VALVE LOCATION IN GAS POWERED PROSTHETIC SERVOMECHANISMS

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Summary

In the design of an upper limb prosthesis which is to be gas powered and position-controlled, a choice has to be made between the possiblities of mounting the valve on (or adjacent to) the actuator, or remote from the actuator and probably at the control site. This choice is not simple and obvious, as it would be with hydraulic actuation, because of a number of conflicting factors. Engineering considerations, such a system response, stability, stiffness and power consumption would dictate actuator mounting. Clinical requirements however, suggest mounting the valve remotely at the control site because of the smaller force/input levels, the direct 'feel' of the input (feed-on) and the improved ability to correlate command and response.

Experimental results for pneumatic system are shown. These have been obtained from gas powered closed loop position-control systems using prosthetic valves, linkages and cables. The clinical aspects provide a guide to the designer from the point of view of the user side of the man-machine interface. The hardware must be tailored to to the user, and thus its input characteristics will in many cases be constrained. Argument are presented with reference to the two types of input currently in use: the joystick type of controller, requiring light forces and suitable for phocomelic digits; and the force feedback controller, viable with stronger control sites, such as the shoulder.

Introduction

In the control of gas-powered arm prostheses, the use of position-control servomechanisms is proving to be useful. At Edinburgh Dr. Simpson has been fitting position-control to arms with a remarkable rate of acceptance and the position-controlled MRC-Hendon arm has been well received by the subjects of a recent clinical trial.

This research is sponsored by the Biomechanical Research and Development Unit, Department of Health and Social Security, Roehampton, London.

The reasons for the success of these two prostheses are somewhat difficult to assess due to the limited number of patients and their age, but it is attributable in part to the range of movement which such an arm with five degrees of movement affords. However, without position-control, the positioning of the arm would present an arduous driving task; therefore the success must also be attributed to the closed-loop nature of the arms which has permitted the development of a multifunctioned prosthesis whilst retaining ease of control at the man-machine interface.

Several engineering problems are thrown up because of the use of a low-pressure pneumatic servosystem which is necessarily under-powered due to the need for gas economy. Such a servo has a strong tendency to be unstable i.e. to exhibit divergent oscillations, if a simple 1:1 follower with no stabilisation by dissipative elements or signal shaping is designed. Also the dynamic response tends to be poor both in terms of the time delays and overshoot characteristics. All of these effects are largely due to the low bulk modulus of the working fluid, and as such, are inherent in the system.

One of the factors having a significant effect on the servo-system performance is the relative location of the valve to the actuator.

Although the best engineering solution in terms of response, stability and efficiency criteria is known to be an actuator-mounted valve location, clinical requirements can indicate that the valve must be remotely mounted in order to obtain the required input control characteristics. Since the clinical requirements are dependent on the fitting at the control site, the best valve location can only be assessed in the light of the desirable characteristic for a particular type of patient.

The arguments are restricted to all-mechanical servosystems using Bowden cable signalling.

Clinical Requirements

One multi-functioned servo-controlled arm requires at least three indipendent control sites with positional sense in order to position the terminal device, and an additional site for the control of grip. Since the use of sequential control would detract from the instinctive correlation between command and response that is the chief advantage of position-control, it is undesirable; and therefore only two indipendent movements can be harnessed from each shoulder site. Thus for amelics who must rely on control from the shoulders, unilateral fitting will probably be indicated. Ectromelic hands allow the more elegant concept of joystick control and bilateral fitting to be considered. Where necessary, less convenient methods of obtaining an input signal have been empoyed, e.g. shrug cables, muscle bulge, shin controls.

The two main and distinctive types of fitting then are shoulder control from the acromium, and joystick control using ectromelic and phocomelic digits. The former group can usually provide a reasonably high force and range of input movement whilst the latter have a tendency to be weak with smaller ranges of motion; data on ectromelic hands is rather scanty at this time, but tests to determine the work and kinesthetic capabilities of a group of ectromelic children are in progress at Chailey Heritage /1/. Clearly, the optimum man-machine interface for one group will not necessarily be the best for the other. On the basis of impedance matching, the shoulder controls should have a heavier 'feel' than those of the joystick. Also, whilst the extremely low power availability from some ectromelic hands may force a sub-optimal engineering solution, there is some scope for design flexibility with the greater work availability from a shoulder site. This is particularly important because it can permit the use of pressure-demand valves in the system, which in general results in higher operating forces but gives advantages in information feedback (feed-in) and stability.

Pressure-Demand Valves

The p.d. valves were originally designed to produce a force servo for the grip of a terminal device /2/ but later its use was extended to position-control servomechanisms /3/ in order to obtain information feedback from the output, in addition to the position indication normally received. However, its use in position servos resulted in an improvement in servo-response as well as the intended feedback, and it is this effect which proves most beneficial in some instances.

The stabilising influence of p.d. valves on the servo response was demonstrated by a series of tests at University College London /4/ using an elbow rig with a remotely-housed valve (Fig. 1).

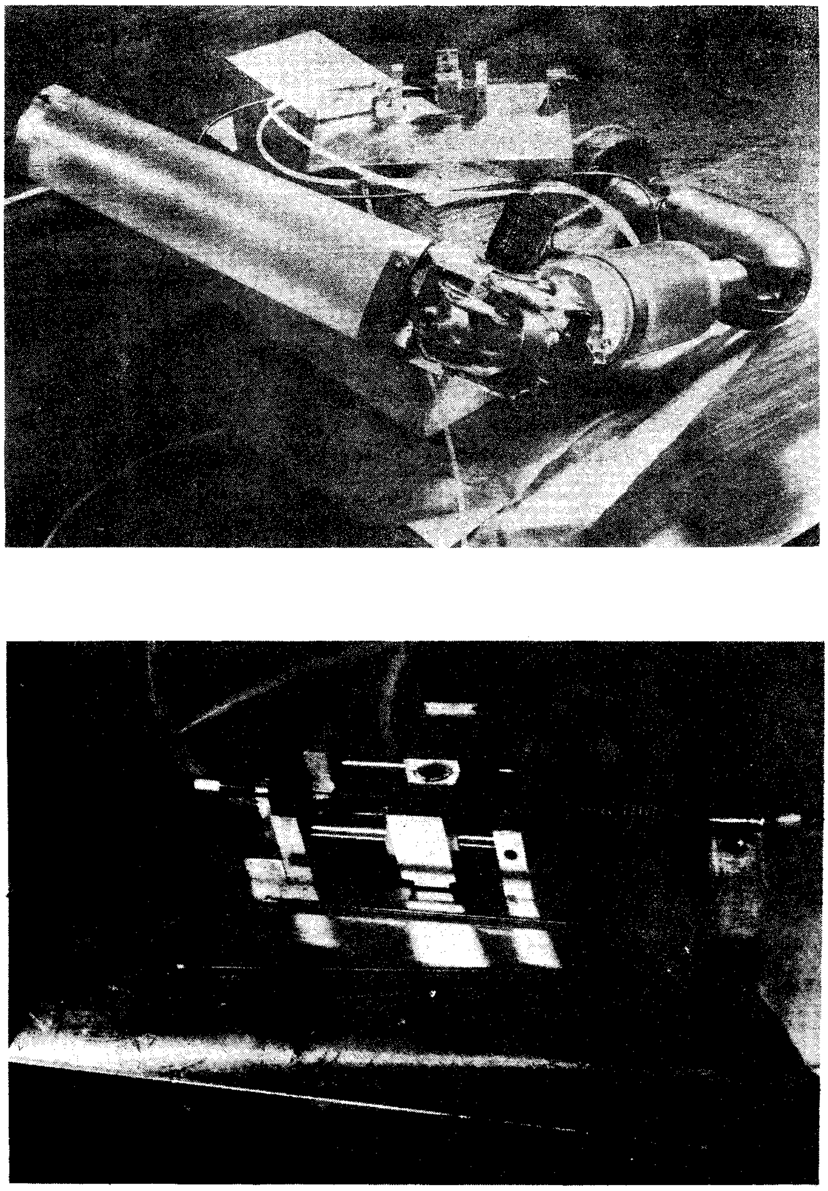

Fig. 1.

(a) Elbow test-rig
(b) Detail of input slider

Initially a poppet valve without force feedback was mounted at the input and this gave an unstable oscillatory response. In order to obtain an input output position curve, the system had to be stabilised by the method of using auxiliary tanks /5/. The poppet valve was then replaced by a p.d. valve with similar flow displacement characteristics (Fig. 2), and the system was found to be inherently stable but exhibited a larger hysteresis in the input/output position curve than previously (Fig. 3). These effects were attributed to the presence of flexibility at the input which reacted with the force-feedback to produce a stabilising pressure-feedback signal to the valve, and also caused an increase in positional error because of force hysteresis in the valve and load.

It should be noted that the original system required auxiliary tanks equal in volume to the actuator swept volume in order to achieve stability and could not be stabilised by the addition of slugging restrictors in the gas lines. Therefore the p.d. valves exhibited a strong stabilising influence on the system.

The value of the information feedback obtained from the use of p.d. valves is somewhat in doubt. The 'feed-in' is intended to provide a correlation between the input force and output loading, but considerable distortion can occur between input and output. Firstly, even in static conditions, the valves can introduce typically up to 20% hysteresis between input force and the output pressure; then the pressure differential is related to the actuator load by an expression concerning Coulomb friction (up to 10% stall force could reasonably be expected) and actuator velocity. Finally the signal will be further distorted by a considerable degree if the valves are actuator-mounted and a Bowden cable introduced between control site and valve input. Thus the final correlation between control force and the output load and velocity must be poor, and may be little better than the information received about stall and velocity saturation unbeatability into the system.

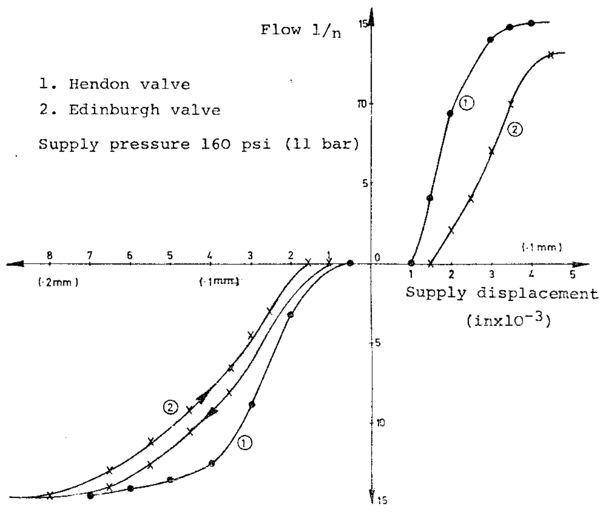

Fig. 2. Flow / displacement

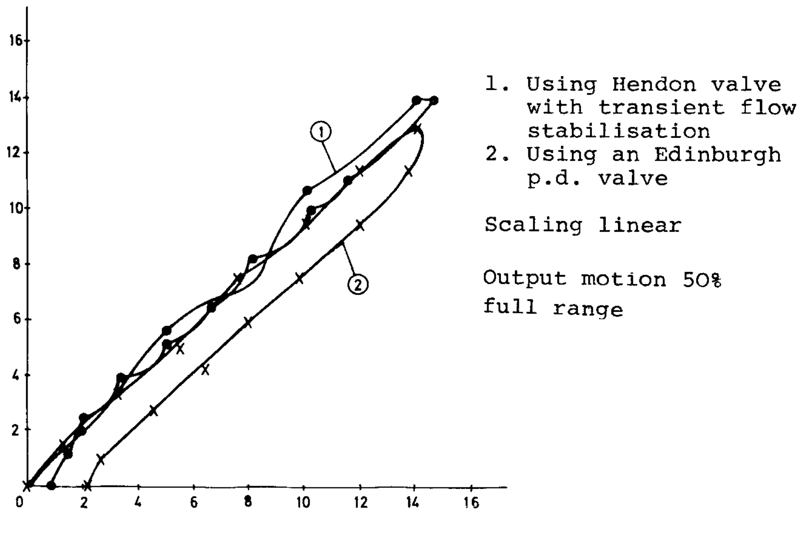

Fig. 3. Input / output traces

Engineering Considerations

In servosystem analysis various criteria of 'goodness' can be applied depending on the intended application; for a position-control servomechanism such a set would include stability, dynamic response, positional accuracy, load sensitivity and efficiency. The dynamic response can be characterised by the time delays, overshoot behaviour, minimum step size and maximum velocity of the system; the positional accuaracy by the linearity and hysteresis of an input/ouput curve; the load sensitivity by the deflection of the output per unit load; and the efficiency by the comparative gas economy of one system to another when performing a set of tasks.

For a prosthetic system, the load sensitivity is a non-linear function; any load which causes an output deflection gives an error signal back to the valves and only if the error signal is taken up by backlash and valve dead-zone can the valves remain closed. Therefore there will be a maximum value of load which the servosystem can tolerate without correction coupled with a maximum error which can develop without causing valve opening. It may not be advantageous to reduce these threshold levels of load and error too låw, since the servosystem would then tend to 'fight back' against any slight load variations during such operations as writing and carrying.

In terms of the criteria listed above, the differences between the location of the valve at the actuator or control site can be evaluated.

With remote mounting, a length of piping is introduced between the valve output port and the actuator, and there are many possible effects due to this volume increase including those concerning response, stability, finite time delays, gas consumption and, of less significance, transport lags and referred inertia. In tests on the elbow rig already mentioned, which had a remotely-housed valve connected to the actuator by 0.6 m (2 ft.) of 2 mm bore tubing, the output pressure fluctuations associated with elbow motion were almost identical when recorded from a pressure transducer in the actuator to a simultaneous recording from a transducer in-line near the valve. A high frequency, low amplitude ripple in the line following valve opening constituted the only difference, and hence it was assumed that the flow dynamics along the pipe can be ignored at the frequencies encountered by the ouput, i.e. that the piping acts merely to increase the effective actuator volume in a quasi-static nature and does not constitute a resistance/capaticance delay in the forward path.

For remotely mounted valves, the increase in transmission delays and referred inertia effects can be shown to be negligible for the scale of system used in arm prosthetics. However, the increase in time delays, the general degrading of response and stability, and in particular the increased gas consumption are all noticeable, and dependent on the percentage increase of pipe volume over the original actuator volume, which can be considerable even when kept at a minimum. With respect to gas consumption, this will increase by approximately the same percentage as the volume increase (the flow of gas into the actuator can be divided into two components, the compressibility flow and the flow allowing position motion; only the first term is increased by the piping volume, but this accounts for a large part of the gas consumption during fast or heavily loaded movements).

The accuracy of the input/output position correlation is dependent on the function of the signal cable. For an actuator-mounted system, the cable is transmitting the input signal from the control site to the summing junction, and hence cable pre-tensioning will alter the 'feel' of the input and necessitate larger input forces. Even the use of constant tension springs at either end of the cable does not provide a solution because the friction between the cable inner and outer is strongly tension-dependent. (Figure 4 gives results of friction tests on a low-friction P.T.F.E. sleeved steel Bowden cable). However, remote housing of the valves allows the cable to be tensioned adequately with no load to the patient since the opposing force is supplied by the actuator. Load/displacement tests on the same Bowden cable (Fig. 5) showed that considerable deformation occured up to tensions of 1 N, this being attributed to the straightening of bends in the inner wire and to the wire bedding into the sleeving which surrounded the inner. After this, a low stretch rate of approximately $15 \times 10^{-5} \frac{mm}{N}$ $(\frac{.024"}{lbf})$ per metre of cable was seen. By maintaining the cable tensioning above 1 N, with a reasonably useful minimum cable travel of say 10 mm, the hysteresis in position introduced by the Bowden cable can be kept at a maximum figure $\frac{0.5\%}{m}$ for a change in tension of 1 N which is acceptably low.

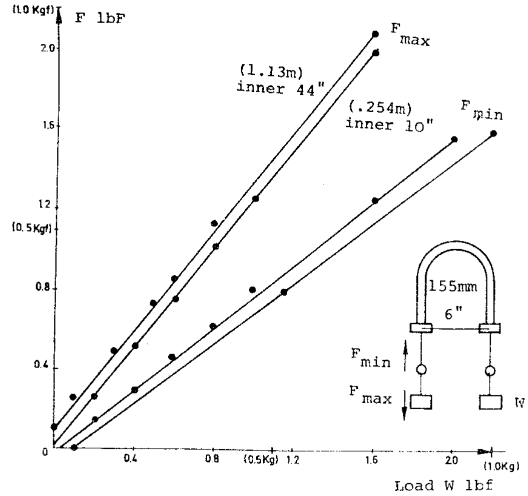

Fig. 4. Friction tests on Bowden cable

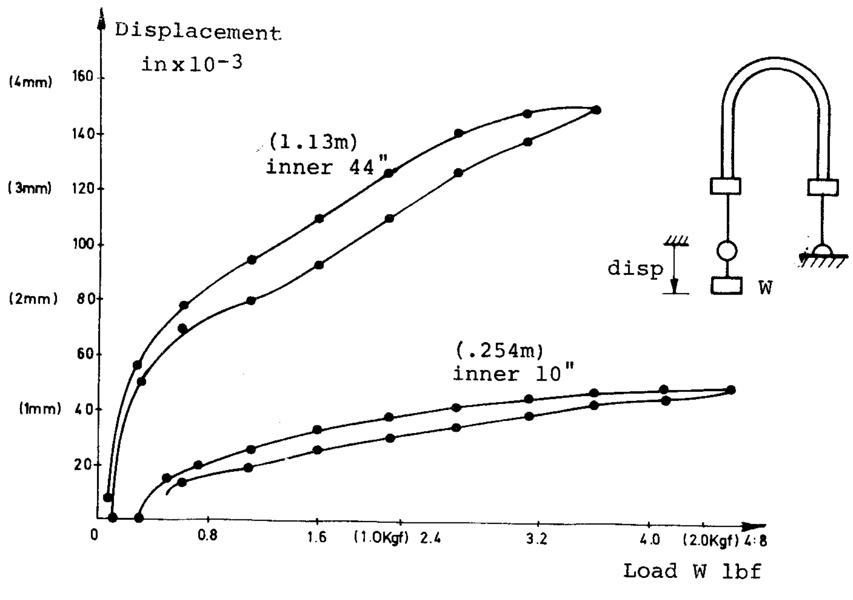

Fig. 5. Stretch of a Bowden cable

However, maintaining the tension in an input signal cable at above 1 N with a minimum travel of 10 mm implies a minimum input work requirement of 10 N mm even without the additional work needed to operate a valve. There is a strong possibility, based on preliminary data on the work available from ectromelic hands and the minimum work input possible for a cable-operated valve, that an actuator valve mounting makes joystick control beyond the capability of some patients, and almost certainly precludes the highly advatageous use of pressure-demand valving.

Conclusions

In summary, the two main types of controller which offer most advantages appear to be the light joystick control which is suited to operation by an ectromelic hand, and the control from the acromium which usually permits the use of pressure-demand valving. Although joyst-ck control can allow bilateral fitting and permits an intuitive relationship between the ectromelic and prosthetic hand position, it probably precludes the use of p.d. valving and may even indicate that the valves must be remotely mounted. Since stability problems are most often incurred under these latter conditions, it may be better to use shoulder controls even when an ectromelic hand is available in order to overcome the tiresome problem of instability.

The engineering considerations all indicate that actuator-mounting of the valves is better than remote mounting, expecially in order to maintain a good response and low gas consumption. The only disadvantages are the heavier feel that is imposed by a Bowden cable input transmission, which is still well within the capabilities of shoulder operation, and the further degradation of the force feed-in obtained from p.d. valves. Since this additional information is already low-grade and difficult to interpret, its loss is not considered to be seriously detrimental.

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