissibility from the installed floor to the isolation table, a controller of the isolation system has to be designed using more precise plant model. K.Matsuda[3] has recently verified a usefulness of a 4SID(State Space Subspace System Identification) method to the system. However, few papers have been published on the related information, the main objective of this study is to report application results of a prediction error method to the electromagnetically levitated vibration isolation system.

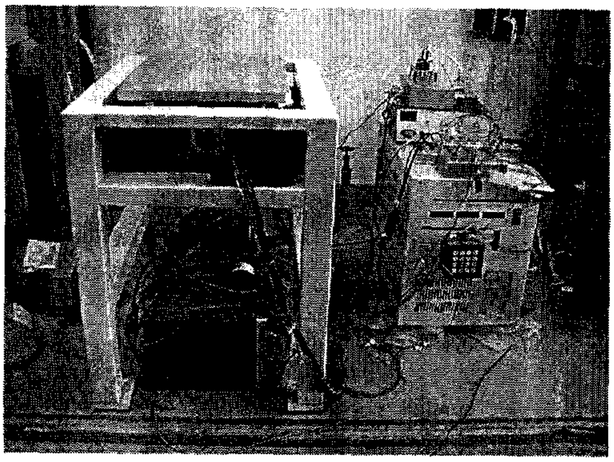

Figure 2. Photograph of magnetic levitated isolator

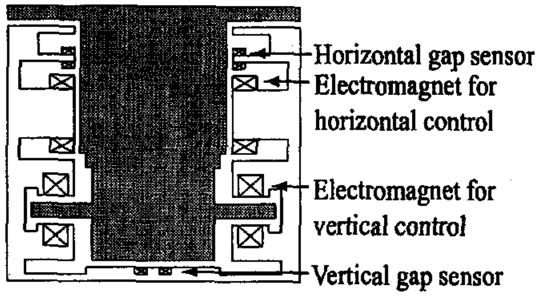

Figure 3. Sectional diagram of the electromagnetic actuator

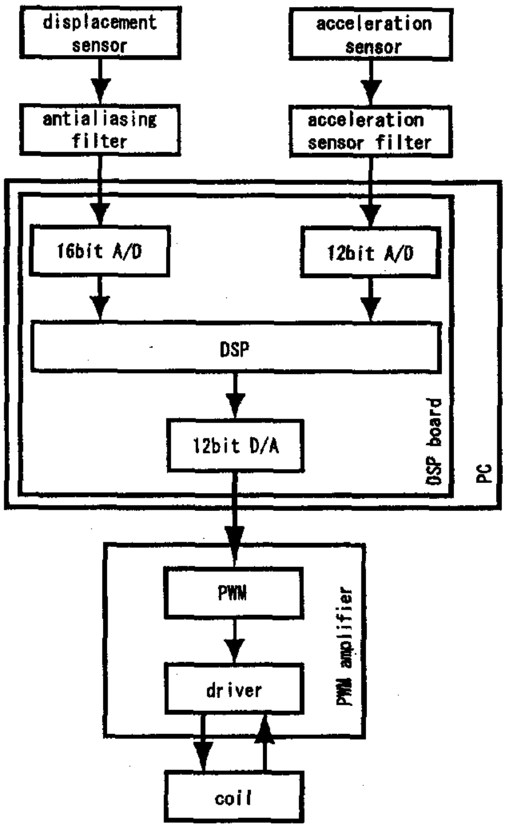

Figure 4. Flowchart of the control system

VIBRATION ISOLATION SYSTEM

The main components of the system are a vibration isolation table, three electromagnetic actuators and a control system with a DSP. Figure 1 shows the arrangement of the vibration isolation table, electromagnetic actuators and acceleration sensors. The isolation table has three acceleration sensors for detecting absolute vibration of the table. Figure 2 shows a comprehensive vision of the system. The table is set on a flame structure in the left side, and the controller box is shown in the right side. The actuators are fixed on a base plate in the flame structure. The base plate is shaken by an electromagnetic shaker put on the floor. Figure 3 shows a sectional diagram of the electromagnetic actuator. Each electromagnetic actuator has built-in electromagnets and eddy-current-type displacement sensors used for detecting the relative displacement of the installation floor and the isolation table. Each electromagnetic actuator generates electric attractive force in the vertical direction and passive restoring force in the horizontal direction produced by the flux leakage of the vertical control flux. As we study the vibration isolation in vertical direction, the electromagnetic actuator for horizontal control is set inactive. Therefore this system is horizontally stable by nature. Figure 4 shows the block diagram of the control system. A digital controller with a DSP built in a PC is employed to control the levitation and vibration of the table in vertical direction. Both relative displacement and absolute acceleration signals are input into the DSP via anti-aliasing low-pass filters(cutoff frequency is 700Hz) and the A/D converter(16-bit resolution). After these signals are processed, control signals are sent to the magnetizing coil in the actuator, via the D/A converter(12-bit resolution) and the PWM amplifier, to control the electromagnetic force for levitating the isolation table.

SYSTEM IDENTIFICATION

It would be necessary to obtain a precise model of the controlled system in order to design a controller with an excellent performance. A system identification allows to built a precise model of a dynamic system based on measured input and output data. A PID controller is firstly designed to levitate the table using the relative displacement of the table. A 15th order Maximum length null sequence signal is chosen as a random binary signal to excite the table. The table is supported by the three elec-

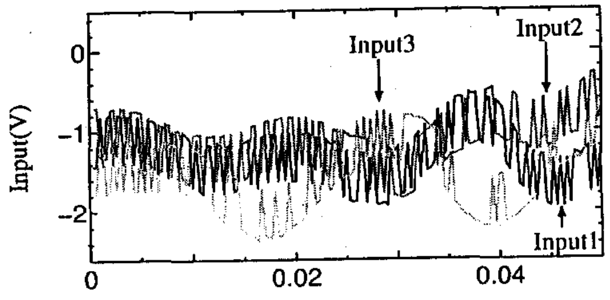

Figure 5. Input data

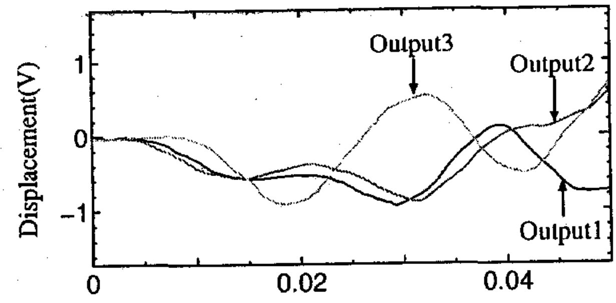

Figure 6. Output data

tromagnetic actuators, therefore three different exciting signals are generated in the DSP and added to each input signal. Sampling frequency of the control system is set at 3000Hz. The input-output data are stored on the DSP memory and transferred from the DSP to the host PC after the random exciting test. Figure 5and Figure 6 show the measured input and output data respectively to identify the system dynamics. Notice that the system has feedback loop, therefore the input data has a correlation with the output data.

This vibration isolation system is assumed to have 3 freedoms of motion, that is, vertical motion and 2 rotational motion around 2 horizontal axes x, y, and is controlled for non-contact levitation by 3 magnetic actuators(3 inputs) and 3 gap sensors(3 outputs) in vertical direction, and then is a MIMO(3input-3output) system. The model to be identified is given by the multivariable ARX structure which has n_u inputs and n_y outputs:

$$\mathbf{A}(q)\mathbf{y}(k) = \mathbf{B}(q)\mathbf{u}(k) + \mathbf{w}(k) \tag{1}$$

where $\mathbf{u}(k)$, $\mathbf{y}(k)$ and $\mathbf{w}(k)$ represent the inputs, the outputs and the white noise. $\mathbf{A}(q)$ and $\mathbf{B}(q)$ are $n_y \times n_y$, $n_y \times n_u$ matrices, and each element is a polynomial of a forward shift operator q. The orders of the polynomials are determined by a cross validation. Using the measured output $\mathbf{y}(k)$ and the estimated output $\hat{\mathbf{y}}(k,\boldsymbol{\theta})$, the prediction error $\boldsymbol{\varepsilon}(k,\boldsymbol{\theta})$ is as follows:

$$\boldsymbol{\varepsilon}(k,\boldsymbol{\theta}) = \mathbf{y}(k) - \hat{\mathbf{y}}(k,\boldsymbol{\theta}) \tag{2}$$

where $\boldsymbol{\theta}$ is a parameter matrix consists of the coefficients of the polynomials which are the element of $\mathbf{A}(q)$ and $\mathbf{B}(q)$. The parameter matrix $\boldsymbol{\theta}$ is determined so as to minimize the performance function J_N:

$$J_N = \frac{1}{N}\sum_{k=1}^{N} \|\boldsymbol{\varepsilon}(k,\boldsymbol{\theta})\|^2 \tag{3}$$

where N is the data number.

Figure 7 shows the bode plot of the transfer function $\mathbf{P}$ from $\mathbf{u}$ to $\mathbf{y}$. The index$_{ij}$ stands for the transfer function from j-th input to i-th output indicated in Figure 1. In case of $j = 1$, because of the arrangement of three actuators(see Fig.1), the gain of P_{11},P_{21},P_{31} in low frequency range are in descending order(9dB, -12dB, -20dB). The first flexible vibration mode of the table appears around 250Hz. The plant contains three unstable poles on the real axis of the complex plane, which corresponds to a feature of linear dynamics of an electromagnet.

The order of the obtained model is 51st, then it become necessary to reduce the order of the model because of the limit of the calculation speed of the DSP. Estimation of the loss function based on the singular-value is used to determine the order of the reduced model. Now, think about n-th model which should be reduced to k-th model($n > k$). The n-th model has n singular-values:

$$\sigma_1 > \sigma_2 > \cdots > \sigma_k > \cdots > \sigma_n \tag{4}$$

The singular-value from σ_{k+1} to σ_n are deleted by the model reduction. Therefore the performance function p is as follows:

$$p = \frac{\sum_{i=1}^{k}\sigma_i}{\sum_{i=1}^{n}\sigma_i} \tag{5}$$

Figure 8 shows the relationship between p and the model order. In this case, considering about the calculation speed of the DSP and the loss of the model, $k = 18$ is chosen($p = 0.851$).

CONTROLLER DESIGN

The system has to be stable against any disturbances from the installation floor and the sensor, therefore the H_∞ controller design method is chosen for stable levitation. The H_∞ control scheme has a potential to make

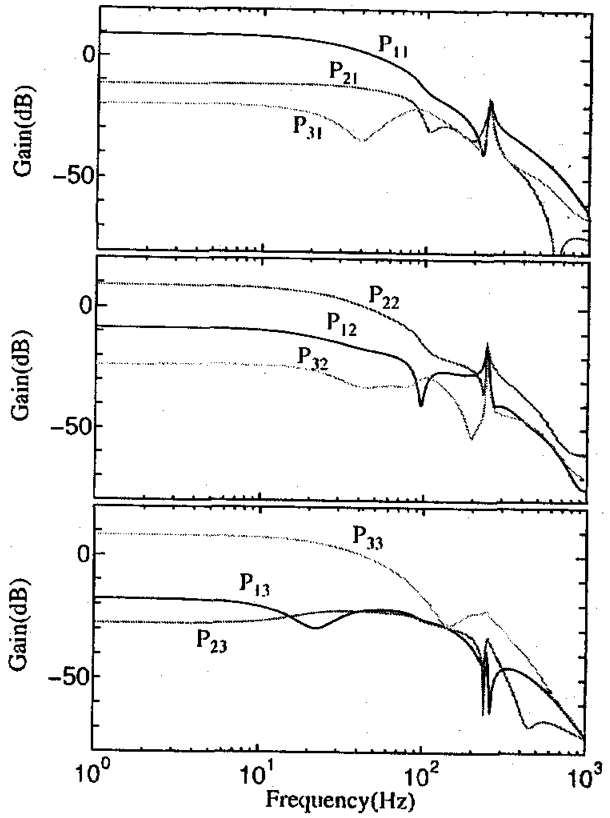

Figure 7. Transfer function from **u** to **y**

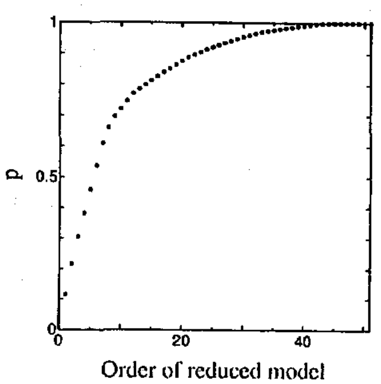

Figure 8. Relationship between p and model order

a feedback system robustly stable against changing parameters and uncertainties. The identified and reduced model, whose order is 18th, is used to design an H_∞ controller. The generalized plant is argued in the standard manner of H_∞ control theory:

$$\begin{bmatrix} z_1 \\ z_2 \\ y \end{bmatrix} = \begin{bmatrix} W_1 y \\ W_2 u \\ y \end{bmatrix} = \begin{bmatrix} W_1 & W_1 P \\ 0 & W_2 \\ I & P \end{bmatrix} \begin{bmatrix} \omega \\ u \end{bmatrix} \tag{6}$$

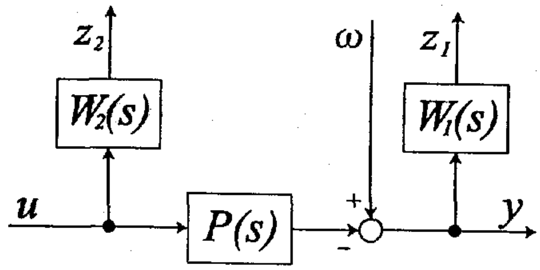

Figure 9. Generalized plant

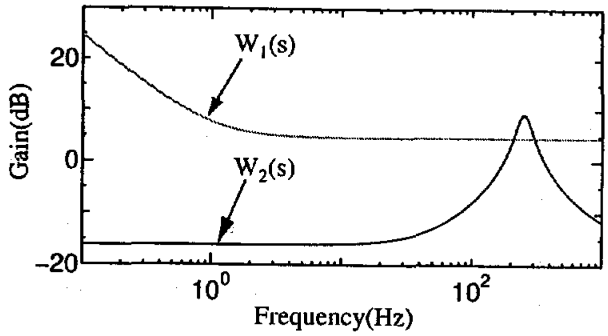

Figure 10. Frequency weighting function

where z_1,z_2 are control values, ω is the external disturbance on the system. Figure 9 shows the generalized plant. W_1,W_2 are the frequency weighting functions shown in Fig.10. W_1 has the larger gain in low frequency range to lift off the table. W_2 has a peak at 250Hz:the natural frequency of the isolation table. W_1,W_2 are as follows:

$$W_1 = \frac{17000\left(\frac{1}{2\pi}s+1\right)}{\frac{1}{2\pi\times 10^{-4}}s+1} \tag{7}$$

$$W_2 = \frac{1.61\times 10^{-1}s^2+1.24\times 10^3 s+3.89\times 10^5}{s^2+4.26\times 10^2 s+2.47\times 10^6} \tag{8}$$

The mixed sensitivity approach of the robust control system design is a direct and effective way of achieving loop shaping. The controller $K(s)$ is designed to minimize H_∞norm of the transfer functions from ω to z_1,z_2, thus $S(s)$, $R(s)$:

$$S(s) \stackrel{\text{def}}{=} \frac{1}{I+L(s)} \tag{9}$$

$$R(s) \stackrel{\text{def}}{=} \frac{K(s)}{I+L(s)} \tag{10}$$

$$L(s) = P(s)K(s) \tag{11}$$

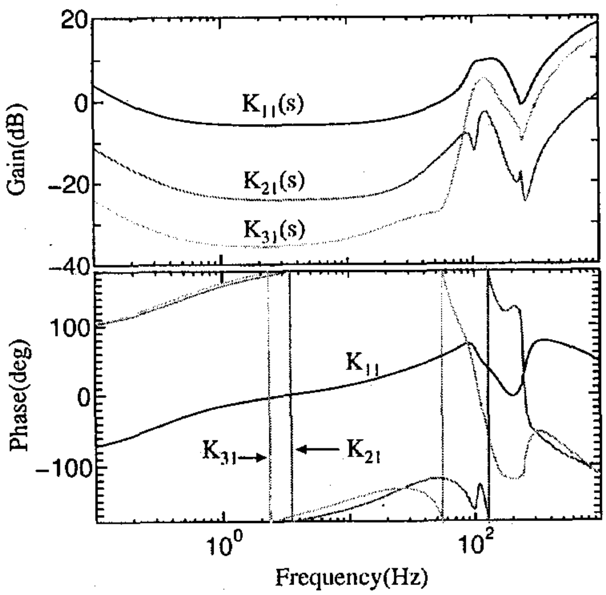

Figure 11. H_∞ controller

where $K(s)$ is a controller. A mixed sensitivity problem is as follows:

$$\left\| \begin{matrix} W_1(s)S(s) \\ W_2(s)R(s) \end{matrix} \right\|_\infty < \gamma \qquad (12)$$

Each frequency weighting function is selected to make the magnetically levitated system stable and to reduce the sensitivity from external disturbance ω to relative displacement z_1 and control input z_2. Figure 11 shows the transfer functions of the designed H_∞ controller($\gamma = 3.92$). The designed H_∞ controller has the larger gain in low frequency range and the notch filter at 250Hz. The order of the obtained controller is 27th.

EVALUATION RESULTS

The H_∞ and PID controller are experimentally compared. Evaluation tests are carried out by the digital controller with the DSP built in the PC. All control programs are written with C-language, and transferred from the host PC to the DSP. The sampling frequency is 3000Hz.

Figure 12 shows the initial response(relative displacement of the table at lift off). With the PID controller, the table lift off vibrating at the natural frequency of the closed loop(60Hz), and it takes about 2.0 sec, whereas with the H_∞ controller, the table lift off smoothly in 0.8 sec. Figure 13 shows the Nyquist plot of open-loop transfer function between input 1 and output 1 from 0.1Hz to 1000Hz. Distance of Nyquist plot from the critical point (-1,0) indicates a margin of system stability. The figure shows that the system with the H_∞ controller is more stable than that with the PID controller. Figure 14 shows the sensitivity function $S(s)$. A sensitivity function is equal to inverse of a distance of a Nyquist plot from the critical point (-1,0) and represents shortages of system stability. The designed H_∞ controller achieves low sensitivity(maximum -10dB) than PID controller for almost all frequencies. Notice that with the PID controller, the sensitivity function has a peak at the natural frequency of the closed loop(60Hz), whereas with the H_∞ controller, the sensitivity function has flat characteristics.

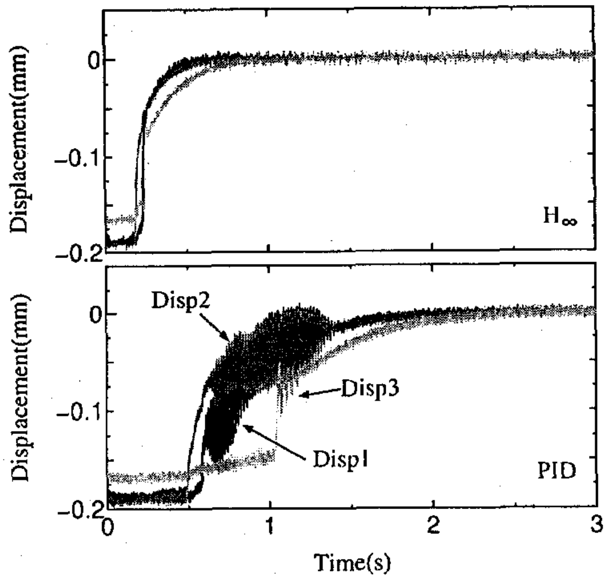

Figure 12. Initial response

CONCLUSIONS

A system identification was successfully applied to the electromagnetically levitated vibration isolation system. A PID controller was firstly designed to levitate the table using the relative displacement of the table. Then a M-sequence signal was add to excite the table. To identify the model of the isolation table, the multivariable ARX model was chosen and the coefficients of the polynomials were identified by the prediction error method. The H_∞ controller was designed for stable levitation without contact. Experimental results revealed that the designed controller achieved better performance than that of the PID controller.

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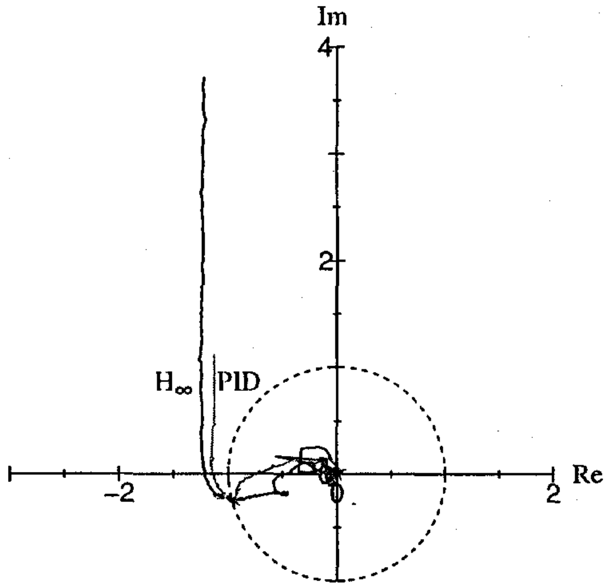

Figure 13. Nyquist plot of open loop transfer function between input 1 and output 1

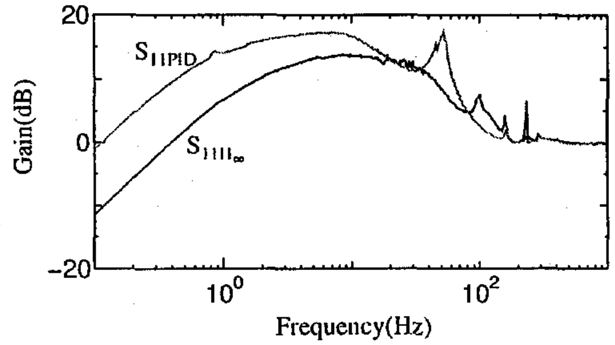

Figure 14. Sensitivity function $S(s)$

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