Accurate Positioning of a Pneumatic Servo System With Air Bearings

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ABSTRACT

This paper presents a pneumatic servo system for trajectory tracking. To reduce the effects of friction force, seals are removed from the pneumatic actuator, and the slider of the actuator is mounted with externally pressurised air bearings. Previous studies of this pneumatic actuator show an accuracy of ±2[μm] for step responses and low constant velocities control tests. In this paper, the pneumatic servo system is tested in the more demanding task of trajectory tracking. Considering the characteristics of the pneumatic servo system, it is clarified that the trajectory with constant jerk is better than trajectory with constant acceleration. An example for a displacement of 180[mm] that is realised in 0.4[s] is shown. Despite the slider reaches a high velocity of 0.8[m/s], an accuracy of ±50[μm] is attained.

KEY WORDS: Pneumatic, Servo System, Positioning Control, Air Bearing, Trajectory Tracking

1. NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
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<tbody>
<tr>
<td>A</td>
<td>Pressurised area</td>
<td>[m²]</td>
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<tr>
<td>a</td>
<td>Acceleration</td>
<td>[m/s²]</td>
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<td>b</td>
<td>Critical pressure ratio</td>
<td>[-]</td>
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<tr>
<td>e</td>
<td>Error</td>
<td>[mm]</td>
</tr>
<tr>
<td>G</td>
<td>Mass flow rate</td>
<td>[kg/s]</td>
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<tr>
<td>Jₐ</td>
<td>Jerk</td>
<td>[m/s³]</td>
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<tr>
<td>Kₐ</td>
<td>Acceleration feedback gain</td>
<td>[Vs/m²]</td>
</tr>
<tr>
<td>Kᵣ</td>
<td>Constant ( Eq.(3) )</td>
<td>[s/m]</td>
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<tr>
<td>Kₚ</td>
<td>Proportional gain</td>
<td>[V/m]</td>
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<td>Flow gain</td>
<td>[m²/V]</td>
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<tr>
<td>Kᵣₑ</td>
<td>Velocity feedback gain</td>
<td>[Vs/m]</td>
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<tr>
<td>M</td>
<td>Slider mass</td>
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</tr>
<tr>
<td>P</td>
<td>Pressure</td>
<td>[Pa]</td>
</tr>
<tr>
<td>R</td>
<td>Gas Constant</td>
<td>[J/(kgK)]</td>
</tr>
<tr>
<td>s</td>
<td>Laplace operator</td>
<td>[s⁻¹]</td>
</tr>
<tr>
<td>Sₑ</td>
<td>Effective area</td>
<td>[m²]</td>
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2. INTRODUCTION

Despite the many benefits of pneumatic systems as low cost, easy maintenance and high power density; pneumatic servo systems experience a lack of attention due to non-linearities associated with the compressibility of air that can significantly degrade performance in terms of both response time and positioning accuracy [1]. One of the most critical problems in servo pneumatic positioning systems is that friction force affects convergence performance near the reference position, decreasing the positioning accuracy [1][2].

In a previous study [3], to reduce the effects of friction force, a pneumatic actuator prototype has been proposed. Seals used in normal pneumatic cylinders are removed and the slider of the pneumatic actuator is mounted with externally pressurized air bearings. An air film separates the slider and its guide, attaining a non-contact drive. Controlling this pneumatic actuator, positioning accuracy is ±2[μm] for step responses and low constant velocities control tests [3].

While the control of step responses is very important, the more demanding task of trajectory tracking is also of crucial importance. When electrical motors are used, a smooth trajectory tracking can be realised by setting a constant acceleration motion. However, in pneumatic servo systems, the characteristics are different from electrical motors, and it is unknown which motion is suitable for the cylinder to follow for an accurate and speedy response.

In this paper, a generation law for the trajectory tracking given to the pneumatic servo is proposed and tested on the pneumatic servo system with air bearings.

3. PNEUMATIC ACTUATOR WITH AIR BEARINGS AND SERVO SYSTEM

Fig.1 shows a schematic view of the pneumatic actuator prototype. This actuator has been developed for product machine, for example the reticle stage, in the semiconductor industry. The slider is the moving part of the actuator and the guide is fixed at its extremes. The pressured wall is attached to the slider; consequently, the slider moves because of the pressure difference at both sides of the pressured wall. The pressured wall forms four chambers between guide and slider. Each of the two chambers at each side of the pressured wall are charged or discharged through the same pipe.

The slider is mounted in the guide through externally pressurised air bearings. The air bearings act through holes in the surface of the guide, attaining a non-contact drive between slider and guide during movement. Air for the bearings is supplied and discharged from both extremes of the guide.

Fig.2 shows the main components of the servo system: pneumatic actuator and two servo valves. The slider of the pneumatic actuator is mounted with externally pressurised air bearings. The pneumatic actuator is driven by two high-speed 3-port, 3-position servo valves.

The spools of the servo valves also attain a non-contact drive through air bearing mechanism. The position of the spool is measured by a linear sensor of resolution 0.1[μm]. This servo valves have a higher performance than commercially available servo valves, with a dynamic frequency of 300[Hz] and a hysteresis of 0.0001%. The servo valves are controlled by the same controller of the pneumatic actuator.
Pressures of the pneumatic actuator chambers, slider displacement and servo valve spool displacement are measured. The displacement of the pneumatic actuator is measured by an autocollimator of resolution 0.05 [μm]. The measured values are passed to a personal computer that acts as a controller and sends the control signals to the servo valves.

![Fig.1 Pneumatic Actuator with Air Bearings](image)

4. CONTROL METHOD

4.1 Mathematical Model

The pneumatic servo system consists of two servo valves, a pneumatic actuator and the connecting pipes. In this study, the influence of the pipes is neglected. The flow equation, state equation of ideal gases and motion equation are written below under the following assumptions:

- State change is isothermal
- Chamber 1 is charged while chamber 2 is discharged
- The flow from/to Chamber 1 and Chamber 2 are not choked
- Friction force is negligible because of the air bearings
- Air leakage is negligible because it is smaller than driving flow rate

**[Flow equation]**

\[ G_1 = K_f S_{e1} P_s \left( 1 - \frac{P_1}{P_s} \right)^2, \quad \frac{P_1}{P_s} > b \]  
\[ G_2 = K_f S_{e2} P_2 \quad \frac{P_a}{P_2} \leq b \]  

where:

\[ K_f = \frac{\kappa}{R \theta_a} \left( \frac{2}{k+1} \right) \frac{k+1}{k-1} \]  

**[State equation of ideal gases]**

\[ V_1 \frac{dP_1}{dt} = R \theta_a G_1 - AP_1 v \]  
\[ V_2 \frac{dP_2}{dt} = R \theta_a G_2 + AP_2 v \]

**[Motion equation]**

\[ M \frac{d^2 x}{dt^2} = (P_1 - P_2) A \]  

4.2 Open loop transfer function

Linearising the equations of flow and state equations of ideal gases, the open loop transfer function is given by Eq.(7):
Where coefficient $K_n$ and natural frequency $\omega_n$ are given by:

$$K_n = \frac{K_f K_m R \theta_n (1+\varphi)}{2A}$$  \hspace{1cm} (8)

$$\omega_n = \sqrt{\frac{2P_0 A^2}{MV_o}}$$  \hspace{1cm} (9)

$$\varphi = \frac{P_x}{P_o} \sqrt{\left(\frac{P_o - b}{1-b}\right)^2}$$  \hspace{1cm} (10)

4.3 Displacement Control

The linear model derived is used as a basis for a controller design. A simple controller that has proven to stabilise pneumatic servo systems is the state feedback controller [5]. Position, velocity and acceleration of the system to be controlled are used to compute the controller output:

$$u = K_p (x_{ref}(t) - x) - K_v v - K_a a$$  \hspace{1cm} (11)

The closed loop transfer function from $x_{ref}$ to $x$ becomes:

$$G_c(s) = \frac{K_p K_n \omega_n^2}{s^3 + K_a K_n \omega_n^2 s^2 + (K_v K_n + 1) \omega_n^2 s + K_p K_n \omega_n^2}$$  \hspace{1cm} (12)

Information on velocity and acceleration can be obtained by differentiating the position signal but the differentiation increases the noise present in the position signal. Therefore, velocity and acceleration are obtained using a Kalman filter.

The value of $K_p$ is decided by the dynamic characteristic of the servo valve and, its value was found from simulation. From Eq.(12), since the poles of the system depend on $K_p$, $K_v$ and $K_n$, the values of $K_v$ and $K_n$ can be found by choosing appropriate poles.

To compensate for non-linear characteristics of the servo valves and parameter variations, a disturbance observer with first order filter $F(s)$ is introduced.

Fig.3 shows the block diagram of the position control.
system with state feedback, Kalman filter and disturbance observer. The closed loop transfer function has a steady state velocity error. When the disturbance observer perfectly compensates the nonlinearity of flow-rate characteristics, the transfer function of air pressure servo system is equal to Eq.(12). To compensate for this steady state error, an inverse model, which is a reciprocal of Eq.(12), has been added.

5. GENERATION OF TRAJECTORY

In the trajectory tracking control of the pneumatic servo system, which is a third order system, tracking error appears from the reference trajectory. To avoid these error, generally, an inverse model of the system is added as a feed forward compensator. The inverse model is shown in Fig.3.

The trajectory reference to drive the pneumatic servo system will be commented: The term $s^3$ is included in the numerator of $G^{-1}_c(s)$. Since the input to $G^{-1}_c(s)$ is position, $s$ represents velocity, $s^2$ represents acceleration, and $s^3$ becomes jerk. On the other hand, the transfer function for servo motor systems is second order, so that the term $s^2$ is included in the numerator when a feed forward compensator is used. Therefore, trajectory reference with constant acceleration is adopted. If the same signal is input to pneumatic servo systems, the output of $G^{-1}_c(s)$ includes the impulse signal form $s^3$, which is not possible to follow in any system.

To avoid this problem, a trajectory reference with constant jerk is adopted as shown in Fig.4, where it can also be seen the acceleration, velocity and trajectory of the slider.

6. EXPERIMENTAL AND SIMULATION RESULTS

The trajectory tracking in the case of constant acceleration and constant jerk are compared in Fig.5. These are simulation results considering a linear model shown in Eq.(7). While it can be seen a maximum error of 10[mm] in the trajectory tracking with constant acceleration, no errors can be seen when constant jerk is
considered, verifying the effectiveness of trajectory tracking with jerk constant.

To validate the performance and effectiveness of the servo pneumatic system, trajectory tracking tests were carried out. The slider is moved from -90[mm] to 90[mm]. Position 0[mm] represents the middle point of the slider.

Fig.6 shows the experimental and simulation results for the trajectory tracking when the constant jerk is 125 [m/s³] and when the acceleration time is 0.16[s], like Fig.4. It can be seen that the slider reaches a maximum velocity of 0.8[m/s] and a maximum acceleration of 10[m/s²]. Despite the high velocity and acceleration of the slider, it can be seen a good accuracy of ± 50[µm].

Concerning experimental and simulation results, it can be seen a good agreement in Fig.6. For this reason, the causes of the ± 50[µm] error was investigated using the simulation. It is found that the biggest influence was that of the non-linearities of the air mass flow.

Currently, compensation methods for the non-linear characteristics of the flow are designed. Also, simulation results show that the pneumatic servo system can be driven at 40[m/s²] and 1.2[m/s].

It is clarified that it is possible the trajectory tracking of the pneumatic servo system with high accuracy at high velocities.

7. CONCLUSIONS

The developed servo pneumatic actuator with air bearing is tested in the more demanding task of trajectory tracking with acceleration of 10[m/s²] and velocity of 0.8[m/s].

Considering the characteristics of the pneumatic servo system, it is clarified that for trajectory tracking, better results are obtained with constant jerk motion instead of constant acceleration motion.

Generating such trajectory reference, and despite the high speed requirements, experimental results show a maximum error of ±50[µm]. Also, the trajectory tracking at high constant velocity could be realised without velocity ripples, showing better results than with linear motors.

REFERENCES