THE DESIGN OF AN HYDRAULICALLY POWERED ARM PROSTHESIS

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Summary

The potential advantages to be obtained from using a hydraulic system can only be realised by an integrated design which takes account of and utilises the properties of the working fluid. The design will differ from that of a pneumatically powered system but will also differ from a conventional hydraulic system. In order to keep the power demands to an acceptable level, both the inertial and service loads are extremely high compared with normal industrial practice. The significant effects of this on the performance of the system are discussed.

The man-machine interface problems, and in particular the effects of complex time delays and their associated damping ratios on operator performance are considered. Results are given to support the choice of parameters for the design.

The selection of an acceptable working fluid within the range of normally available hydraulic fluids are discusses in the light of possible toxic or carcinogenic risks.

There remain, however, two major engineering problems; the interaction of the power unit behaviour on system performance, and the optimisation of the valve-actuator combination.

A prototype hydraulically actuated arm prosthesis is being developed, and experimental results are presented.

Choice of System

The application of external power to upper limb prostheses has hitherto been restricted to electromechanical or compressed gas systems. The former have been used extensively in North America, while the latter, in the specific form of CO_2 gas, has found favour in Europe. Electromechanical systems have the advantage of using a compact, safe energy store with a high stored energy to weight ratio which is capable of being conveniently and economically re-charged. Due to the low saturation flux density and high weight density of magnetic materials, electromechanical actuators are heavier and have much slower response times than their fluid powered equivalents. The weight of electric actuators fitted to the distal parts of the arm (for example:actuators for prehension or wrist rotation) add significantly to the already considerable inertia of the arm structure and the large inertial loads reflected on to the elbow or shoulder actuators degrade the response even further. The best power to weight ratio that can be obtained with electromechanical actuators is an order of magnitude worse than that obtainable with fluid power actuators and at present can only be achieved by the use of small high speed motors in conjuction with a reduction gear box. Unless this gear box is made irreversible which normally implies a low efficiency, considerable problems arise in the design of the motor and control amplifier in order to permit the device to operate in the stall condition when sustaining steady loads. The only alternative is to use some form of electromechanical brake fitted to the motor which adds to the already high weight and significantly increases the complexity of the control strategy. The need for a gear box within the system carries a further disadvantage in that the need to minimise weight results in a relatively fragile component which can be damaged by accidental shock loading on the arm.

Fluid power actuators therefore offer real advantages particularly where a multifunction complete arm prosthesis is required, and one is left with a choice between gas or liquid as the working fluid. In terms of weight there is little to choose between the two as although the weight of working fluid contained in the actuator and piping is obviously less in the case of gas, this is largely offset by the reduction of actuator weight and volume associated with the use of higher working pressures in the case of liquid. These are permissible with hydraulic systems, but undesirable with CO_2 powered systems for two reasons. Firstly higher working pressures will reduce the overall efficiency which can be shown to be a maximum between 150 and 250 lbf/in^2 and secondly the use of pressures above 250 lbf/in^2 could result in the actuators being classified as pressure vessels and therefore subject to national regulations regarding their design and safety.

Choice of Fluid

Leakage is obviouslu undesirable in both types of system, but whereas slight leakage of CO_2 gas has no effect other than a loss of energy (the gas is normally exhausted to atmosphere anyway), seepage of an hydraulic fluid could have much more serious effects. Contamination of Clothing and other articles could occur, and rigorous precautions should be taken to minimise the risk of leakage. To create the degree of integrity required to guarantee absolutely no leakage under any condition may not be feasible at this stage and it is therefore important to choose a fluid which is non-toxic and safe in contact with the skin. Some concern has been expresses about the risk of carcinogenic effects from hydraulic oils. It is believed that some skin tumours have occurred amongst industrial workers as the result of their carrying rags impregnated with cutting oils in pockets adjacent to the skin, the heat of the body causing slow vapourisation of the oil. The possible carcinogenic agent has been identified as certain long chain poly hydrocarbons and these are removed from hydraulic fluids during the refining process (they are now removed from cutting oils as well). The majority of hydraulic oils contain small quantities of anti-scuff or similar additives and these may act as mild irritants with sensitive skins and possibly promote dermatitis if contact were prolonged.

A number of oils are available of appropriate viscosity which are free from additives. These include medicinal oils refined to B.P. standards and which may be taken internally and the range of technical white oils which are widely used in the food processing industry. The latter usually contain a proportion of vegetable (ground nut) oil which enhances boundary lubrication properties and tests on the hydraulic power pack using such oils have shown them to give a small improvement in efficiency. Gradual oxidation of the vegetable oil content at elevated temperatures reduces the life of the hydraulic fluid but this is not expected to be a problem in view of the light duty (by industrial standard) to which the oil will be subjected.

Design Considerations

The major difference between gas and fluid as a working medium in the arm lies in the performance that can be achieved. Tests described later have indicated that for best performance of the patient-prosthesis (man-machine) system it is necessary to achieve fast response times with a high damping ratio of 0,8-1,0. This latter is much higher than is normally obtained in many industrial servomechanisms. Before considering the factors affecting the response of a fluid powered control system it is worth noting the large inertial loads to which the system can be subjected in prosthetic applications. Consider for example an elbow actuator and mechanism with an effective working radius of 2,5 cm. A typical forearm (elbow to terminal device) length for an adult would be about 40 cm and thus an inertial mass of 1 kg at the terminal device will be equivalent to an interval load at the actuator of 1 x $\left(\frac{40}{2,5}\right)^2$ that is 256 kg. In the case of a shoulder actuator with the elbow extended this could rise to around 400 kg. This simple calculation, of course, makes the assumption that structure of the arm is rigid and in practice this is far from true. The effect of compliance in the structure is to some extent to reduce the effects of distal inertial loads on response and stability, but the simple calculations are nevertheless useful in indicating the magnitude of the problem.

By making linearizing assumptions, the forward path transfer operator of a fluid powered position control system can be described by

$$G(D) = \frac{1}{TD\ (1 + 2\ \nu\ T_1\ D + T_1{}^2\ D^2)} \qquad (1)$$

The integrating time constant is determined by the valve flow/opening characteristic and the actuator area and must be kept reasonably small if significant following errors with a velocity input are to be avoided. The complex time constant is determined by the ratio of the inertial load to the stiffness of the actuator. In the case of fluid powered systems this stiffness is determined by the actuator dimensions and the bulk modulus of the working fluid. The damping ratio ν is determined by dissipative effects in the system such as viscous friction or leakage across the actuator piston or valve. Coulomb friction associated with the piston and piston rod seals makes a contribution to the damping of fluid powered systems. Such non-linear effects can be allowed for in the simple linearized theory by using energy arguments to determine an equivalent viscous friction coefficient /1/.

With unity feedback the closed loop transfer operator of the system becomes

$$H(D) = \frac{1}{1 + TD + 2\ \nu\ T\ T_1\ D^2 + T\ T_1{}^2 D^3} \qquad (2)$$

The requirement for fast response times indicates that both T and T_1 must be small, while the requirement for a well damped transient also imposes the constraint that T_1 must be small compared with T. This can be seen qualitatively by applying the Routh stability criterion to the denominator of Equation 2 which is the characteristic equation determing the transient response of the system. This shows that for stability $2 \nu \frac{T}{T_1} > 1$. The more that $2 \nu \frac{T}{T_1}$ exceeds unity, the greater will be the damping of the transient response and thus either ν must be large which would require undesirable amounts of dissipative damping, or $\frac{T}{T_1}$ must be large. Since the need for fast response times requires T to be small, this means that T_1 must be very small and the performance of the system will be critically dependent upon its value.

It has been shown previously that the high bulk modulus of hydraulic oils permits a complex time constant T_1 to be achieved which is at least an order of magnitude smaller than that obtainable from a low pressure pneumatic system /2/. Thus a hydraulic system will offer a unique opportunity for the desirable performance criteria to be realised.

Man-machine Considerations

The values of certain parameters in any prosthesis design have important effects on the performance of an operator. In particular the time constant and damping ratio of the complex delay inherent in inertially loaded servos require close attention. A comprehensive study of these effects has been completed at University College London /3/ and the results provide important guidelines.

The experimental apparatus resembles, and has the same dimensions as, an elbow unit. However, it is bench mounted and has moveable forearm and fixed upper arm. The position of the forearm is controlled by a fast-acting electrohydraulic servomechanism with imperceptible delay. Interposed between this servo and the operator's input is an electronic complex delay whose time constant and damping ratio can be varied over a wide range by the investigator. A large number of subjects co-operated in a series of experiments involving both target acquisition and continuous tracking tasks. Some of the experiments involved the more realistic task of raising a glass of liquid without spilling, while still attempting to retain speed and accuracy.

Figure 1. shows results for the latter type of experiment used in a target acquisition task, avaraged over a number of subjects. Acquisition time is plotted against damping ratio for three values of rise time. Rise time, R, is related to the complex time constant, T_1, and the damping ration ν as follows

$$R = \frac{\pi T_1}{1 - \nu^2} \qquad (3)$$

Clearly, performance improves as the rise time is reduced and as the damping ratio is increased. There is also evidence of a significant interaction between these two parameters whereby the effect on acquisition time of increasing the damping ratio is greatest with the longest rise time.

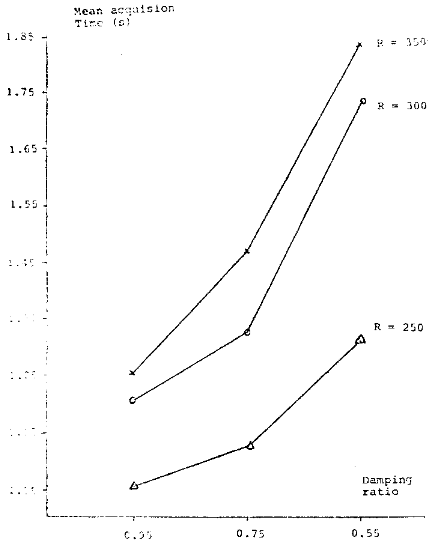

Fig. 1. Interaction between rise time and damping ratio on human operators´ acquistion times

Throughout these experiments, the results were consistently the same and statistically significant. The trends in the data are sufficiently clear that confident predictions can be made about man-machine systems with more than one degree of freedom. The more control functions required, the greater would be the importance of having small time constants and heavy damping.

Although it is not surprising that the time constant should be as small as can be reasonably achieved, a damping ratio as high as critical is unexpected. For the engineer designing a prosthesis, it means that the servo performance criteria, if the system is to be operated by a man, are altered because the overall man-machine performance criteria by which servo systems performance is optimized (e.g. integral squared error - I.S.E.,etc.) are not applicable here.

Energy Considerations

Since any source of energy for powering a prosthesis has to be carried by the user, considerations of minimizing energy consumption and energy losses must be paramount at every design stage. A light and portable electric to hydraulic conversion unit is described by Davies and Davies /4/. It has in overall efficiency of 45% and is likely to be improved by further refinements. As designed, it is intended to be operated through an hydraulic accumulator to provide fast acting valve controlled positioning. It is possible, however, to envisage considerable energy savings if an alternative mode of operation is made available when loads are light - for instance in gesticulating or combing hair. In conditions like these, the accumulator might be by-passed, making the system sensibly a hydraulic transmission, operating at reduced pressure and reflecting the dynamic characteristics provide a downgraded performance capability, which, however, is adequate for light loading. Switching back to high performance constant pressure valve actuation must be instantaneous and automatic when the load increases.

Piping must also be considered in terms of energy losses. Because of the minute scale of valve/actuator combination in this design, pipes leading into and out of the servo have to be as small as 0.080 inches in internal diameter. The frictional losses in oil flow through pipes of this size are in the order of 30 $\mathrm{lbf/in}^2$ per foot length. It is necessary, therefore, to minimise the lengths of these pipes, and to provide larger diameter pipes (about 0.19 in I.D.) for the major runs. This reduces pipes losses to less than 1 lbf/in per foot length, but introduces a new problem. The stiffness of these larger pipes, in order to safely withstand the system pressure, is too high to allow small radius bends in the pipe run. It is therefore necessary to consider the possibility of adapting the sealed rotary joints used in aero-space applications, and work is proceeding along this line.

Variable area hydraulic actuation can also provide energy savings, and a great deal of work has been done on this strategy /5,6/. An actuator with two or more working areas has been designed and these areas are employed in a manner which minimises energy consumption for a given standard of respose, whatever the system loading. The areas are switched automatically according to the demands of the system.

Work is also proceeding on another strategy for reducing energy consumption. This involves a mode of operation which allows the prosthesis to yield in a controlled fashion to the effects of an externally applied force (usually gravity) when it is acting in the desired direction. In this way the system need only be active when the situation is reversed (work being done against gravity). This possibility clearly offers energy savings approaching 50% over conventional servo control.

Current Research

In parallel with the development of a prototype hydraulically actuated arm prosthesis, a bench mounted load arm has been built and experimental work is in progress. The hydraulic servomechanism used for positioning this arm is shown in Figure 10 of the paper by Broome and Lambert /7/. It can be used to simulate elbow or shoulder prosthetic configurations, with realistic inertial and service loads. As an elbow actuating system, it has an unloaded

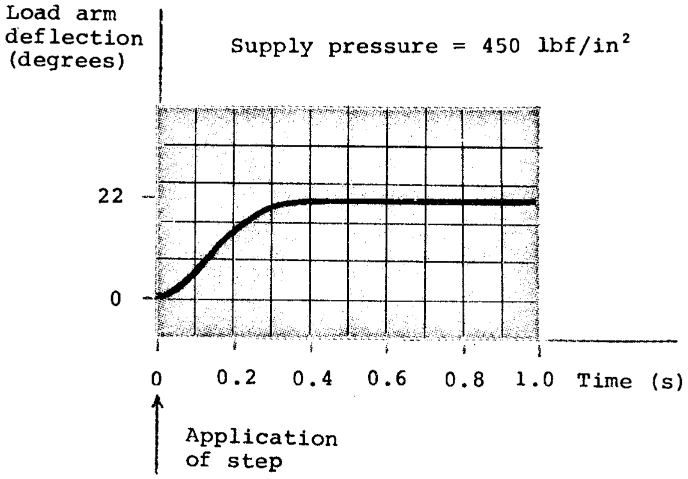

Fig. 2. Load arm response to a step input of 10 x full valve opening

capability of a stall torque of 100 lbf/in, a maximum speed of 3 rad/s and a 60% rise time of 35 ms. Figure 2 shows the response of the system to a step input of 10 x valve opening under a load equivalent to 1½ lbf in the hand. Clearly the system has adequate stability, with a damping ratio of just over unity and a second order time constant of about 8 ms. These are performance characteristics which have been designed for, on the basis of the man-machine research described above. Further tests have shown the system to have satisfactory dynamic characteristics under a wide variety of inertial and steady load conditions.

Economic Considerations

The application of hydraulic power to upper limb prostheses is attractive from an economic point of view. The CO_2 storage bottle is inevitably an expensive component if the stringent requirements of weight and safety are to be met. Recharging by post from a central depot is not only a significant recurrent cost, but also means that the patient must be provided with an adequate stock of full bottles. More cylinders are required to cover those in transit and at the re-filling depot, and it is not unreasonable to assume that 25 - 30 bottles would be required for each patient. On this basis, and allowing for capital depreciation, refurbishing and refilling charges, the cost per patient could easily exceed £1000 per annum.

Although home re-filling would significantly reduce the capital and recurrent costs, this method would not be suitable for use by all patients and the total cost would still be high.

As prostheses become more flexible their usage and therefore their fuel consumption will increase which will multiply the cost of gas powering, perhaps exorbitantly. This places hydraulic actuation in a very competitive position economically because of its comparable capital costs and its lower running costs.

With the current trends, it is not only costs, but also weight which will rise more steeply with gas powered systems. If, as seems likely, prosthetic systems are to be stretched to store enough energy for a full day's activity, battery weight for driving a hydraulic pump would be increased by about ½ lb. A similar extension in a pneumatic system would require two extra cylinders with a corresponding increase weight of 4½ lbs.

Discussion

Various aspects of the work on hydraulically powered arm prostheses are being reported in this Symposium - the power pack, the valve actuator combination, the man-machine studies, the variable load arm, the fluid characteristics and the mutual interaction of these considerations. The intention in all the work is to develop a viable product which can be clinically tested for use by limb deficient people. Of necessity the efforts of the U.C.L. team have been devoted to solving basic engineering problems with considerations of energy, weight, loading, safety and controllability on a scale which is unique from the point of view of hydraulic actuation. These studies are now being brought together to produce an arm prosthesis. The framework of the prosthesis will be Dr. D. Simpson's Edinburgh arm with five degrees of freedom - r, θ, ϕ, wrist rotation and grip. All motion will be hydraulically actuated with pressurized fluid from the electric to hydraulic energy converter. It is thought that the potential advantages of hydraulic operation can be realised in this system.

References

/1/ Lambert, T.H. and Davies, R.M., "Investigation of an Hydraulic Servomechanism with Inertial Load", *J. Mech. Engng. Sci.*, Vol. 5, No. 3, p. 281, 1963.

/2/ Davies, R.M. and Lambert, T.H., "Dynamic Characteristics of Pneumatic, Electric and Hydraulic Actuation of Prosthetic and Orthotic Devices", *Proc. 2nd Int. Symposium on External Control of Human Extremities*, Dubrovnik, p. 65. 1966.

/3/ Rudd, J.M., *Control of Powered Artificial Arms*, Final Report on D.H.S.S. contract No. Y 7093, 1970.

/4/ Davies, B.L. and Davies, R.M., "Portable Power Units for Hydraulic Prostheses", *4th Int. Symposium on External Control of Human Extremities*, Dubrovnik, 1972.

/5/ Davies, R.M. and Sillitoe, J., "On Optimizing Response and Efficiency in Hydraulic Actuation of Powered Prostheses", *3rd Int. Symposium on External Control of Human Extremities*, Dubrovnik, p. 583, 1969.

/6/ Sillitoe, J., *"Optimising Response and Efficiency in Hydraulically Actuated Limb Prostheses"*, Ph.D. Thesis, University of London, 1971.

/7/ Broome, D.R. and Lambert, T.H., "Valves and Actuators for Hydraulically Powered Prostheses", *4th Int. Symposium on External Control of Human Extremities*, Dubrovnik, 1972.