Technical Report No. 2

GAS-LIQUID PRESSURE TRANSMITTER

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I. INTRODUCTION

When considering possible means of providing external power to orthotic and prosthetic devices, pneumatic systems are usually regarded as the most promising general type.\(^1\)\(^2\)

Associated with using pneumatic power is the problem of providing an ambulatory patient with an energy-storage unit of adequate capacity and yet sufficiently light and compact. This problem becomes serious when considering devices called upon to do substantial amounts of work. Elbow flexing and humeral rotating devices, for example, are required to lift substantial "pay loads" carried by the hand.

The three types of pneumatic actuators currently considered for orthotic and prosthetic devices are the braided pneumatic actuator (McKibbom "artificial muscle"), the bellows, and the pneumatic cylinder. These are illustrated in Figs. 1 and 2. The braided actuator and the bellows waste an appreciable portion of the gas consumed because of the compressibility of the initial, or residual volume of gas contained within the device. But for many applications the braided actuator, in particular, possesses advantages over the cylinder in spite of the gas-consumption problem. Hence a study of means of reducing the gas consumption of these preferred actuator types appears timely.

Figure 1 shows the three actuator types mentioned above. Control valves, shown diagrammatically, are turned so as to vent the actuators to atmosphere. The bellows and braided actuators have a residual volume, \(V_0\), as shown. In Fig. 2, the valves are turned so as to pressurize the actuators. Each device experiences an increase in internal volume designated as \(\Delta V\). In the braided actuator and bellows, the incoming gas must fill not only volume \(\Delta V\), but also a portion of the initial volume \(V_0\). This excess volume of incoming gas needed to operate the actuator is equal to the amount by which the residual gas compresses. The magnitude of this compressibility loss depends on the operating pressure and on the ratio of volumes \(V_0\) and \(\Delta V\). Detailed relationships will be developed in Section IV.

Recognition of the above principle led Schulte (Appendix H of Ref. 1) to suggest that a portion of this loss could be eliminated in the case of the braided actuator by using a solid cylindrical plug, shown in Fig. 3. The loss was eliminated for that portion of \(V_0\) occupied by the plug. Unfortunately, the plug must be no longer than the shortest operating length of the actuator, and the diameter no larger than the smallest operating diameter.

The thought behind the present study is that by completely filling the actuator with a liquid, all of the actuator compressibility loss can be eliminated. Furthermore, by using liquid in the high-pressure tubing connected to
Fig. 1. Pneumatic actuators—not pressurized.

Fig. 2. Pneumatic actuators—pressurized.
the actuator, a similar (though usually very much smaller) compressibility loss in the tubing can be eliminated. Figure 4 shows diagrammatically how this can be accomplished. A chamber containing a diaphragm is mounted immediately adjacent the valve. Note that, with the valve turned so as to vent the actuator, there is no residual gas volume except for the very small volume in the

![Cylindrical Plug Diagram](image1)

**Fig. 3.** Cylindrical plug in braided actuator.

![Liquid-Gas Pressure Transmitter Diagram](image2)

**Fig. 4.** Liquid—gas pressure transmitter.
valve itself and in the diaphragm unit inlet fitting. When the valve is turned so as to pressurize the actuator, only the amount of gas needed to fill the actuator expansion volume, $\Delta V$, is required. The diaphragm is to be "limp," or unstretched, in all positions. Thus, the diaphragm is virtually unstressed except for uniaxial compression, and the liquid pressure in the actuator (under all static conditions) is precisely equal to the gas pressure at the diaphragm.

II. PURPOSE

The purposes listed in the Task Plan statement (included in the Appendix) are:

1. To evaluate the desirability of using a gas-liquid pressure transmitter at the control valve outlet for fluid orthetic actuators generally, and the McKibben muscle in particular.

2. To develop, if warranted, a transmitter suitable for use with one or more specific orthetic actuators.

III. CONCLUSIONS

1. Gas savings produced by the transmitter vary widely with actuator design and operating conditions; however, savings in the range of 25% to 75% were indicated for the four types of braided actuators tested. (See Fig. 21 for summary curves.)

2. Functional side-effects, all of which appear to be minor, are:
   a. Minimizing the residual gas volume tends to provide a more positive and quick-acting response, due to the decreased elasticity of the system.
   b. Using liquid in the connecting tubing increases viscous friction. This factor tends to slow down the response (thereby opposing side effect "a," above), and to add damping. The magnitude of this factor is largely controlled by the tubing inside diameter. If liquid is used only in the actuator and not in the tubing, this factor is, of course, not involved.

3. Disadvantages of the unit are increased cost, weight, bulk, and possibility of system failure. By proper design it appears that these will be more than offset by gas savings in certain installations involving gas-consumption problems.

4. Figures 5 and 6 illustrate an embodiment of the transmitter principle which has been built and tested, and which is suggested for field trial. This particular
transmitter has a displacement of 25 cc, and thus is suitable for use with any braided or bellows type actuator having a volume displacement, \( \Delta V \), of 25 cc or less. Ideally, the transmitter volume should be just slightly greater than the actuator displacement, \( \Delta V \). Transmitters having substantially larger volumes are disadvantageous only because of size and weight consideration.

IV. ANALYSIS OF GAS SAVINGS

A. SELECTION OF ISOTHERMAL PROCESS AS BASIS FOR ANALYSIS

The extent to which the residual volume of \( \text{CO}_2 \) in the actuator is compressed by the incoming high-pressure \( \text{CO}_2 \) depends not only on the pressure but also on the transfer of heat to or from the residual gas. For example, if the residual charge is compressed with no heat transfer (adiabatic compression), the compression causes the gas temperature to increase. This, in turn, tends to expand the compressed residual gas, thereby reducing the volume which must be filled by the
Fig. 6. Gas-liquid pressure transmitter—25 cc capacity.
incoming high-pressure gas. If the residual gas is cooled during compression so as to maintain a constant temperature (isothermal compression), this action is prevented. Figure 7 shows adiabatic and isothermal compression curves for C\textsubscript{2}O\textsubscript{2} which illustrate the magnitude of the above effect. The isothermal curve would be the same for any gas, whereas the adiabatic curve is a function of \(k\), the ratio of the specific heat at constant pressure \(c_p\) to the specific heat at constant volume \(c_v\), and varies for different gases. Note also that the pressures \(P_1\) and \(P_2\) in the Fig. 7 formulas are absolute pressures. At standard atmospheric pressure, absolute pressures are 14.7 psi greater than gage pressures.

Actually, the incoming high-pressure C\textsubscript{2}O\textsubscript{2} is at an extremely low temperature because it has been expanded from the supply pressure of 800 psi, and hence probably cools the residual gas enough to reduce its temperature during compression. This reduction in temperature would make the gas tend to contract, thereby increasing the volume to be filled by the incoming charge. A curve for this type of "compression during refrigeration" would fall below the isothermal curve of Fig. 7.

Depending on how rapidly the actuator is cycled, heat transfer from the air surrounding the actuator will raise the temperature of the gas inside the pressurized actuator (causing some increase in pressure within the actuator after the valve is turned off) to a point more or less approximating the initial temperature of the residual charge. Hence, the net effect of the residual gas compression is probably reasonably well approximated by the isothermal curve. (If the actuator is unused long enough to reach ambient temperature and then operated through one quick cycle of pressurizing and venting, the compressibility loss would be greater than the isothermal loss. If, on the other hand, the actuator is operated through one very slow cycle which immediately follows several fast cycles, the loss will be less than the isothermal value.)

Fortunately, the differences between calculated gas savings based on the various thermodynamic processes discussed are not sufficiently large to affect significantly the conclusions sought in this study. Hence, the analyses which follow are based on the simple isothermal process.

B. THEORETICAL GAS SAVING

As shown in Fig. 7, the pressure-volume relationship for isothermal compression of a gas is:

\[
P_2/P_1 = V_1/V_2, \text{ or } P_1V_1 = P_2V_2
\]  

(1)

Solving either equation for \(V_2\), we have:

\[
V_2 = P_1V_1/P_2.
\]  

(2)
Fig. 7. Compressibility of CO$_2$ isothermal vs. adiabatic.
The symbols in these equations have the following meanings:

\[ V_2 = \text{volume of residual gas after compression} \]

\[ P_1 = \text{initial pressure of residual gas, which is assumed to be atmospheric pressure, or 14.7 psi} \]

\[ V_1 = \text{initial volume of residual gas, referred to previously in this report as } V_0. \]

\[ P_2 = \text{final absolute pressure of residual gas, equal to the applied pressure, } p, \text{ plus 14.7 (lb per sq in.)} \]

Substituting the above relationships into Eq. (2) gives:

\[ V_2 = \frac{14.7 \ V_0}{p + 14.7} \quad (3) \]

The shrinkage in volume of the residual gas, \( V_0 - V_2 \), is equal to the volume of high-pressure actuating gas which is wasted, and will be designated by \( V_w \).

\[ V_w = V_0 - V_2 = V_0 - \frac{14.7 \ V_0}{p + 14.7} = V_0 \left( 1 - \frac{14.7}{p + 14.7} \right) \]

\[ = V_0 \left( \frac{p}{p + 14.7} \right) \quad (4) \]

To express the degree to which the compression of residual gas penalizes the gas consumption of the actuator, the term "gas utilization efficiency" (abbreviated U.E.) will be used and defined as follows:

\[ \text{U.E.} = \frac{\Delta V}{\Delta V + V_w} \quad (5) \]

Substitution of (4) in (5) yields:

\[ \text{U.E.} = \frac{1}{1 + \frac{V_0}{\Delta V} \left( \frac{p}{p + 14.7} \right)} \quad (6) \]

Utilization efficiency is thus the percent of gas supplied to the actuator which is useful in performing work. For example, a utilization efficiency of 70% would indicate that 70% of the gas used served to expand the actuator whereas the remaining 30% merely filled the space vacated by compression of the residual gas. Since use of the
gas-liquid transmitter would eliminate the wasted 30%, a utilization efficiency of 70% indicates a potential gas saving with the transmitter of 30%.

For clarification, Fig. 8 illustrates a pressurized braided actuator with volumes \( V_0 \), \( V_2 \), \( \Delta V \), and \( V_w \) indicated.

![Diagram of actuator with labeled volumes](image)

**Fig. 8.**

Figure 9 shows a plot of utilization efficiency (and potential gas saving) vs. the ratio \( V_0/\Delta V \) for various pressures, in accordance with Eq. (6). Figure 10 shows the same equation plotted with coordinates U.E. and \( p \). Pressures are plotted in pounds per square inch, gage (psig).

In applying Fig. 9 or 10 to determine potential gas savings for the braided actuator, complications arise because the ratio of residual volume to expansion volume varies both with applied pressure, \( p \), and with the axial force to which the actuator is subjected. This subject is dealt with below.
Fig. 9. Utilization efficiency (and potential gas saving) for various values of \( p \) and \( V_0/\Delta V \).
Fig. 10. Utilization efficiency (and potential gas saving) for various values of $p$ and $V_o/\Delta V$. 
C. GAS SAVING FOR CURRENTLY AVAILABLE BRAIDED ACTUATORS

At low pressures, braided actuators and bellows have high ratios $V_0/\Delta V$, and vice versa. Thus, when one of the two factors has a value tending to give large gas savings, the other factor tends to give a small saving. In a very general way, therefore, there is an inherent compensating action tending to equalize the potential savings over the pressure range.

To study the potential savings over the full operating range of a variety of existing braided actuator types, tests were made to determine the internal volume of typical W-1, W-2, W-31, and W-4 actuators. These types are described in Table I. The "W" designations correspond to those assigned by Schulte (Appendix II of Ref. 1) and indicate the chronological order in which actuators of various weaves were received from Rancho Los Amigos Hospital. The dimensions of the actuators tested are given in Table II. The results are represented in Figs. 11-14. Internal volume measurements were obtained as follows:

1. The actuator, end plate, and graduated cylinder were assembled as shown in Fig. 15. The system was partially filled with water. The actuator was alternately compressed and released several times to work out all entrapped air.

2. A spacer tube (one of a series, used to provide various fixed actuator lengths) was attached to the actuator, and the CO$_2$ system was attached to the graduated cylinder, as shown in Fig. 16.

3. Changes in actuator internal volume corresponding to various actuator lengths and pressures were determined by noting the corresponding changes in water level in the graduated cylinder.

4. With the actuator set at a fixed length and with the calibrated cylinder vented, the actuator was disconnected and drained into a burette. Special care was taken to insure complete drainage.

Figures 17-20 contain utilization efficiency (and potential gas saving) curves based on the internal volume data given in Figs. 11-14. In all cases, initial volume, $V_0$, is taken as the value measured at the free length, $L_0$.

Figure 21 shows the variation of utilization efficiency (and potential gas saving) for all four actuators as a function of percent of axial contraction. Pressure was held constant at 50 psig for this figure; however, examination of Figs. 17-20 indicates that there is relatively little variation of utilization efficiency with pressures over 30 psig. The two dotted curves illustrate the additional loss in utilization efficiency (additional potential gas saving) associated with a four foot length of 1/16-in. bore tubing attached to the W-2 and W-4 actuators. As shown, tubing of this internal volume drops the utilization efficiency in the order of 3 to 5%, and hence increases potential gas savings by the same percentage.
<table>
<thead>
<tr>
<th>Code No.</th>
<th>Weave Type</th>
<th>Type of Fibers</th>
<th>Type of Strand and Approx. Thickness</th>
<th>Helix Angle θ Degrees</th>
<th>Weave Spacing pics per inch</th>
<th>Inner Tube</th>
<th>End Fittings</th>
</tr>
</thead>
<tbody>
<tr>
<td>W-1</td>
<td>Single</td>
<td>Twisted Nylon Yarn Black</td>
<td>Double fiber twisted together 0.05 in. thick</td>
<td>40°</td>
<td>20</td>
<td>Penrose Surgical drainage tubing or equivalent</td>
<td>Male and Female conical surfaces, bolted</td>
</tr>
<tr>
<td>W-2</td>
<td>Double</td>
<td>Twisted Nylon Yarn Black</td>
<td>Double fiber twisted together 0.06 in. thick</td>
<td>40°</td>
<td>14</td>
<td>&quot;</td>
<td>&quot;</td>
</tr>
<tr>
<td>W-31*</td>
<td>Single</td>
<td>Untwisted Nylon Yarn White</td>
<td>Untwisted Yarn 0.10 in. thick</td>
<td>25°</td>
<td>7</td>
<td>Latex Rubber with carbon black added dip fabricated together 0.020 in thick</td>
<td>Male and Female cylinders crimped together</td>
</tr>
<tr>
<td>W-4</td>
<td>Single</td>
<td>&quot;</td>
<td>&quot;</td>
<td>40°</td>
<td>9</td>
<td>&quot;</td>
<td>&quot;</td>
</tr>
</tbody>
</table>

*This is an impregnated unit. The inner tube is bonded to the braid by dipping the braid with tube inserted in liquid rubber, thus forming an integral unit.*
### TABLE II

**ACTUATOR DIMENSIONS**

<table>
<thead>
<tr>
<th>Code No.</th>
<th>Free Length, $L_0$, in.</th>
<th>Flat Width, $W$, in.</th>
</tr>
</thead>
<tbody>
<tr>
<td>W-1</td>
<td>5</td>
<td>.63</td>
</tr>
<tr>
<td>W-2</td>
<td>5</td>
<td>.95</td>
</tr>
<tr>
<td>W-31</td>
<td>4</td>
<td>.95</td>
</tr>
<tr>
<td>W-4</td>
<td>4-3/4</td>
<td>.75</td>
</tr>
</tbody>
</table>

$L_0$ = Free length between end fittings (with zero inflation pressure and zero external tension).

$W$ = Width of actuator when flattened (with zero inflation pressure and zero external tension).

![Diagram of actuator dimensions](image)

Figure 21 also indicates an interesting correlation between maximum possible actuator contraction and utilization efficiency.

Figures 11-14 show that the W-1, W-2, and W-4 actuators have reduced initial volumes when stretched. Thus, when these actuators are subjected to an initial tension before pressurizing, their utilization efficiencies would be somewhat higher.
Fig. 11. Internal volume—W-1 actuator—5" free length.
Fig. 12. Internal volume—W-2 actuator—5" free length.
Fig. 13. Internal volume—W-31 actuator—4” free length.
Fig. 14. Internal volume—W-4 actuator—4-3/4" free length.
Fig. 15. Preliminary test setup for internal volume measurement.
Fig. 16. Internal volume measurement test setup.
Fig. 17. Utilization efficiency and potential gas saving—W-1 actuator—5" free length.
Fig. 18. Utilization efficiency and potential gas saving—W-2 actuator—5" free length.
Fig. 19. Utilization efficiency and potential gas saving—W-31 actuator—4" free length.
Fig. 20. Utilization efficiency and potential gas saving—W-4 actuator—4-3/4" free length.
Fig. 21. Utilization efficiency and potential gas savings vs. actuator contraction—four actuators, 50 psig.
D. EXPERIMENTAL RESULTS

Laboratory gas consumption tests were made using the W-14 actuator. Two test procedures were used:

1. Direct Volume Measurement—This procedure, illustrated in Figs. 22 and 23, involves first pressurizing the actuator under selected conditions and then exhaust- ing the gas from the system into an inverted water-filled burette. A direct reading of the volume of gas used (reduced to atmospheric pressure) is thereby obtained. Comparative volume measurements obtained with and without the transmitter indicate utilization efficiency, or, gas saving associated with use of the actuator. Ac- count must be taken of the internal volume of the connecting tubing in the pres- surized part of the system (unless this factor is made negligible by using very short, small-bore tubing).

2. Comparison of Number of Operating Cycles—This procedure involved using the setups illustrated in Figs. 22 and 23 except that discharge volumes were not determined, and the initial weight of liquid CO₂ in the supply tank was carefully measured. Gas savings was determined by direct comparison of the number of oper- ating cycles obtained in each case when using the same quantity of CO₂.

When sufficient care was taken to minimize experimental errors, experimental verification of the theoretical values could be obtained within about 5%. This was considered adequate for the present purpose. Two points involving experi- mental technique were found to be of particular importance:

1. Realization of the full theoretical gas saving of the transmitter depends on making the fluid on the transmitter side of the diaphragm incompressible. Hence care must be taken to eliminate all entrapped air.

2. With the transmitter properly installed, the only compressibility loss is due to the volume of gas between the valve and the diaphragm. To minimize this loss, the diaphragm must be in contact with the cavity wall when the system is vented (i.e., non-pressurized). For this, the cavity and diaphragm must be properly matched, and the diaphragm must not block the passage leading to the valve while any gas is trapped between the diaphragm and cavity wall. An improper design resulting in gas entrapment is shown in Fig. 24.

V. SIDE EFFECTS

In addition to saving gas, the transmitter introduces other influences upon the performance of the actuator. All these side influences appear to be negligible except, possibly, when more sophisticated control systems become available. The various side effects are listed below.
Fig. 22. Direct gas consumption measurement—without transmitter.
Fig. 23. Direct gas consumption measurement—with transmitter.
A. REDUCED ELASTICITY

Without the actuator, residual volume $V_0$ contributes elasticity to the system. The compression of this volume serves as a "cushion" over and above that provided by the compressibility of the "useful" gas, $AV$. If a completely hydraulic system were used (i.e., replacing the CO$_2$ tank with a high-pressure liquid source), virtually all elasticity would be eliminated and the control would be "positive" in the sense that admission of a given volume of high-pressure liquid into the system would force the actuator to assume a definite internal volume. In the other extreme, use of a pneumatic system with very large volumes would give the characteristic that admission of a given quantity of high-pressure gas would produce a definite actuator internal pressure, and this pressure would not change significantly with variations in actuator internal volume. In general, the all-hydraulic system tends to provide positive displacements (regardless of the force that must be developed to obtain the displacement), whereas the large-volume pneumatic type provides constant forces (which are independent of the displacement).

Use of the transmitter alters the characteristic of the system in the direction toward the all-hydraulic type. With conventional braided actuators this change may take the system something less than half-way to the full hydraulic characteristic. Present indications are that this is of minor importance, but probably results in slightly improved control characteristics.
B. ADDED VISCOUS DAMPING

The flow of liquids (even water, which has been used exclusively during the preliminary tests) through the connecting tubing gives rise to viscous friction or damping which has two effects: (1) a time lag, due to the longer time required for the liquid to flow through the tubing, and (2) the damping of vibratory oscillations which might be present in the system under certain conditions. The former effect is in the direction of offsetting the more rapid response associated with reduced elasticity.

It is likely that optimum tubing sizes when the transmitter is used will be a little larger than optimum sizes without the transmitter. By adjusting tubing size, response time could be made as fast as desired. The damping associated with optimum tubing sizes would likely be small, and perhaps slightly beneficial from a control standpoint.

An increase in tubing size would of itself be somewhat undesirable for the added weight and bulk.

VI. ALTERNATE TRANSMITTER DESIGNS

The two designs of diaphragm-type transmitters which have been tested are represented by Fig. 25 and by Figs. 5 and 6. The flat-diaphragm type represented

Fig. 25. First experimental gas-liquid transmitter.
by Fig. 25 performed satisfactorily except that the metal spring in the rim of the standard contraceptive-type diaphragm used eventually punctured the rubber. The housing was made of plexiglass to permit observation of the diaphragm action.

The cylindrical diaphragm type, shown in Figs. 5 and 6 appears to have a more desirable shape, and is less costly to make. Both types are designed so that the diaphragm is never stretched, and is, therefore, subjected to only minimal stresses.

Chemical deterioration of the standard surgical latex diaphragm material used in the experimental transmitters did not present a problem in this investigation. However, some deterioration of the rubber was evident at the end of tests. This indicates that future diaphragms should be made of more completely cured rubber, or from another material. Polyethylene film should be an ideal material for this application, as it is readily formed into the desired shape, and is chemically inert in the presence of water and CO₂.

The principal advantage of the transmitter can be realized by installing inside the braided actuator a volume of liquid exactly equal to the residual volume, and enclosed by a thin rubber-like membrane. Such a unit would eliminate the viscous damping effect (see Section V, B, above), and would avoid the necessity of a separate transmitter unit. The gas saving would be decreased slightly because compressibility losses in the tubing would not be eliminated. Some problems might be encountered due to rubbing friction between the inner wall of the actuator and the outer surface of the liquid container. This modification appears to be worthy of further consideration, however.

REFERENCES


APPENDIX

DEVICE DESIGN AND DEVELOPMENT

Task Plan:  D.D. 4 - Approved November 15, 1960

Subject:  Gas-Liquid Pressure Transmitter

Purpose:

1. To evaluate the desirability of using a gas-liquid pressure transmitter at the control valve outlet for fluid orthotic actuators generally, and the McKibben muscle in particular.

2. To develop, if warranted, a transmitter suitable for use with one or more specific orthotic actuators.

Suggested Procedure:

1. To design and construct a transmitter functionally adequate for evaluation studies, preferably incorporating a transparent housing permitting observation of the diaphragm.

2. Evaluate gas savings.

3. Evaluate influence on control characteristics (correlate with D.D. 3, proportional pneumatic control study).

4. Evaluate anticipated weight and bulk of a final design.

5. If warranted, develop a transmitter suitable for use with one or more specific orthotic actuators.

   a. Conduct life tests on diaphragm-cavity design.

Schedule:


2. By February 15, 1961, report items through suggested procedure 4, and set a scheduled completion date.

Personnel:

R. C. Juvinall (chairman), Armin Jocz, Wasyl Ohar.