INTRODUCTION
Externally pressurized gas-lubricated thrust bearings (aerostatic bearings) keep the bearing clearance constant under a constant supply pressure. We investigated how controlling the supply pressure with an electro-pneumatic servovalve can be used to dynamically adjust the bearing gap height. As a result of our investigation, we developed an electro-pneumatic servo-actuator “pneumatic servo bearing actuator (PSBA)” for position control, force control, and acceleration control. This paper describes a new approach to ultraprecise positioning that uses PSBAs with multiple-layered thin bearing pads in a tandem arrangement.

The wide range of potential uses of PSBAs requires the use of bearing pads with diameters ranging from small to large, or a bearing with various numbers of the layered pads. We tested the load capacity of single-pad, 3-layered-pad, 10-layered-pad, and 30-layered-pad PSBAs. We also tested the dynamic response of the ten-layered-pad actuator.

FEATURES OF PNEUMATIC SERVO BEARING ACTUATION SYSTEMS
Pneumatic servo bearing actuation systems have a number of attractive features that form a baseline against which alternate technology systems should be compared.

- simple structure
- simple energy storage and power conversion
- wide temperature capability
- long-term stability
- no EMI or radiation susceptibility
- low hysteresis
- low noise
- high resolution
- high accuracy
- high dynamic response
- high backdrive stiffness (high bearing stiffness)
- slight temperature rise over entire actuation range

SYSTEM COMPONENTS
Servovalve
A three-way, voice-coil-motor-operated nozzle-flapper valve controls the pneumatic flow into and out of the PSBA supply port. Changes in this flow control the pressure of the bearing clearance.

A schematic diagram of servo valve is shown in Figure 1.

The nozzle-flapper uses the cylindrical curtain orifice area formed by a flapper (driven by a voice coil motor) moving towards a sharp edged orifice and RS restrictor (fixed orifice).

In a typical application, the bandwidth frequency of the force motor is 200 Hz.

The block diagram in Figure 2 illustrates the system dynamics.

Figure 1. Nozzle-flapper type servo valve.

Figure 2. Block diagram for NF type servovalve.
The servovalve specifications are summarized in Table 1.

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated Current</td>
<td>1.5A</td>
</tr>
<tr>
<td>Operating Pressure</td>
<td>~ 1MPa</td>
</tr>
<tr>
<td>Rated Flow</td>
<td>8 l/min at 0.4MPa</td>
</tr>
<tr>
<td>Hysteresis</td>
<td>Less than 0.1%</td>
</tr>
</tbody>
</table>

### Table 1. Specifications of servovalve.

#### Bearing actuator

A model of the bearing actuator with the tandemly arranged bearing pads is shown in schematic form in Figure 3.

![Figure 3. Dynamic model of bearing actuator.](image)

The patterns of grooves on the bearing pad surface is shown schematically in Figure 4.

![Figure 4. Bearing pad.](image)

The specifications of a typical bearing pad are listed in Table 2.

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outer radius of bearing pad</td>
<td>18mm</td>
</tr>
<tr>
<td>Radius of inlet port</td>
<td>5mm</td>
</tr>
<tr>
<td>Spool mass</td>
<td>350g</td>
</tr>
<tr>
<td>Volume, V</td>
<td>3cc</td>
</tr>
</tbody>
</table>

Clearly, a number of simplifying assumptions have been made to arrive at the matrix model.

- the mass of layered pad is negligible (0.6g),
- the performance is modeled for a small stroke at the operating point,
- the gap height between identical configuration pads can be assumed to create the same operation,
- a lumped parameter model is used for the bearing actuator so the admittance matrix can be made linearization

A bearing model with many tandemly arranged pads that was developed for analysis and matching between the bearing and the servovalve or load is shown in Figure 5.

![Figure 5. Bearing actuator model.](image)

Five parameters are used in the model.

- \( n \) : number of bearing pads
- \( Y_{11} \) : input admittance
- \( Y_{12} \) : flow gain across bearing
- \( Y_{21} \) : thrust force gain
- \( Y_{22} \) : stiffness and damping coefficient

The equations relating the number of pads to the stiffness, damping, and mass of the tandem-layered bearing actuator are:

\[
(Mx_n^2 + \frac{D}{n}s + \frac{K}{n})\Delta v = \Delta f_x
\]  

(1)

where

- \( \Delta f_x = Y_{12}\Delta p_c \)
- \( \Delta f_s = \Delta f_x = \Delta f_1 \cdot \cdots \cdot \Delta f_n \)
- \( Y_{21} = \Delta f / \Delta P_c \)
- \( \Delta v = n \cdot \Delta x \)

The meanings of the symbols should be referred to Figure 3 and 5. Equation (1) is effectively used to simulate numerically the motion of the top pad.

### PSBA SYSTEM MODEL

A PSBA system is constructed of a servo amplifier, a servovalve, a thrust bearing, and position transducer (for closed-loop control).

The PSBA system model depicted in Figure 6 is for two system configurations, an open-loop system without position feedback and a closed-loop system with position feedback.

External disturbances due mainly to servovalve null shift are labeled “E.D.”.

The advantages of pressure-generation are combined with the high accuracy and high responsibility of the nozzle-flapper valve operated by the moving coil type force motor.
The open-loop PSBA system has good time response and high accuracy. An electrical position feedback PSBA has better linearity, better null stability with external disturbances, (such as supply pressure change, temperature change, and external force change), and higher dynamics, resulting in a higher closed loop gain.

TEST APPARATUS
The static characteristics and dynamic characteristics of the PSBA system were measured using the test apparatus illustrated in Figure 7.

A high resolution and high response stroke sensor (ADE Ltd.) was attached to the outside of the actuator to measure the actuator stroke with sub nano resolution. A single-axis tandem-arranged actuator is diagrammed in Figure 8.

RESULTS UNDER OPEN-LOOP CONTROL
Static Characteristics
The load capacities for the four types of actuators, (single-pad, 3-layered-pads, 10-layered-pads, and 30-layered-pads) are shown in Figure 9. Note that the bearing stiffness can be obtained by $\frac{\Delta f_s}{\Delta y}$ from the results.

Response Characteristics
We tested a ten-layered-pads PSBA controlled by a servovalve with precise eight-step input. As shown Figure 10 each step covered about 10 nm, so the PSBA controlled the stroke with a high resolution, high stability, and low noise.
Dynamic Characteristics

The bearing gaps of a ten-layered-pads PSBA were controlled by adjusting the input pressure. The bearing inherent dynamics is represented by the frequency response plots in Figure 11.

![Frequency response plot](image1)

*Figure 11. Inherent frequency response.*

Indicate cutoff frequency may be 200 Hz and that damping ratio may be 0.7 assuming a 2nd order system.

The frequency response in the amplifier input versus output stroke of the ten-layered-pad PSBA with open-loop control is shown in Figure 12.

![Frequency response plot](image2)

*Figure 12. Frequency response (open-loop).*

The stiffness of the closed-loop PSBA at the operating point was the 12 times larger than that of the open-loop one.

Dynamic Characteristics

The frequency response results are shown in Figure 14. The amplifier gain was adjusted to achieve a loop gain which resulted in a peak amplitude ratio of 1 (0dB).

![Frequency response plot](image3)

*Figure 14. Frequency response (closed-loop).*

CONCLUSION

The excellent performance capabilities of the pneumatic servo bearing actuator mean that it should be directed primarily at applications in the semiconductor industry requiring ultraprecise positioning.

REFERENCES