Flow Disturbance Compensation Based on Off-Line Estimated Signal for a Pneumatic Isolation Table*

Habiburahman SHIRANI**, Yukinori NAKAMURA** and Shinji WAKUI**
**Department of Electronic and Information Engineering, Tokyo University of Agriculture and Technology, 2-24-16 Naka-cho, Koganei City, Tokyo, 184-8588, Japan
E-mail: yukino-n@cc.tuat.ac.jp

Abstract
The flow disturbance to a pneumatic vibration isolation table causes periodic fluctuation of the table. In current study, one cycle of flow disturbance is estimated offline using a disturbance observer. The time series data of one cycle estimated disturbance is then stored in the memory of digital signal processor. The program codes are prepared which can detect every cycle of the flow disturbance based on the threshold of table position. The estimated signal is then repeatedly injected from the memory through a compensator to the servo valve to suppress table fluctuation due to periodic actual flow disturbance. The effectiveness of this method is demonstrated by experimental results.

Key words: Pneumatic Isolation Table, Supplied Air, Flow Disturbance, Estimated Disturbance

1. Introduction
Actively controlled pneumatic vibration isolation tables are employed to protect semiconductor manufacturing and precision measurement equipment from vibration(1-4). A pneumatic isolation table is mounted on air springs which are actively controlled by servo valves. During the compression process by the air compressor, the pressure of the compressed air varies, which causes the variation of the supplied air known as flow disturbance(5,6) to the air spring. The air compressor periodically compresses the air. Therefore, the flow disturbance becomes a periodic disturbance and results in periodic fluctuation of the table. For the suppression of the flow disturbance, multi-connection air regulators are often used. However, they lead to decompression and pressure loss of the supplied air.

Previously, we used two feedforward control schemes based on the measured supplied air pressure signal. One scheme employed an air spring whereas the other used a voice coil motor (VCM) as the actuators(5,6). The supplied air pressure was measured by an expensive and sophisticated pressure sensor for feedforward control. The drawback associated with both schemes is the use of an expensive pressure sensor for the measurement of the supplied air pressure.

In order to circumvent the use of a sensor for the measurement of a disturbance, disturbance observers (DOBs)(7) are widely used for the rejection of disturbances to the systems in various applications(8-11). For the implementation of DOBs, low pass filters which are known as Q-filter are used together with inverse nominal plant. The purpose of Q-filters is to filter out the noise of the sensors. In this study, we employ a DOB for
estimating flow disturbance. However, since the inverse nominal system of the pneumatic isolation table is high order, position sensor noise is amplified. It leads to the degradation of estimation performance. One approach to overcome the issue is to use a higher order Q-filter. Moreover, the break point frequency of the filter should be lower for better rejection of noise which falls into the control bandwidth. Increasing the order of the filter can further remove the noise. However, a higher order filter can adversely degrade the performance of the closed-loop control system due to phase lag. In addition, the break point frequency of the Q-filter can also affect the performance of the system (8). When the break point frequency of the filter is within the control bandwidth, the nominalization of the system cannot be achieved (10,11). As a result, the frequency characteristics of the closed-control system (i.e., pneumatic isolation table) in the frequency region within the control bandwidth can be changed which creates the need for redesign of the feedback controller. Therefore, it is not practical to feed back the estimated signal of the DOB with high order Q-filter and lower break point frequency.

Taking all these into account, we consider a different approach as follows: One cycle of the flow disturbance is estimated offline by a DOB with higher order filters. The time series data of the one cycle estimated signal is then stored in the memory of the digital signal processor (DSP) controller. The program codes are built in such way that can inject repeatedly one cycle estimated signal based on the detection of table fluctuation. Since the flow disturbance varies periodically, we can use effectively the offline one cycle estimated signal for the compensation of all cycles of the flow disturbance. The performance of our disturbance suppression method is evaluated by experiments.

Nomenclature

\[
\begin{align*}
A_0 & : \text{effective received area, m}^2 \\
\beta_0 & : \text{compressibility, l/Pa} \\
c & : \text{flow conductance, m}^3/\text{s/Pa} \\
d & : \text{viscous damping coefficient, N·s/m} \\
d_f & : \text{flow disturbance, m}^3/\text{s} \\
\hat{d}_f & : \text{estimated flow disturbance, V} \\
d_{pr} & : \text{pressure of supplied air, Pa} \\
e & : \text{error of table position, V} \\
f_{air} & : \text{driving force of air spring, N} \\
G_p(s) & : \text{transfer function from pressure to flow, m}^3/\text{s/Pa} \\
G_q & : \text{flow gain of the servo valve, m}^3/\text{V} \\
k & : \text{spring constant, N/m} \\
k_c & : \text{DOB gain for inverse nominal plant, V/V} \\
k_{ff} & : \text{gain of the compensator, V/V} \\
k_p & : \text{position PI gain, V/V} \\
k_{pos} & : \text{position sensor sensitivity, V/m} \\
k_q & : \text{DOB gain for inverse nominal } G_q, \text{ V/V} \\
M & : \text{mass of table, kg} \\
p & : \text{pressure of air spring, Pa} \\
T_0 & : \text{time constant of } Q_0\text{-filter, s} \\
T & : \text{time constant of } Q\text{-filter, s} \\
T_f & : \text{time constant of compensator, s} \\
T_{pos} & : \text{time constant of position PI, s} \\
V_0 & : \text{air spring volume, m}^3 \\
w & : \text{input voltage to servo valve, V} \\
x & : \text{displacement of table, m} \\
x_{ref} & : \text{reference displacement of table, V}
\end{align*}
\]
2. Active Control of Pneumatic Isolation Table and Flow Disturbance

2.1 Actively Controlled Pneumatic Isolation Table

A photograph of a single degree-of-freedom pneumatic isolation table which used in the experiments of this study is shown in Fig. 1(a). The bellows type air spring supports a table of approximately 120 kg. The air spring is actively controlled by a nozzle-flapper type servo valve (SMS, XT511-1) to regulate the compressed air to the air spring. A special order, maximum 300 N VCM is set under the hung frame of the table. An acceleration sensor (JAE, JA-5V) which detects the acceleration of the table is set on top of the table. A pressure sensor (Setra, 204) which measures the inner pressure of the air spring is connected to the air spring. A position sensor (SDL, NS2300/A) which is used to detect the vertical displacement of the table is installed on one side to the bottom of the hung frame of the table. An air slider is used to control the horizontal movement of the table.

Figure 1(b) depicts the control block diagram of the experimental pneumatic isolation table. The feedback controller is a position PI compensator which maintains the position of the table. The transfer function of the isolation table from the input voltage \( w \) of the controlled signal to the servo valve to the position \( x \) of the table can be expressed as

\[
x = \frac{A_0 G_d}{\beta_0 V_0 s + c} \cdot \frac{1}{M s^2 + d s + k + \frac{A_0^2 s}{\beta_0 V_0 s + c}},
\]

where \( A_0 G_d/(\beta_0 V_0 s + c) \) is the pneumatic part in which the input is the voltage \( w \) to the servo valve and the output is the driving force \( f_{air} \) of the air spring. \( M s^2 + d s + k \) is the mechanical part of the isolation table in which the input is the force \( f_{air} \) of the air spring and output is the position \( x \) of the table.

![Fig. 1 Experimental pneumatic isolation table, (a) photograph, (b) control block diagram](image)

2.2 Flow Disturbance

Figure 2 illustrates the experimental setup of the pneumatic isolation table which comprises an air compressor, signal connection air regulator, servo valve, isolation table, and DSP. The air compressor is employed to provide compressed air to the air spring of the isolation table. During the compression process of air by the air compressor, the pressure of the compressed air varies. The pressure variation of the compressed causes the variation of the supplied air. A single connection air regulator can reduce the level of supplied air variation; however, it cannot suppress the variation completely. Figure 3 shows the experimental results illustrating the problem of flow disturbance. As illustrated in Fig. 1(b), for the active control of the isolation table, a position PI is implemented. The values of the position PI parameters are: \( k_p = 0.05 \) and \( T_{pos} = 0.053 \) s. The reference \( x_{ref} \) is set to zero. In Fig. 3, the flow disturbance which is actually the pressure variation of supplied air is measured at the output of air compressor. We can see from Fig. 3 that the supplied air pressure linearly increases from low pressure to high and again linearly decreases back to low pressure. This variation of supplied air becomes a disturbance which is known as flow...
disturbance to the isolation table. Furthermore, we can also find that the supplied air pressure is periodic. This is because the air compressor compresses the air periodically. Thus, the isolation table fluctuates intermittently. This problem is undesirable while using the pneumatic isolation table in real industrial scenes.

3. Compensation of Flow Disturbance Using Estimated Signal

In this section, we will describe the control method for suppressing all cycles of the flow disturbance to the isolation table using estimated flow disturbance signal. This method has two stages. At first, a DOB is designed and used offline to estimate one cycle of the flow disturbance. Secondly, the time series data of one cycle estimated flow disturbance signal is stored in the memory of the DSP. The program codes are prepared that can inject estimated signal from the memory to the servo valve for the suppression of all cycles of the flow disturbance. Since the flow disturbance is a periodic disturbance, one cycle offline estimated signal can effectively compensate all cycles of the flow disturbance.

3.1 Estimation of Flow Disturbance

The estimation of the flow disturbance is based on the commonly considered principles for a DOB. Figure 4 depicts the pneumatic isolation table with DOB, where the subscript \( n \) denotes the nominal parameters of the pneumatic isolation table. The nominal values of the parameters used in the DOB are given in Table 1 and the value of \( k_{pa} \) is 6670 V/m. The inverse nominal model \( P_n^{-1}(s) \) of the pneumatic isolation table and the third order low pass filter (LPF) \( Q(s) \) are respectively expressed in Eqs. (2) and (3).

\[
P_n^{-1}(s) = \frac{1}{G_{qn}} \frac{c_nk_n}{A_{0n}} \left( \frac{M_n}{k_n}s^2 + \frac{d_n}{k_n}s + 1 \right) \left( \frac{B_{0n}V_{0n}}{c_n}s + 1 \right) + \left( \frac{A_{2n}}{c_nk_n} \right), \quad (2)
\]

\[
Q(s) = \frac{1}{(Ts + 1)^3}. \quad (3)
\]

The inverse nominal model of the plant is a third order improper system. In order to make it proper and suppress the noise, we need the third order LPF \( Q(s) \). The exact identification of some parameters such as \( c_n, k_n, \) and \( G_{qn} \) is difficult in the case of the pneumatic isolation table. Therefore, to obtain better estimation, the tunable gains \( k_c \) and \( k_q \) in Fig. 4 are respectively used for \( c_{ud}/A_{0u} \) and \( 1/G_{qn} \) in Eq. (2). Moreover, the third order LPF \( Q_0(s) \) with time constant \( T_0 \) shown in Fig. 4 is used to reject the amplified noise of the table position sensor.

We have conducted experiments using the DOB shown in Fig. 4 for the estimation of the flow disturbance. The experimental results are shown in Figs. 5, where the vertical axes show voltage [V] which refer to the output voltage of the pressure sensor signal. Experiments are conducted in two steps. At first, we apply the DOB without using the third order filter \( Q_0(s) \) which results are shown on the left side of Fig. 5. However, the estimation
signal is extremely noisy. Then, we implemented \( \mathcal{Q}_0(s) \) at the output of position sensor which results are shown on the right side of Fig. 5, where the gains \( k_q \) and \( k_c \) are tuned based on trial and error. The better estimation can be obtained while setting \( k_q \) to 10 and \( k_c \) to 0.1.

![Fig. 4 Flow disturbance estimation scheme](image)

**Table 1 Nominal values of the DOB parameters**

| Parameter | Value   | Parameter | Value   |
|-----------|---------|-----------|---------|
| \( A_{n_0} \) | 7.80 \times 10^{-3} | \( k_n \) | 5120   |
| \( \beta_{n_0} \) | 2.74 \times 10^{-6} | \( M_n \) | 120    |
| \( c_n \) | 4.60 \times 10^{-10} | \( T \) | 3.00 \times 10^{-3} |
| \( d_n \) | 479     | \( T_0 \) | 1.59 \times 10^{-3} |
| \( G_{n_0} \) | 1.60 \times 10^{-8} | \( V_n \) | 1.50 \times 10^{-3} |

![Fig 5 Experimental results of the estimated signal with and without \( \mathcal{Q}_0(s) \)](image)

**3.2 Compensation of Flow Disturbance**

Figure 6 illustrates the concept of injecting the estimated signal for compensation of flow disturbance. The time series data of one cycle estimated flow disturbance which is obtained on the right side of Fig. 5 (\( k_q = 10 \) and \( k_c = 0.1 \)) is stored in the memory of the DSP. The program codes are built that can repeatedly inject one cycle estimated signal for every cycle of the flow disturbance. The period of flow disturbance slightly varies from cycle to cycle. We selected one cycle with shortest period and the injection of this one cycle is based on detection of the fluctuation of the table position due to flow disturbance. The estimated flow disturbance \( \tilde{d}_f \) is actually the estimate of the pressure variation \( d_{pr} \) [Pa] of supplied air.
The real flow disturbance which causes the fluctuation of the table is the flow variation \( df [m^3/s] \) of the supplied air to the air spring. To achieve better compensation, we need to make the dimension of estimated signal same as real flow disturbance by using the following relationship\(^{12} \):

\[
d_f(t) = C \frac{df}{dt}(t).
\]

(4)

where \( C \) is a constant. From Eq. (4), we can see that the flow \( df \) of the compressed air is equal to the derivative of the pressure \( dp \). To implement the derivative element in the DSP, we use the pseudo differentiator \( k_f \frac{T_f}{1 + T_f s} \) as shown in Fig. 6(a). The gain \( k_f \) and time constant \( T_f \) of the compensator are tuned based on trial and error to provide better compensation and their appropriate values are chosen as \( k_f = 0.08 \) and \( T_f = 10 \) s. The procedure of the injection of estimated signal is depicted in the flow chart of Fig. 6(b) and the detail is provided in the following four steps:

**Step 1**: When we start the isolation table for the first time, there is no injection of the time series data from the DSP to the servo valve until the table settles at its reference. If the injection starts within the settling time of the table, it results in destabilization of the table.

**Step 2**: After the table settles at its reference, then the compensation scheme looks for the threshold of position sensor output, \( k_{posx} < -0.03 \). Although, the threshold should be set to zero, however, due to position sensor noise; we set it to -0.03 V. At the instant that displacement of the table due to flow disturbance gets less than -0.03 V, the injection of estimated time series data starts.

**Step 3**: The injecting continues until the period of the estimated time series data completes. After the completion of the period, the compensation scheme again looks for the threshold due to next cycle of the flow disturbance. When it detects the threshold of the next cycle, it again repeats the same procedure of the injection.

**Step 4**: This procedure goes round and round until we manually stop the isolation table. In this way, by using one cycle of the estimated flow disturbance signal, all cycles of the real flow disturbance can be compensated.

![Flow disturbance compensation using estimated signal, (a) compensation scheme, (b) flow chart](image)

**Fig. 6 Flow disturbance compensation using estimated signal, (a) compensation scheme, (b) flow chart**

Figure 7 shows the experimental results for the compensation of flow disturbance. Two signals are shown in Fig. 7, actual flow disturbance (i.e., supplied air pressure) (upper part) and table position (lower part). We can see from Fig. 7 that by injecting the estimated signal, the compensation of the fluctuation of the table due to flow disturbance is improved compared to the without estimated compensation scheme.
Next, we evaluate the performance of our method for the repeatability improvement of several cycles of the flow disturbance. Figures 8 and 9 show the results of the mean absolute values (MAV) and standard derivation (SD) for the table position errors within 15 cycles of the flow disturbance. In these figures, the MAV and SD of table position errors for each cycle are calculated without and with compensation signal. Let $e_k (k = 0, 1, 2, \ldots)$ be a discrete point on the table position error $e$. The starting point $e_0$ is the error when table just starts to fluctuate due to flow disturbance. The MAV and SD from the starting point $e_0$ up to 850 discrete points within a 17 s window are calculated as

$$J_{\text{ MAV}} = \frac{1}{851} \sum_{i=0}^{850} |e_i|,$$

$$J_{\text{ SD}} = \left( \frac{1}{851} \sum_{i=0}^{850} (e_i - \bar{e})^2 \right)^{1/2},$$

where $\bar{e}$ is the average of error. It is clear from Figs. 8 and 9 that with compensation signal, the position errors $e$ of the table are reduced. Therefore, the method of this study is effective for the suppression of flow disturbance.

*Fig. 7 Experimental results of flow disturbance compensation by injecting the estimated signal*

*Fig. 8 MAV of table position error for 15 cycles of flow disturbance*

*Fig. 9 SD of table position error for 15 cycles of flow disturbance*
4. Conclusion

In this study, we considered the suppression of the isolation table fluctuation caused by flow disturbance. In our study, the flow disturbance is estimated offline. The time series data of estimated signal is stored in the memory of the DSP and is injected to the servo valve based on the detection of table fluctuation due to flow disturbance. The experimental results demonstrated that the proposed method can reduce the fluctuation of the table caused by flow disturbance.

Acknowledgements

This work is supported in part by grant from Fluid Power Technology Promotion Foundation.

References

(1) T. Kato, K. Kawashima, K. Sawamoto, and T. Kagawa: Active Control of a Pneumatic Isolation Table with Pressure Differentiator, *Precision Engineering*, Vol. 31, No. 2 (2007), pp. 139-145.
(2) Y.-H. Shin and K.-J. Kim: Performance Enhancement of Pneumatic Vibration Isolation Tables in Low Frequency Range by Time Delay Control, *Journal of Sound and Vibration*, Vol. 321, Issues 3-5 (2009), pp. 537-553.
(3) M. Heertjes and N. van de Wouw: Nonlinear Dynamics and Control of a Pneumatic Vibration Isolator, *Journal of Vibration and Acoustics*, Vol. 128, No. 4 (2006), pp.439-448.
(4) B. H. Wilson, C. Erin, and A. Messac: Optimal Design of a Vibration Mount Using Physical Programming, *ASME Journal of Dynamic Systems, Measurement, and Control*, Vol. 121 (1999), pp. 171-178.
(5) H. Shirani and S. Wakui: Control of an Isolated Table’s Fluctuation Caused by Supplied Air Pressure Using a Voice Coil Motor, *Journal of System Design and Dynamics*, Vol. 4, No. 3 (2010), pp. 406-415.
(6) S. Wakui, K. Uryu, M. Takahashi, and K. Yamamoto: Feedforward Control of Supplied Air Pressure and Air Fluctuations for Pneumatic Type Anti-Vibration Apparatus, *Journal of the Japan Society for Precision Engineering*, Vol. 73, No. 11 (2007), pp. 1215-1219. (in Japanese)
(7) K. Ohnishi, M. Shibata, and T. Murakami: Motion Control for Advanced Mechatronics, *IEEE/ASME Transactions on Mechatronics*, Vol. 1, Issue 1 (1996), pp. 56-67.
(8) C. W. Lee and C. C. Chung: Design of a New Multi-Loop Disturbance Observer for Optical Disk Drive Systems, *IEEE Transactions on Magnetics*, Vol. 45, No. 5 (2009), pp. 2224-2227.
(9) S. Sadhu and T. K. Ghoshal: Sight Line Rate Estimation in Missile Seeker Using Disturbance Observer-Based Technique, *IEEE Transactions on Control Systems Technology*, Vol. 19, No. 2 (2011), pp. 449-454.
(10) S. Komada and K. Ohnishi: Force Feedback Control of Robot Manipulator by the Acceleration Tracing Orientation Method, *IEEE Transactions on Industrial Electronics*, Vol. 37, No. 1 (1999), pp. 6-12.
(11) S. Komada, N. Machii, and T. Hori: Control of Redundant Manipulators Considering Order of Disturbance Observer, *IEEE Transactions on Industrial Electronics*, Vol. 47, No. 2 (2000), pp. 413-420.
(12) C. W. de Silva: Modeling and Control of Engineering Systems, CRC Press, Taylor & Francis Group (2009)