PORTABLE POWER UNITS FOR HYDRAULIC PROSTHESES

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Summary

Hydraulically powered prostheses show many potential advantages over pneumatic or electro-mechanical systems. One of the prime reasons that hydraulic servomechanisms have not been exploited in this application is the lack of a portable power unit that is small, light and reasonably efficient.

This paper describes a prototype power unit which is believed to be an adequate solution to this problem. In this unit, rechargeable electric batteries power a small D.C. motor which is used to drive a miniature hydraulic pump. An hydraulic accumulator is provided to store enough energy to meet peak power demands.

The accumulator design is investigated with reference to the effects on efficiency of motor transients, duty cycle and the quantity of pressurised liquid stored. The investigation considers alternative mechanical arrangements; for example piston or bag separation; and alternative energy storage media; for example nitrogen which is used conventionally, or sulphur hexafluoride which is a liquifiable gas. The discussion includes the dynamic effects of variations in accumulator temperature, pressure, flow and stored volume.

The effects of the prosthesis duty cycle on the design and performance of the power unit components are considered - particularly with reference to percentage load and stall load. Experimental results are presented and prototype components are displayed.

Introduction

It has long been the objective of the UCL team to exploit the potential of valve controlled hydraulic servomechanisms in application to the design of upper limb prostheses /1, 2/. The promising advantages derive from the use of battery energy storage which is compact, safe and capable of being conveniently and economically recharged /3/, in combination with hydraulic actuation which uses light weight components giving good dynamic response /4/.

The overall philosophy and the design of the actuation system are being reported in other papers presented to this symposium /5, 6/. The work reported in this paper concentrates on the energy storage, both low density, long term (batteries) and high density, short term (accumulator), and on energy conversion.

The Power Unit

Figure 1 shows, in block diagram form, the components of interest. Two points need to be made before detailed discussion. Firstly the servo system referred to is valve controlled so that with a sensibly constant pressure supplied at the valve inlet, the system dynamics are fast, reliable and, through the agency of the accumulator, independent of the pump. The alternative of supplying an actuator directly from a pump and using a valve only as a switch merely reflects the characteristics of the pump motor, using the fluid only as a link and losing the dynamic potential of fluid powered servos. Secondly, to realise this potential it is necessary to employ energy conversion, since the high bulk modulus of hydraulic fluids, which accounts for stiff, stable, safe response, also implies the impossibility of storing significant amounts of energy in the fluid.

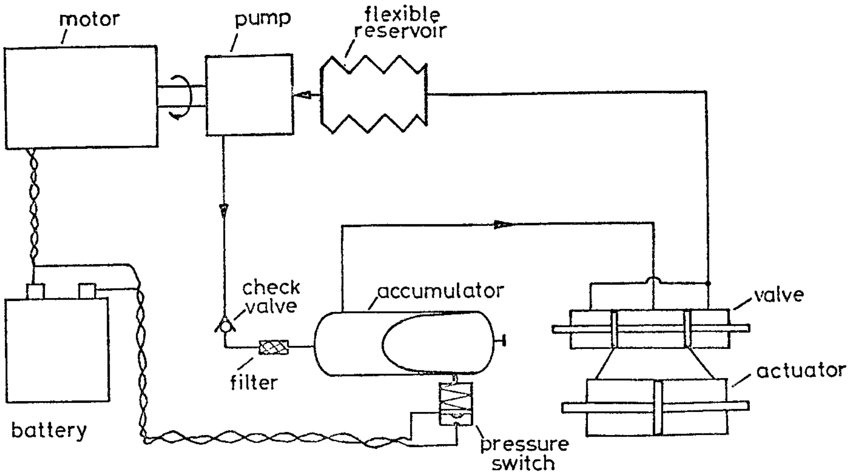

Fig. 1. Block diagram of hydraulic system

A great deal of work has been done on batteries, motor, pump and reservoir and this was reported by B.L. Davies last year /7/. It is convenient, however, to summarize the results here as a background to the current efforts on accumulator design and characteristics.

The batteries must satisfy the criteria of supplying the motor current without shortening their useful life, and of storing sufficient energy to meet the average power demand for whatever is thought to be the minimum acceptable period before recharging. For realistic estimates of average power demand, the second is the limiting criterion. In practice, the period between recharging is likely to be determined primarily by the battery weight that can be reasonably carried - particularly if vented, low cycle life silver zinc cells are discarded in favour of heavier, sealed, nickel cadmium cells. The use of light weight AD/DC converters will be effective for seated activities.

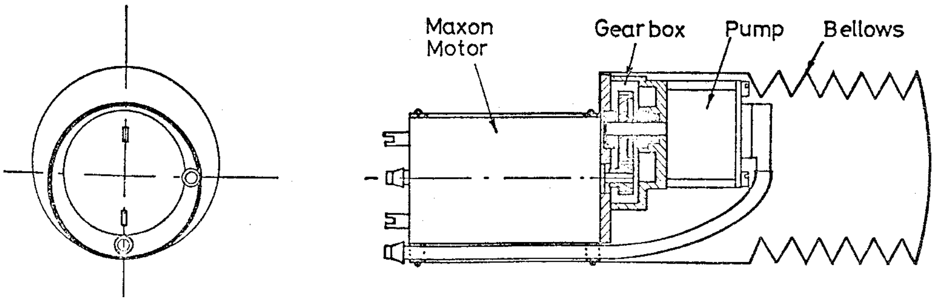

Fig. 2. Pump unit assembly

The energy conversion unit comprises a D.C. electric motor geared to a positive displacement pump. An American "Globe" motor has been used to date, with a rating of 25 watts and a weight of 11 oz (312 gr). A Swiss "Maxon" motor is now being tested. With a rating of 20 watts and half the size and weight of the "Globe", but a higher efficiency, it promises a smaller, lighter power unit. The pump developed by Lucas Gas Turbine Advanced Projects Division is a radial piston type, sized at less than a cubic inch. It weights 2 oz (57 gr) and has a peak efficiency at 400 lbf/in^2 (27.6 bar) of about 70%. A 3/1 gearbox is required to match the high speed motor to the optimum efficiency speed of the pump. Figure 2 shows the motor gearbox and pump immersed in the oil reservoir, which consists of a flexible bellows. This arrangement provides thermal and acoustic insulation. The size and noise of the pump are likely to be further reduced by design modifications which are in progress at Lucas´. For reasons of safety, should oil escape from the system, a variety of medicinal oils are being tested in the system. Their viscosities are similar to that of the "Shell Tellus" commercial range normally used. The most promising so far is "Risella M.27", a Technical white oil containing 20% ground nut oil, which gives an overall efficiency increase of 1·5% over that of the equivalent "Tellus" oil.

The Accumulator

The peak power required rrom the power unit, specified as the ability to make 4 cycles of an elbow actuator during 4 seconds, is about 30 watts. If this were provided directly by the pump and motor, then the size of motor required would be excessive and, to cope with the large current drain, the size of battery store would also be large. In addition the characteristics of the motor pump would affect the dynamic performance of the load. Since the peak power demand is intermittent it is possible to use some form of short term, high density energy storage. The most suitable means in this application would be to store energy in an hydraulic accumulator, e.g. by compressing nitrogen gas contained in a flexible bag or within a piston in cylinder. The need for a small light device which has a good overall efficiency rules out the use of springs as an energy store, since to give the required volume change of oil at around 450 lbf/in^2 (31 bar) pressure, the weight of spring material would be 1/2 Kg. Alternatively a liquifiable gas, in which the fluid is in the mixture phase at room temperature, could be used to store energy. When the fluid is compressed more of the mixture enters the liquid phase and provided the temperature remains constant, the hydraulic oil is stored at constant pressure There are few liquifiable gases which are non-toxic, non-flammable and have a suitable vapour pressure at room temperature /8/. These are sulphur hexafluoride (310 lbf/in^2 at 21°C); Freon 13 (459 lbf/in^2 at 21°C) and Freon 116 (430 lbf/in^2 at 21°C). The freons are commonly used as refrigerants and the sulphur hexafluoride as a spark suppressant in transformers. The difficulty with liquifiable gases is that their temperature does not remain constant during the charge/discharge cycle. When the mixture is compressed the gas becomes liquid, giving off its latent heat of vapourisation. This heat is absorbed in part by the container but the majority goes into raising the temperature, and hence the pressure, of the gas. The pressure thus rises as the accumulator is being charged and falls during discharge, leading to poor efficiency. A further difficulty with liquifiable gases is that the state of charge of the accumulator cannot be monitored by sensing the pressure as it can when charged with gas, but must be indicated by the volume of oil in the accumulator. Using a piston type accumulator, this can be accomplished fairly readily by sensing piston position with either a reed switch or potentiometer.

However, if a flexible bag type accumulator is used, the bag position will only indicate the state of accumulator charge if the bag collapses in a repeatable and uniform manner. The bag type accumulator, however, is more efficient than the piston type as the latter requires high friction piston seals to prevent gas passing into the hydraulic oil.

There are also difficulties inherent in the use of pure gas accumulators. To avoid too large a pressure fluctuation they require a larger volume than the liquifiable gas type. When the gas is compressed isothermally the pressure rises and the pump delivers oil over a range of efficiencies. As the supply pressure varies with the state of accumulator charge, it also varies the stall load capability of the actuator. This causes a variation in prosthesis performance even under constant loading of the terminal device and may lead to extended learning times when using the prosthesis. An additional factor is that, as with liquifiable gases, the process is not isothermal but has an index of around 1·2. Thus the work done on the gas during charging cannot be fully realised during discharge. Whilst this source of inefficiency is not as great as for liquifiable gases, it is significant, e.g. a 7% loss in efficiency due to cooling after charging an 8 in^3 accumulator from 300 to 450 lbf/in^2 (21 to 31 bar) at a rate of 12 watts.

In order to indicate the effects of variations in discharge rates for various gases, a piston type accumulator has been instrumented to read pressure, piston position, temperature and oil flow rate. These readings were logged into a Honeywell 316 mini-computer, which was also used for logic switching. The results were displayed on a Benson-Lehner flat bed plotter. Figure 4 shows the results for the sulphur hexafluoride charged accumulator filled and emptied three times. With the accumulator empty, the motor was switched on and the accumulator filled with enough fluid to meet peak demands, at which point the computer turned the motor off. During this period the pressure increased by 70 lbf/in^2 (4.9 bar) and the temperature rose 5°C above ambient. The accumulator was then discharged, resulting in a fall in pressure and a fall in temperature of 11°C. The motor was then switched on and the cycle repeated.

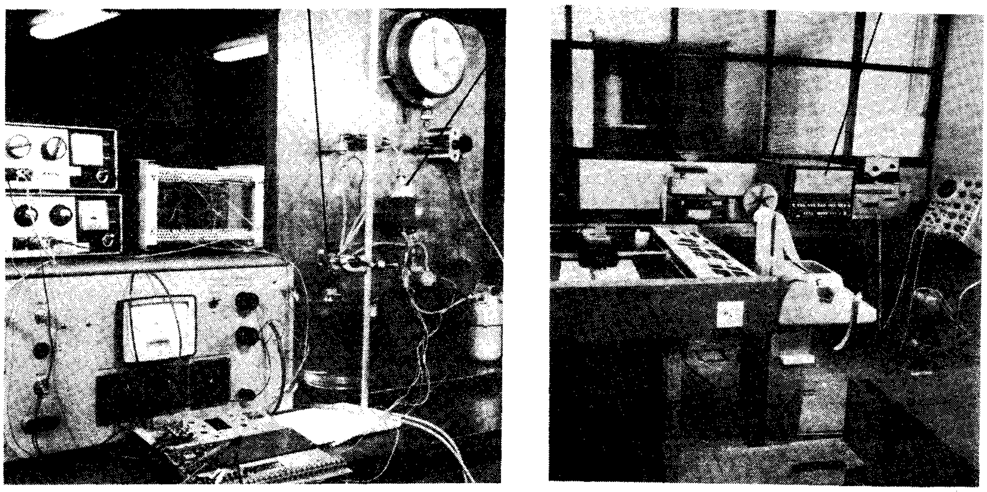

Fig. 3. Accumulator test equipment

Figures 5 and 6 show the effects of the rate of discharge on temperature and pressure. The maximum discharge rate of 1½/min is that which is expected when all the prosthesis actuators are moving at saturation velocity. Further tests are proceeding with other liquifiable gases and with nitrogen to compare their suitability for use in the accumulator.

Figure 6 was obtained using the mini-computer and shows that with a 20 watt output "Globe" motor driving the pump, the motor current reaches 90% of its final value in about 100 ms after switching on. Thus if the motor were arranged to switch on again when the accumulator had discharged only a small quantity of oil then at the low flow rates, which are the most usual operating condition, the motor could cycle on and off so frequently that transients occupied a large percentage of the time, thus reducing the efficiency.

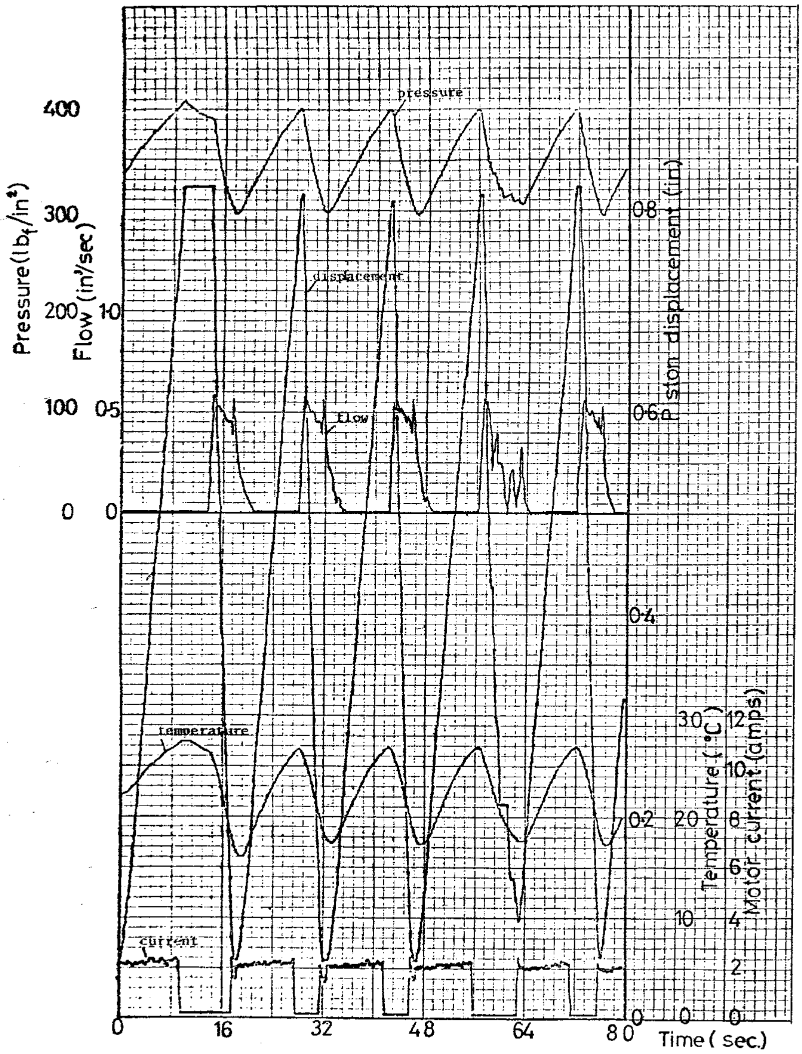

Fig. 4. Accumulator cycling tests

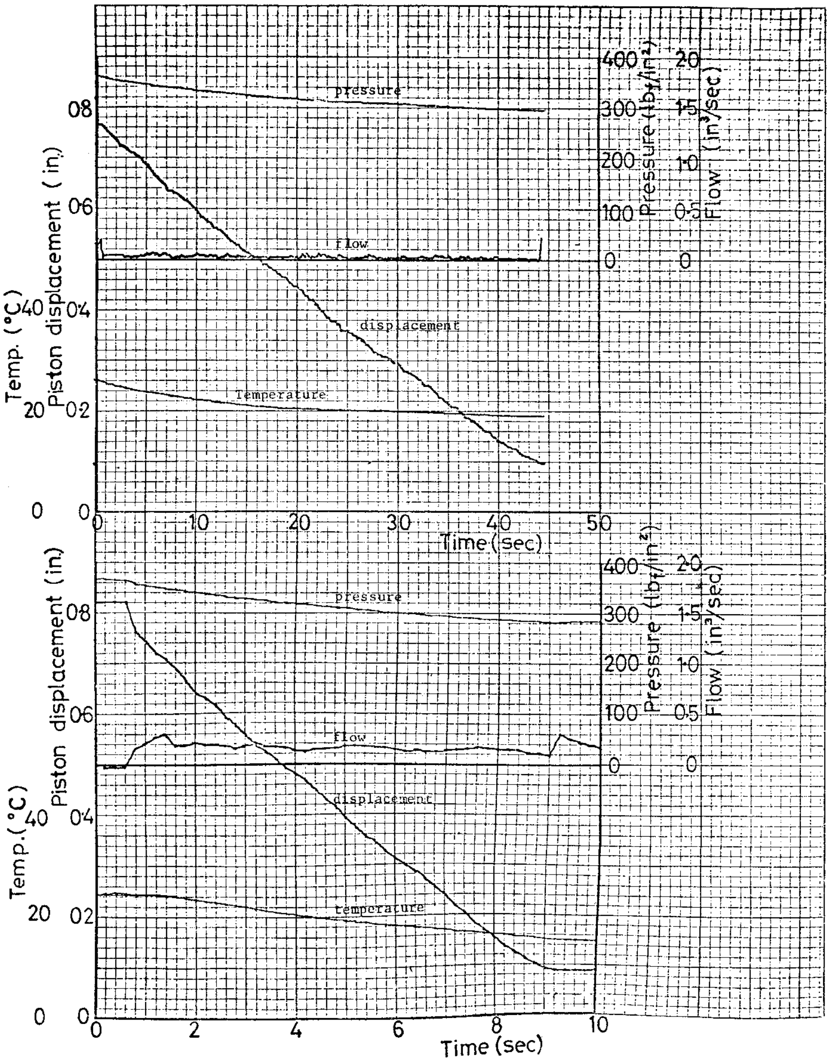

Fig. 5. Accumulator discharge tests

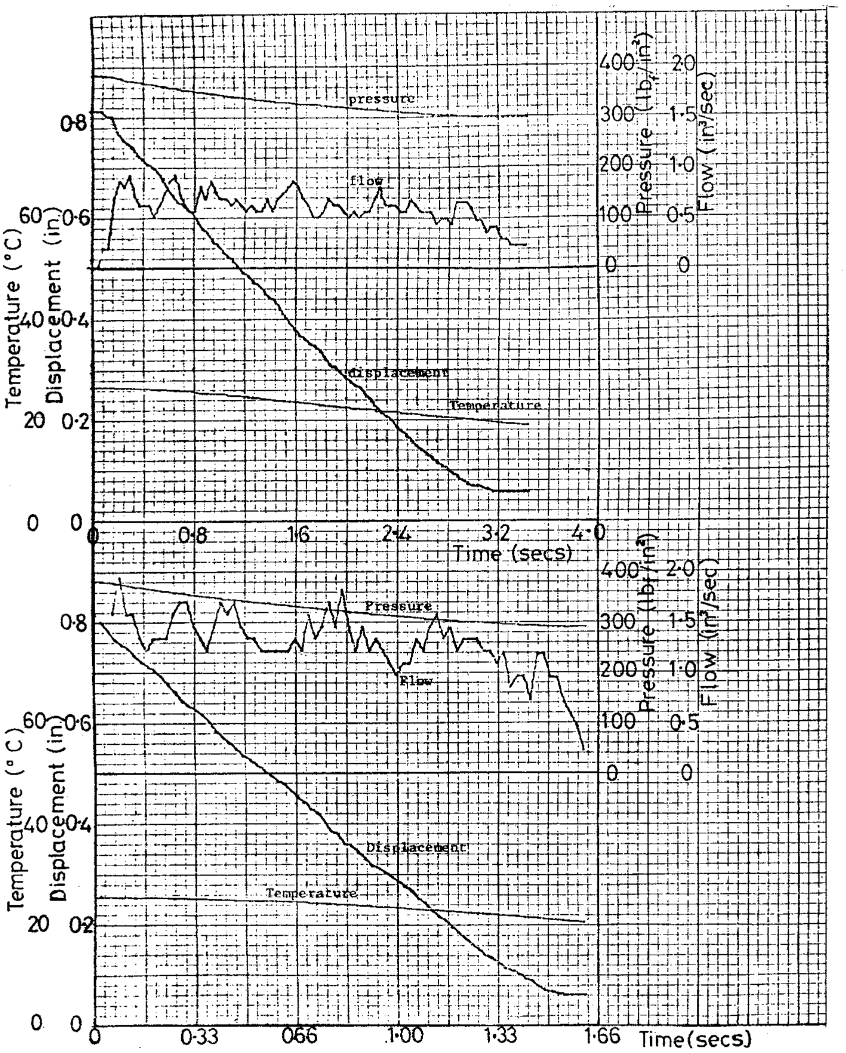

Fig. 6. Accumulator discharge tests

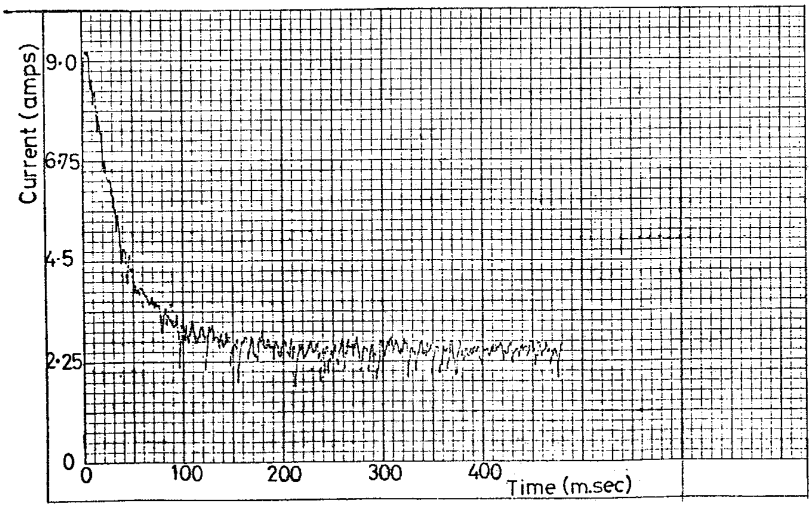

Fig. 7. "Globe" motor current transient

In addition to the work on accumulators, ancillary equipment is also being developed; e.g. filter, accumulator bursting disc, pressure relief valve, current sensor and motor switch.

Load Tests

The need for good overall efficiency has led to the design of a prosthesis in which the applied loading can be a high percentage of the stall load. This results in a situation in which load forces and inertias can be reflec ed at the hydraulic actuator which are much larger than is usual in commercial practice. In order to investigate the stability of this heavily loaded system, an analogue computer simulation was carried out of a valve and actuator under load using supply pressures and oil flows of the order likely to be produced by the pump unit. The effects of various amounts of leakage, coulomb frinction, dead zone and transient pressure feedback were considered. With a forward loop gain of unity in which the valve is mounted directly on the actuator, it was found that the system was stable when reasonable amounts of dead zone were added to friction and leakage (Fig. 8). However, from the pressure traces it can be seen that when the large load force aids the motion of the actuator, cavitation of the oil in

the actuator is likely to occur. This may have detrimental effects on the actuator life and performance /9/.

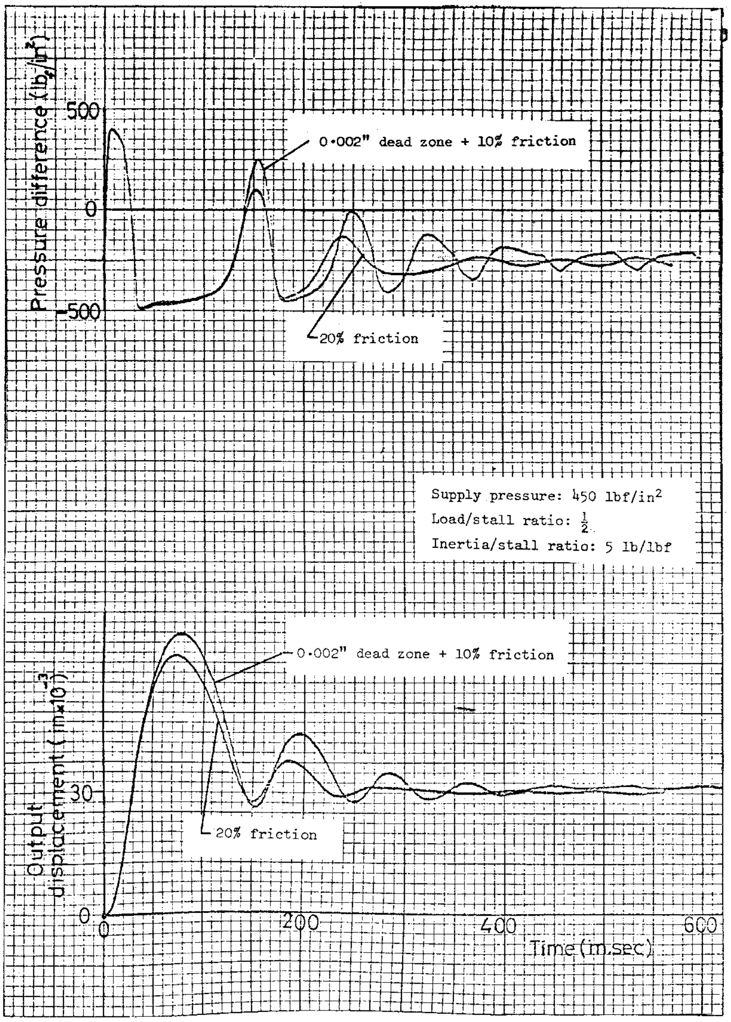

Fig. 8. Step response of loaded actuator

Conclusion

A prosthetic power unit has been produced with a continuous output of 12 watts and adequate to provide a peak power of 30 watts for 4 seconds. Further work is in progress to reduce size and weight without reducing the overall efficiency. The total power unit, including motor, gearbox, pump, low pressure reservoir, accumulator, burst disc, filter motor switch and non-return valve, together with associated piping, connectors and oil, will have a mass of less than one Kg. Furthermore this mass, which is comparable to that of the standard gas container in the U.K., can be distributed by, for instance, enclosing the first four items listed above as ballast in a passive arm, and mounting the remaining items on the harness.

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