DESIGN AND DEVELOPMENT
OF A SERVOCONTROLLED GAS INBLEED SYSTEM
FOR A HIGH VACUUM CALIBRATION CHAMBER

Albert J. Mathews and Fred M. Shofner
ARO, Inc.

May 1968

This document has been approved for public release
and sale; its distribution is unlimited.

AEROSPACE ENVIRONMENTAL FACILITY
ARNOLD ENGINEERING DEVELOPMENT CENTER
AIR FORCE SYSTEMS COMMAND
ARNOLD AIR FORCE STATION, TENNESSEE

PROPERTY OF U. S. AIR FORCE
ARDC LIBRARY
AF 40(600)1200
NOTICES

When U. S. Government drawings specifications, or other data are used for any purpose other than a definitely related Government procurement operation, the Government thereby incurs no responsibility nor any obligation whatsoever, and the fact that the Government may have formulated, furnished, or in any way supplied the said drawings, specifications, or other data, is not to be regarded by implication or otherwise, or in any manner licensing the holder or any other person or corporation, or conveying any rights or permission to manufacture, use, or sell any patented invention that may in any way be related thereto.

Qualified users may obtain copies of this report from the Defense Documentation Center.

References to named commercial products in this report are not to be considered in any sense as an endorsement of the product by the United States Air Force or the Government.
DESIGN AND DEVELOPMENT
OF A SERVOCONTROLLED GAS INBLEED SYSTEM
FOR A HIGH VACUUM CALIBRATION CHAMBER

Albert J. Mathews and Fred M. Shofner*
ARO, Inc.

This document has been approved for public release and sale; its distribution is unlimited.

*F. M. Shofner is a consultant to ARO, Inc., and a professor of electrical engineering at the University of Tennessee Space Institute, Tullahoma, Tennessee.
FOREWORD

The work reported herein was done at the request of Headquarters, Arnold Engineering Development Center (AEDC), Air Force Systems Command (AFSC), under Program Element 6540215F, Project 4344, Task 434421.

The results of research reported herein were obtained by ARO, Inc. (a subsidiary of Sverdrup & Parcel and Associates, Inc.), contract operator of AEDC, AFSC, Arnold Air Force Station, Tennessee, under Contract AF40(600)-1200. The work was conducted under ARO Project No. SW5806, and the activities directly associated with the work extended from March 1 to September 1, 1967. The manuscript was submitted for publication on March 22, 1968.

This technical report has been reviewed and is approved.

J. G. Clark  
Major, CF  
Research Division  
Directorate of Plans  
and Technology

Edward R. Feicht  
Colonel, USAF  
Director of Plans  
and Technology
ABSTRACT

A servocontrolled gas inbleed system for a dynamic, calibrated conductance type of vacuum calibration system was designed and fabricated. The servocontrolled gas inbleed system automatically regulates the flow of gas into the test region of the calibration system by maintaining a constant pressure on the upstream side of a molecular leak. Constant pressure on the molecular leak is established and maintained by a shunt control technique in which a gas inlet valve and a gas pumpout valve are operated in parallel. An analog computer was used to aid in the design of the system. The transient and steady-state response of the servocontrolled gas inbleed system is predicted by the computer. Good agreement was obtained between the analog computer data and the experimental performance data obtained from the gas inbleed system. The gas inbleed system can control the flow rate in the range from $10^{-5}$ torr-liters/sec to $10^{-3}$ torr-liters/sec. Other flow rates are obtainable by changing system components; however, the same design procedure is applicable.
# CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABSTRACT</td>
<td>iii</td>
</tr>
<tr>
<td>NOMENCLATURE</td>
<td>rii</td>
</tr>
<tr>
<td>I. INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>II. DESIGN APPROACH</td>
<td>1</td>
</tr>
<tr>
<td>III. DESCRIPTION OF THE VACUUM CALIBRATION SYSTEM</td>
<td>2</td>
</tr>
<tr>
<td>IV. DESCRIPTION OF THE SERVOCONTROLLED GAS INBLEED SYSTEM</td>
<td>5</td>
</tr>
<tr>
<td>V. ANALYSIS AND EVALUATION OF THE SERVOCONTROLLED GAS INBLEED SYSTEM USING NONLINEAR ANALOG COMPUTER TECHNIQUES</td>
<td>6</td>
</tr>
<tr>
<td>VI. EXPERIMENTAL RESULTS</td>
<td>6</td>
</tr>
<tr>
<td>VII. CONCLUSIONS</td>
<td>8</td>
</tr>
<tr>
<td>REFERENCES</td>
<td>8</td>
</tr>
</tbody>
</table>

# APPENDIXES

## I. ILLUSTRATIONS

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Vacuum Calibration System Schematic</td>
<td>11</td>
</tr>
<tr>
<td>2</td>
<td>Vacuum Calibration System Flow Diagram</td>
<td>12</td>
</tr>
<tr>
<td>3</td>
<td>Mechanical Schematic for the Servocontrolled Gas Inbleed System</td>
<td>13</td>
</tr>
<tr>
<td>4</td>
<td>Valve Conductance versus Gas Inlet Valve Shaft Angle</td>
<td>14</td>
</tr>
<tr>
<td>5</td>
<td>Valve Conductance versus Gas Pumpout Valve Shaft Angle</td>
<td>15</td>
</tr>
<tr>
<td>6</td>
<td>Servocontrolled Gas Inbleed System Flow Diagram</td>
<td>16</td>
</tr>
<tr>
<td>7</td>
<td>Error Signal ($V_E$) versus Gas Pumpout Amplifier Input Signal ($V_{Phil}$)</td>
<td>17</td>
</tr>
<tr>
<td>8</td>
<td>Error Signal ($V_E$) versus Gas Inlet Amplifier Input Signal ($V_{Phil}$)</td>
<td>18</td>
</tr>
<tr>
<td>Figure</td>
<td>Description</td>
<td>Page</td>
</tr>
<tr>
<td>--------</td>
<td>-----------------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>9.</td>
<td>Gas Pumpout Amplifier Input Signal ($V_{phil}$) versus Gas Pumpout Servomotor Control Voltage ($V_{SM}$)</td>
<td>19</td>
</tr>
<tr>
<td>10.</td>
<td>Gas Inlet Amplifier Input Signal ($V_{phil}$) versus Gas Inlet Servomotor Control Voltage ($V_{SM}$)</td>
<td>20</td>
</tr>
<tr>
<td>11.</td>
<td>Analog Computer Flow Diagram</td>
<td>21</td>
</tr>
<tr>
<td>12.</td>
<td>Transient Response for a Forepressure Set Equal to $1 \times 10^{-2}$ torr</td>
<td>22</td>
</tr>
<tr>
<td>13.</td>
<td>Transient Response for a Forepressure Set Equal to $3.33 \times 10^{-2}$ torr</td>
<td>23</td>
</tr>
<tr>
<td>14.</td>
<td>Transient Response for a Forepressure Set Equal to $1.0 \times 10^{-1}$ torr</td>
<td>24</td>
</tr>
<tr>
<td>15.</td>
<td>Transient Response for a Forepressure Set Equal to $3.3 \times 10^{-1}$ torr</td>
<td>25</td>
</tr>
<tr>
<td>16.</td>
<td>Transient Response for a Forepressure Set Equal to 1.0 torr</td>
<td>26</td>
</tr>
<tr>
<td>17.</td>
<td>Transient Response for a Forepressure Set Equal to 1.0 torr</td>
<td>27</td>
</tr>
<tr>
<td>II.</td>
<td>SAMPLE CALCULATION FOR THE NUMERICAL VALUES OF $C_3$</td>
<td>28</td>
</tr>
<tr>
<td>III.</td>
<td>SAMPLE CALCULATION FOR THE NUMERICAL VALUES OF $C_4$</td>
<td>29</td>
</tr>
<tr>
<td>IV.</td>
<td>TABLES</td>
<td></td>
</tr>
<tr>
<td>I.</td>
<td>EXPERIMENTAL DATA USED TO CALCULATE $C_3$</td>
<td>30</td>
</tr>
<tr>
<td>II.</td>
<td>EXPERIMENTAL DATA USED TO CALCULATE $C_4$</td>
<td>31</td>
</tr>
</tbody>
</table>
NOMENCLATURE

C  
Equivalent capacitance for volume between molecular leak, gas inlet valve, gas pumpout valve, and differential pressure meter

C₁  
Molecular leak conductance

C₂  
Circular orifice conductance

C₃  
Gas inlet valve conductance

C₄  
Gas pumpout valve conductance

CCW  
Counterclockwise

CW  
Clockwise

Kₘᵢ  
Gas inlet servomotor gain constant

Kₘₒ  
Gas pumpout servomotor gain constant

n'  
Moles of gas

P₂  
Vacuum chamber test region pressure

P₃  
Diffusion pump pressure

Pₑₐ  
Molecular leak forepressure

Pᵣ  
Differential pressure meter reference pressure

Pₐ  
Alphatron pressure

Q  
Gas flow rate into volume V

ΔQ  
Net flow rate

Q₁  
Gas flow rate through molecular leak C₁

Q₂  
Gas flow rate through calibrated orifice C₂

Q₃  
Gas flow rate through gas pumpout valve

Q₄  
Gas flow rate through gas inlet valve

R₀  
Universal gas constant

T  
Temperature of gas

T₁  
Servomotor time constant

T₂  
Servomotor time constant

T₃  
Servomotor time constant

V  
Volume between V₂, differential pressure meter, C₁, and V₁
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_1$</td>
<td>Gas inlet valve</td>
</tr>
<tr>
<td>$V_2$</td>
<td>Gas pumpout valve</td>
</tr>
<tr>
<td>$V_E$</td>
<td>Error signal, numerical difference between the reference signal and the differential pressure meter signal</td>
</tr>
<tr>
<td>$V_{EB}$</td>
<td>Differential pressure meter signal, equivalent to the actual test region pressure</td>
</tr>
<tr>
<td>$V_{Phil}$</td>
<td>Gas pumpout amplifier and gas inlet amplifier signal, limit switches not activated</td>
</tr>
<tr>
<td>$V_R$</td>
<td>Reference signal, equivalent to desired test region pressure</td>
</tr>
<tr>
<td>$V_{SM}$</td>
<td>Gas inlet servomotor control voltage</td>
</tr>
<tr>
<td>$\theta_{in}$</td>
<td>Gas inlet valve shaft angle</td>
</tr>
<tr>
<td>$\theta_{out}$</td>
<td>Gas pumpout valve shaft angle</td>
</tr>
</tbody>
</table>
SECTION I
INTRODUCTION

Space simulation and testing require accurate measurement of total and partial pressures below $10^{-4}$ torr. Ionization gages and mass spectrometers are commonly used and are basically gas density measuring devices whose sensitivities vary with the type of gas. Vacuum measurement with these instruments is a complicated process involving calibration of instrument response to absolute pressure and a careful application of this calibration in measurement of unknown pressures.

To establish working standard pressures for the calibration of total and partial pressure instruments below $10^{-4}$ torr, a dynamic, calibrated conductance type of vacuum calibration system was designed and fabricated at the Arnold Engineering Development Center Aerospace Environmental Facility (AEF) (Ref. 1).

Working standard partial pressures have been established with an accuracy of ±5 percent throughout the range from $10^{-8}$ to $10^{-4}$ torr. A standard pressure was established by introducing nitrogen (N$_2$) gas through a porous leak into a test region which is exhausted through an orifice in a thin diaphragm. The accuracy with which the pressure in the test region can be established is dependent on establishing a constant, known flow rate through the porous leak.

The purpose of this study was to design and develop a servocontrolled gas inbleed system to maintain constant flow rates into the test region of the calibration system. The design approach is generally applicable to other gas inbleed control systems.

SECTION II
DESIGN APPROACH

After the study of other servotechniques, a shunt controller was developed by Shofner for use in the study of large signal transient response in dc-pumped helium-neon plasma lasers (Ref. 2). Although this was an electronic circuit involving a tetrode shunt tube in parallel with a laser to shunt current away from the laser, the same principle of operation can be applied to a gas inbleed system. The gas inbleed valve can be shunted by a gas pumpout valve to shunt gas away from the inbleed valve. Consequently, the overshoot transient response of the flow system is greatly reduced and contamination problems of the gas inbleed system are eliminated by purging the system through the gas pumpout valve.
The conventional approach to the design of servocontrolled systems is to use linear network analysis to determine system stability and optimization. Techniques for the analysis of linear systems include Routh's stability criteria and root-locus stability criteria (Ref. 3). To apply these techniques to nonlinear systems, operating points are chosen, and linear approximations are made around these points. These techniques can then be utilized to determine stability and optimization. However, a linear analysis of nonlinear systems is only an approximation. A better approach than linear approximations is a nonlinear analysis made on an analog computer. The insertion of the characteristics of various nonlinear elements such as control valves and amplifiers is readily made on an analog computer. The transient and steady-state response of each element in the servoloop, as well as their combined effect, can be recorded. In addition, the computer can show the results in "real time" or in "fast time." A feature of the "fast time" selector is the ability to speed up the computer so that the steady-state response for an extended period of time can be represented during a short period.

SECTION III
DESCRIPTION OF THE VACUUM CALIBRATION SYSTEM

Figure 1 (Appendix I) shows the major components of the calibration system. To maintain a constant test region pressure, \( P_2 \), the forepressure \( P_{EB} \) must be held constant. Any drift in the forepressure is corrected by means of the servocontrolled valves \( V_1 \) and \( V_2 \). Opening valve \( V_1 \), a needle valve, enables an increase in the foreline pressure, whereas opening valve \( V_2 \), a coarse valve, enables a decrease in the foreline pressure. A needle valve was chosen for the gas inlet valve so that a very fine control over the increase in forepressure could be obtained. A coarse valve was chosen for the pumpout valve so that purging of the system could be accomplished in a minimum amount of time, and the overpressure transient response would be short. The capacitance manometer provides a control signal for the gas inbleed servosystem. The reference pressure, \( P_r \), of this instrument is held constant at \( 2 \times 10^{-3} \) torr by means of a mechanical pump. The range of the instrument is from 0.01 to 30.0 torr.

The flow diagram for the test region portion of the vacuum calibration system is shown in Fig. 2. Gas is introduced into the test region through a molecular leak of conductance \( C_1 \) and is pumped from the test region through a circular orifice of conductance \( C_2 \). The test region pressure, \( P_2 \), is calculated by equating the flow through the leak to the
flow through the circular orifice at equilibrium. At constant temperature, this leads to the following relationship

\[ C_i (P_{EB} - P_2) = C_2 (P_2 - P_3) \]  \hspace{1cm} (1)

By choosing a molecular leak with a small value of conductance, \( P_2 \) can be made much smaller than \( P_{EB} \). Similarly, \( P_3 \) can be made much smaller than \( P_2 \) by using a diffusion pumping speed much larger than the orifice conductance. The above equation can then be reduced to (Ref. 1)

\[ P_2 \approx \frac{C_i}{C_2} P_{EB} \]  \hspace{1cm} (2)

For the vacuum system used in this work, the conductances for \( N_2 \) were

\[ C_1 = 6.85 \times 10^{-3} \text{ liters/sec} \]

\[ C_2 = 6.00 \times 10^{-1} \text{ liters/sec} \]

Diffusion Pumping = 6 \times 10^3 \text{ liters/sec}

\( P_{EB} \) varies from 10^{-2} to 1.0 torr

With these values the calibrated pressure, \( P_2 \), in the test region can be set between the limits of 1.14 \times 10^{-6} to 1.14 \times 10^{-4} \text{ torr}.

The flow diagram for the servocontrolled portion of the vacuum calibration system is shown in Fig. 3. The flow as a function of time can be calculated from the equation of state for an ideal gas.

\[ PV = n' R_o T \]  \hspace{1cm} (3)

where \( n' \) is the number of moles in volume \( V \) at temperature \( T \); \( R_o \) is a universal gas constant. Taking the total time derivative gives

\[ P \frac{dV}{dt} + V \frac{dP}{dt} = \frac{d}{dt} R_o T = Q \]  \hspace{1cm} (4)

Since

\[ \frac{dV}{dt} = 0 \]  \hspace{1cm} (5)

\[ Q = V \frac{dP}{dt} \]  \hspace{1cm} (6)

The net flow in the forepressure line is given by

\[ \Delta Q = Q_4 - Q_1 - Q_3 \]  \hspace{1cm} (7)
where:
\[ Q_s = C_s (P_a - P_{EB}) \]
\[ Q_i = C_i P_{EB} \]
\[ Q_o = C_o P_{EB} \]

The forepressure, \( P_{EB} \), as a function of time can then be written
\[
\frac{dP_{EB}}{dt} = \frac{1}{V} \left[ C_s (P_a - P_{EB}) - C_i P_{EB} - C_o P_{EB} \right]
\]  
\( (8) \)

where \( V \) is the volume between \( V_2 \), the capacitance manometer, \( C_1 \), and \( V_1 \) in Fig. 3. This volume was determined to be 1.235 liters. The pressure \( P_a \), on the upstream side of valve \( V_1 \) is measured with an Alphatron gauge and maintained constant by means of the vacuum regulator. The forepressure, \( P_{EB} \), is measured with the capacitance manometer and provides the control signal for the servosystem. The molecular leak conductance, \( C_1 \), remains constant and was determined to be \( 6.85 \times 10^{-3} \) liters/sec by a procedure given in Ref. 1. The conductance \( C_3 \) of the gas inlet valve as a function of valve shaft angle, \( \theta_{in} \), and Alphatron pressure, \( P_a \), is given in Fig. 4. The curves were obtained by closing the gas pumpout valve, \( C_4 = 0 \), and letting the system reach steady state for various valve shaft angles. The conductance \( C_3 \) was then calculated (see Appendix II) directly from Eq. (8). Figure 4 shows that the conductance of the inlet valve as a function of shaft angle is nonlinear. The fact that the conductance of the inlet valve is a nonlinear function of Alphatron pressure indicates that the valve is operating in the transition flow region. Molecular flow equations were used throughout this study, and the appropriate curve for a particular Alphatron pressure was used. Molecular flow equations assume the conductance terms to be independent of pressure. By operating along a single Alphatron pressure curve, this requirement is satisfied.

The conductance \( C_4 \) of the gas pumpout valve as a function of valve shaft angle, \( \theta_{out} \), and forepressure is given in Fig. 5. The downstream pressure of the gas pumpout valve, \( 2 \times 10^{-3} \) torr, is negligible when compared to the upstream forepressure. These curves were obtained by presetting the inlet valve to give a nominal forepressure. The gas pumpout valve was then opened, and the system was allowed to reach steady state for various valve shaft angles. The conductance \( C_4 \) was then calculated (see Appendix III) directly from Eq. (8). The above comments that were made about the curves shown in Fig. 4 are also applicable to Fig. 5.
The fact that the conductance of the pumpout valve is a function of the foreline pressure indicates that the valve is operating in the transition flow region. To use molecular flow equations, the appropriate curve for a particular foreline pressure must be used so that the conductance terms in the equations are independent of pressure.

SECTION IV
DESCRIPTION OF THE SERVOCONTROLLED GAS INBLEED SYSTEM

The servocontrolled gas inbleed system is shown schematically in Fig. 6. A reference signal, equivalent to the desired test region pressure, is compared to the differential pressure meter signal which is proportional to the actual test region pressure. The resulting dc error signal is amplified and chopped. This error signal is applied to the gas pumpout power amplifier and the gas inlet power amplifier, respectively. The resulting signal from each power amplifier is applied to the gas pumpout servomotor and gas inlet servomotor, respectively. The gas inlet servomotor then drives the gas inlet valve, \( V_1 \), open or closed depending on the polarity of the error signal. Likewise, the gas pumpout servomotor drives the gas pumpout valve, \( V_2 \), open or closed depending on the polarity of the error signal. The phase shift of the servomotors is such that the rotation of the gas inlet and gas pumpout valves is opposite for a given error signal polarity. Full close and full open limit switches were installed on the valves to keep them from mechanically binding when they reach the end of their travel. This was accomplished by substituting 1.37 v for \( V_{ar} \) and opposite in polarity to \( V_{ar} \) when the full open and full closed limit switches were activated by stops on the valve shafts.

Figures 7 and 8 show the characteristics of the dc amplifier as an integral part of the servosystem. As indicated, the rotation of the valve shafts is opposite for a particular error signal polarity. Also, a dead zone exists whereby the error signal must exceed +1 mv before the valves will start to open or close. As indicated by the graphs, a dc level exists; that is, for zero error signal, -0.3 v were obtained at the input to the power amplifiers.

Figures 9 and 10 show the characteristics of the gas pumpout and gas inlet power amplifiers, respectively. Dead zone and motor shaft rotation is indicated in the graphs. To eliminate the possibility of the valves oscillating against each other, the gain of the inlet valve was set lower than the pumpout valve. Thus, for a certain error voltage, the
inlet valve rotates at a lower speed and comes to rest before the gas pumpout valve.

SECTION V
ANALYSIS AND EVALUATION OF THE SERVOCONTROLLED GAS INBLEED SYSTEM USING NONLINEAR ANALOG COMPUTER TECHNIQUES

The analog computer flow diagram for the servocontrolled gas inbleed system is shown in Fig. 11. The reference signal, \( V_R \), which is equivalent to the desired test region pressure, is compared to the differential pressure meter signal, \( V_{EB} \), which is equivalent to the actual forepressure. The error signal, \( V_E \), which is equivalent to the error pressure, is amplified by a dc amplifier — depicted by the first two blocks. If neither of the limit switches on the gas pumpout valve and on the gas inlet valve is activated, the error signal proceeds to both the gas pumpout and gas inlet power amplifiers. If one or both of the valves are near the full open or full close position, the appropriate limit switch will be activated according to valve shaft position to apply a constant error signal of 1.37 V to keep the valve from binding open or closed. The error signal is applied to the servomotor transfer functions. The resulting valve shaft angle positions are applied to the conductance function generators to give conductance values as a function of valve shaft angle. The particular operating curve of the gas pumpout conductance function generator is chosen according to the forepressure range; the operating curve of the gas inlet conductance function generator is chosen according to the Alphatron pressure. The instantaneous value of the gas pumpout conductance \( C_4 \), and the gas inlet conductance \( C_3 \), is substituted into the differential equation, which describes the vacuum portion of the gas inbleed system (see Eq. (8)). The forepressure line volume \( V \), the molecular leak conductance \( C_1 \), and the Alphatron pressure \( P_\alpha \) are constants. The computer solves for the resulting forepressure \( P_{EB} \) and plots it as a function of time.

SECTION VI
EXPERIMENTAL RESULTS

Figures 12 through 17 show the analog computer solutions for various operating conditions. The experimental data obtained from the physical system are plotted in the same graph so that a direct comparison between analog computer and experimental data can be made. The forepressure, error signal, gas inlet valve shaft position, and gas pumpout valve shaft
position are plotted as functions of time in each graph. Full close on each valve is represented by zero shaft degrees. The gas inlet valve is full open at 4590 deg; the gas pumpout valve is full open at 1710 deg.

Figure 12 shows the transient and steady-state response of the system for an Alphatron pressure of 3.1 torr and a voltage step of +10 mv at the reference input. The capacitance manometer output at a steady-state forepressure of $1 \times 10^{-2}$ torr is +10 mv when the manometer range is set at $30 \times 10^{-3}$ torr full scale. The response time of the physical system is better than that predicted by the analog computer. The pumpout valve oscillation which occurred in the computer solution is not understood. The experimental and computer data show the system to be stable for at least 150 sec. Since experimental data were not obtained beyond 150 sec, the oscillation cannot be verified or denied by experimental data. The computer data show the system to be stable for at least 450 sec. It is believed, however, that the system is capable of holding a steady forepressure of $1 \times 10^{-2}$ torr indefinitely.

Figure 13 shows the transient and steady-state response of the system for an Alphatron pressure of 3.1 torr, a voltage step input of +10 mv, and a capacitance manometer range of $1 \times 10^{-1}$ torr full scale. These settings establish a steady-state forepressure of $3.3 \times 10^{-2}$ torr. The data obtained in Fig. 13 are similar to the data obtained in Fig. 12. The oscillation of the pumpout valve is verified by experimental data. Even so, the system is capable of holding a steady forepressure of $3.3 \times 10^{-2}$ torr.

Figure 14 shows the transient and steady-state response of the system for an Alphatron pressure of 25.0 torr, a voltage step input of +10 mv, and a capacitance manometer range of 0.30 torr full scale. The same characteristics that were made evident by Figs. 12 and 13 are shown in Fig. 14. Again the system is capable of holding a steady forepressure of $1 \times 10^{-1}$ torr for the above conditions.

Figure 15 shows the system to be stable for an Alphatron pressure of 28.0 torr, a voltage step input of +10 mv, and a capacitance manometer range of 1.0 torr full scale; however, oscillation of the pumpout valve is of such magnitude as to keep the error signal from reaching zero and the forepressure from stabilizing. The pressure snubber effect of the molecular leak $C_1$ (see Fig. 2) was sufficient to keep the test region pressure constant; thus a constant test region pressure of $3.7 \times 10^{-5}$ torr, which is equivalent to a forepressure of $3.3 \times 10^{-5}$ torr, can be obtained.
Figures 16 and 17 show the system to be stable and capable of holding a steady forepressure of 1.0 torr for an Alphatron pressure of 29.5 and 82.0 torr, respectively. The effect of the upstream pressure of the inlet valve on system response is evident from Figs. 16 and 17. The greater the Alphatron pressure, the faster the system responds, as would be expected.

To summarize, Figs. 12 through 17 show that the gas inbleed system is capable of holding a constant pressure in the test region between the limits of $1.14 \times 10^{-6}$ torr to $1.14 \times 10^{-4}$ torr.

SECTION VII
CONCLUSIONS

The feasibility of a shunt servocontrolled gas inbleed system for a high vacuum calibration chamber has been demonstrated. By shunting the gas inlet valve with a gas pumpout valve, the overshoot and time response of the inbleed system can be improved over using only a gas inbleed valve. The many advantages of using an analog computer for a nonlinear system analysis were demonstrated during the design and evaluation of the system.

REFERENCES


APPENDIXES

I. ILLUSTRATIONS
II. SAMPLE CALCULATION FOR THE NUMERICAL VALUES OF C_3
III. SAMPLE CALCULATION FOR THE NUMERICAL VALUES OF C_4
IV. TABLES
Fig. 1 Vacuum Calibration System Schematic
Molecular Leak

\[ \text{Surge Volume} \]

\[ Q_1 = C_1 (P_{EB} - P_2) \]

Instrument Port

Leak Forepressure, \( P_{EB} \)

Calibrated Orifice, \( C_2 \)

Test Region \( P_2 \)

Q. 2 = \( C_2 (P_2 - P_3) \)

\[ P_2 = \frac{C_1}{C_2} P_{EB} \text{ when } P_2 \ll P_{EB} \text{ and } P_3 \ll P_2 \]

Fig. 2 Vacuum Calibration System Flow Diagram
Fig. 3  Mechanical Schematic for the Servocontrolled Gas Inbleed System
Fig. 4 Valve Conductance versus Gas Inlet Valve Shaft Angle
Fig. 5 Valve Conductance versus Gas Pumpout Valve Shaft Angle
Fig. 6 Servocontrolled Gas Inbleed System Flow Diagram

- $V_R$ - Reference Signal, Equivalent to the Desired Test Region Pressure
- $V_E$ - Error Signal
- $V_{EB}$ - Differential Pressure Meter Signal, Equivalent to the Actual Test Region Pressure
Fig. 7 Error Signal ($V_E$) versus Gas Pumpout Amplifier Input Signal ($V_{Phil}$)
Fig. 8  Error Signal ($V_E$) versus Gas Inlet Amplifier Input Signal ($V_{Phi}$)
Fig. 9 Gas Pumpout Amplifier Input Signal ($V_{\text{Phil}}$) versus Gas Pumpout Servomotor Control Voltage ($V_{\text{SM}}$)
Fig. 10 Gas Inlet Amplifier Input Signal ($V_{Phil}$) versus Gas Inlet Servomotor Control Voltage ($V_{SM}$)
Vacuum Portion of the Gas Inlet System

Fig. 11 Analog Computer Flow Diagram
Fig. 12 Transient Response for a Forepressure Set Equal to $1 \times 10^{-2}$ torr

Conditions:
- Alphatron Pressure = 3.1 torr
- Capacitance Manometer Meter Range = $30 \times 10^{-3}$ torr
- Full Scale = 30 mv Full Scale
- Error Signal = $+10$ mv
Conditions:
Alphatron Pressure = 3.1 torr
Capacitance Manometer Meter Range = 0.10 torr Full Scale = 30 mv Full Scale
Error Signal = +10 mv

Fig. 13 Transient Response for a Forepressure Set Equal to $3.33 \times 10^{-2}$ torr
Conditions:
Alphatron Pressure = 25.0 torr
Capacitance Manometer Meter Range = 0.30 torr
Full Scale = 30 mv Full Scale
Error Signal = +10 mv

Fig. 14 Transient Response for a Forepressure Set Equal to $1.0 \times 10^{-1}$ torr
Fig. 15 Transient Response for a Forepressure Set Equal to $3.3 \times 10^{-1}$ torr
Conditions:
Alphatron Pressure = 29.5 torr
Capacitance Manometer Meter Range = 3.0 torr
Full Scale = 30 mv Full Scale
Error Signal = +10 mv

Fig. 16 Transient Response for a Forepressure Set Equal to 1.0 torr
Conditions:
Alphatron Pressure = 82.0 torr
Capacitance Manometer Meter Range = 3.0 torr
Full Scale = 30 mv Full Scale
Error Signal = +10 mv

Fig. 17 Transient Response for a Forepressure Set Equal to 1.0 torr
APPENDIX II
SAMPLE CALCULATION FOR THE NUMERICAL VALUES OF C₃

The conductance C₃ of the gas inlet valve as a function of valve shaft angle, θₜₒ, and the Alphatron pressure, Pₐ, is given in Fig. 4. The curves were obtained by closing the gas pumpout valve, C₄ = 0, and letting the system reach steady state for various valve shaft angles. The conductance C₃ was then calculated from Eq. (8) which is given below.

\[ \frac{dP_{EB}}{dT} = \frac{1}{V} \left[ C_3 (P_a - P_{EB}) - C_1 P_{EB} - C_4 P_{EB} \right] \]  \hspace{1cm} (9)

Applying the above conditions, Eq. (8) can be reduced to

\[ C_3 (P_a - P_{EB}) - C_1 P_{EB} = 0 \]  \hspace{1cm} (10)

\[ C_3 = \frac{C_1 P_{EB}}{P_a - P_{EB}} \]  \hspace{1cm} (11)

C₁ = 6.85 x 10⁻³ liters/sec. The experimental data used to calculate C₃ are given in Table I (Appendix IV).
APPENDIX III
SAMPLE CALCULATION FOR THE NUMERICAL VALUES OF C₄

The conductance C₄ of the gas pumpout valve as a function of valve shaft angle, θₑₒᵤᵗ, and forepressure, PₑB, is given in Fig. 5. The pressure downstream of the gas pumpout valve, 2 x 10³ torr, is negligible compared to the upstream pressure, that is, the forepressure. These curves were obtained by presetting the inlet valve to give a nominal forepressure. The gas pumpout valve was then opened and the system was allowed to reach steady state for various valve shaft angles. The conductance C₄ was then calculated directly from Eq. (8) which is given below.

\[
\frac{dP_{EB}}{dT} = \frac{1}{V} \left[ C₁(P_a - P_{EB}) - C₁P_{EB} - C₄P_{EB} \right]
\]  

(12)

Applying the above conditions, Eq. (8) can be reduced to

\[
C₄(P - P_{EB}) - C₁P_{EB} - C₄P_{EB} = 0
\]

(13)

\[
C₄ = \frac{C₁(P_a - P_{EB}) - C₁P_{EB}}{P_{EB}}
\]

(14)

C₁ = 6.85 x 10⁻³ liters/sec. The experimental data used to calculate C₄ are given in Table II (Appendix IV).
### Table I
**Experimental Data Used to Calculate \( C_3 \)**

<table>
<thead>
<tr>
<th>Gas Pumpout Valve</th>
<th>Gas Inlet Valve Stem Position, deg</th>
<th>( P_{EB} ), torr</th>
<th>( P_\alpha ), torr</th>
<th>( C_3 ), liters/sec</th>
</tr>
</thead>
<tbody>
<tr>
<td>Closed</td>
<td>Closed, 0</td>
<td>0</td>
<td>32</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>180</td>
<td>0.38</td>
<td>32</td>
<td>6.91 x 10(^{-5})</td>
</tr>
<tr>
<td></td>
<td>360</td>
<td>0.40</td>
<td>32</td>
<td>8.68</td>
</tr>
<tr>
<td></td>
<td>540</td>
<td>0.44</td>
<td>33</td>
<td>9.31</td>
</tr>
<tr>
<td></td>
<td>720</td>
<td>0.49</td>
<td>33</td>
<td>1.03 x 10(^{-4})</td>
</tr>
<tr>
<td></td>
<td>900</td>
<td>0.53</td>
<td>34</td>
<td>1.08</td>
</tr>
<tr>
<td></td>
<td>1080</td>
<td>0.59</td>
<td>34</td>
<td>1.21</td>
</tr>
<tr>
<td></td>
<td>1260</td>
<td>0.68</td>
<td>34</td>
<td>1.39</td>
</tr>
<tr>
<td></td>
<td>1440</td>
<td>0.74</td>
<td>34</td>
<td>1.52</td>
</tr>
<tr>
<td></td>
<td>1620</td>
<td>0.78</td>
<td>34</td>
<td>1.61</td>
</tr>
<tr>
<td></td>
<td>1800</td>
<td>0.84</td>
<td>34</td>
<td>1.74</td>
</tr>
<tr>
<td></td>
<td>1980</td>
<td>0.93</td>
<td>34</td>
<td>1.93</td>
</tr>
<tr>
<td></td>
<td>2160</td>
<td>0.97</td>
<td>34</td>
<td>2.01</td>
</tr>
<tr>
<td></td>
<td>2520</td>
<td>1.05</td>
<td>34</td>
<td>2.18</td>
</tr>
<tr>
<td></td>
<td>2880</td>
<td>1.13</td>
<td>33</td>
<td>2.42</td>
</tr>
<tr>
<td></td>
<td>3240</td>
<td>1.20</td>
<td>33</td>
<td>2.59</td>
</tr>
<tr>
<td></td>
<td>3600</td>
<td>1.30</td>
<td>32</td>
<td>2.90</td>
</tr>
<tr>
<td></td>
<td>3960</td>
<td>1.45</td>
<td>32</td>
<td>3.26</td>
</tr>
<tr>
<td></td>
<td>4320</td>
<td>1.65</td>
<td>31</td>
<td>3.86</td>
</tr>
<tr>
<td></td>
<td>4680</td>
<td>2.00</td>
<td>29.5</td>
<td>4.99</td>
</tr>
<tr>
<td></td>
<td>5040</td>
<td>2.45</td>
<td>27.0</td>
<td>6.83</td>
</tr>
<tr>
<td></td>
<td>5085</td>
<td>2.70</td>
<td>26.0</td>
<td>7.93</td>
</tr>
<tr>
<td>Gas Pumpout Valve, deg</td>
<td>Gas Inlet Valve Stem Position, deg CCW</td>
<td>$P_{EB}$, torr</td>
<td>$P_{\alpha}$, torr</td>
<td>$C_3$, liters/sec</td>
</tr>
<tr>
<td>------------------------</td>
<td>----------------------------------------</td>
<td>----------------</td>
<td>------------------</td>
<td>------------------</td>
</tr>
<tr>
<td>Closed</td>
<td>1800</td>
<td>14.0</td>
<td>105.0</td>
<td>$1.05 \times 10^{-3}$</td>
</tr>
<tr>
<td>180</td>
<td>1800</td>
<td>14.0</td>
<td>105.0</td>
<td>1.05</td>
</tr>
<tr>
<td>360</td>
<td>1800</td>
<td>14.0</td>
<td>105.0</td>
<td>1.05</td>
</tr>
<tr>
<td>540</td>
<td>1800</td>
<td>14.0</td>
<td>105.0</td>
<td>1.05</td>
</tr>
<tr>
<td>720</td>
<td>1800</td>
<td>14.0</td>
<td>105.0</td>
<td>1.05</td>
</tr>
<tr>
<td>900</td>
<td>1800</td>
<td>14.0</td>
<td>105.0</td>
<td>1.05</td>
</tr>
<tr>
<td>1080</td>
<td>1800</td>
<td>13.8</td>
<td>105.0</td>
<td>1.05</td>
</tr>
<tr>
<td>1260</td>
<td>1800</td>
<td>13.6</td>
<td>105.0</td>
<td>1.05</td>
</tr>
<tr>
<td>1440</td>
<td>1800</td>
<td>12.8</td>
<td>105.0</td>
<td>1.05</td>
</tr>
<tr>
<td>1620</td>
<td>1800</td>
<td>12.0</td>
<td>105.0</td>
<td>1.05</td>
</tr>
<tr>
<td>1800</td>
<td>1800</td>
<td>9.3</td>
<td>105.0</td>
<td>1.05</td>
</tr>
<tr>
<td>1980</td>
<td>1800</td>
<td>6.0</td>
<td>105.0</td>
<td>1.05</td>
</tr>
<tr>
<td>2025</td>
<td>1800</td>
<td>4.0</td>
<td>105.0</td>
<td>1.05</td>
</tr>
</tbody>
</table>
### Design and Development of a Servocontrolled Gas Inbleed System for a High Vacuum Calibration Chamber

**Abstract**

A servocontrolled gas inbleed system for a dynamic, calibrated conductance type of vacuum calibration system was designed and fabricated. The servocontrolled gas inbleed system automatically regulates the flow of gas into the test region of the calibration system by maintaining a constant pressure on the upstream side of a molecular leak. Constant pressure on the molecular leak is established and maintained by a shunt control technique in which a gas inlet valve and a gas pumpout valve are operated in parallel. An analog computer was used to aid in the design of the system. The transient and steady-state response of the servocontrolled gas inbleed system is predicted by the computer. Good agreement was obtained between the analog computer data and the experimental performance data obtained from the gas inbleed system. The gas inbleed system can control the flow rate in the range from $10^{-5}$ torr-liters/sec to $10^{-3}$ torr-liters/sec. Other flow rates are obtainable by changing system components; however, the same design procedure is applicable.
<table>
<thead>
<tr>
<th>KEY WORDS</th>
<th>LINK A</th>
<th>LINK B</th>
<th>LINK C</th>
</tr>
</thead>
<tbody>
<tr>
<td>gas inbleed systems</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>servocontrolled systems</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>transient response</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>steady-state response</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>vacuum calibration systems</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>automatic flow regulation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>shunt control technique</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

2. Gases -- Flow control
4. Flow -- Regulation
6. Vacuum calibration system

1-2