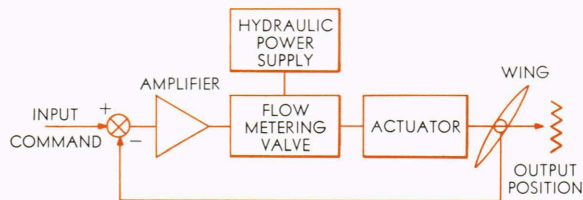


Feedback Technique Efficiency

W. Seamone

A hydraulic servomechanism is often chosen for flight control applications because of its known capability of high dynamic response from a small package. This performance advantage is usually gained at the expense of low system efficiency that is characteristic of hydraulic systems. The reason for this characteristically low efficiency may be understood by examining the basic operation of a hydraulic servomechanism. A typical block diagram of a hydraulic servo is as follows:



The basic controller in this loop is the flow-metering valve whose function is to meter or control the flow rate to the actuator in accordance with the amplifier drive signals. This is accomplished by varying an orifice restriction between the hydraulic supply and actuator. Assuming a constant pressure-supply source, the metering process has a maximum efficiency of 66% when the actuator pressure drop due to load is $2/3$ of the supply pressure, and is progressively less efficient as the actuator load is decreased to zero.¹ Since many flight-control servos commonly undergo simulta-

neous high actuator velocities and low loads, system efficiency may suffer as a result.

The need for improved system efficiency while maintaining performance is particularly acute in small missiles and in space applications, where size and weight of the primary power source are at a premium. Assuming that a hydraulic servomechanism is chosen for these applications in order to meet performance requirements, the hydraulic power source should be designed for minimum power consumption. This source must be capable, however, of furnishing peak power upon servo demand without affecting dynamics of the servo.

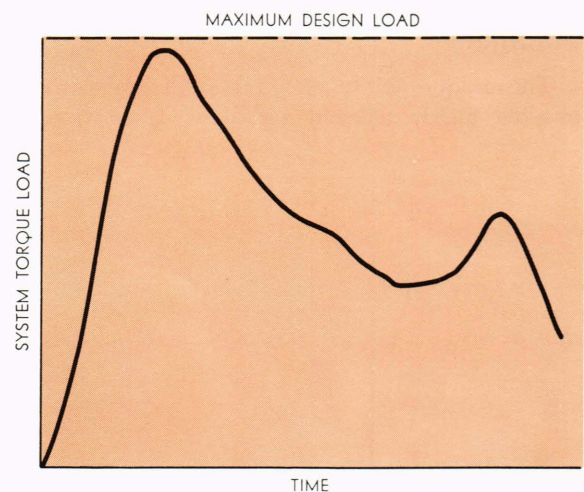


Fig. 1—Typical flight load-time history for an anti-aircraft-missile control servo.

¹ W. A. Good and F. C. Paddison, "A Method for the Selection of Valves and Power Pistons in Hydraulic Servos," CM-717, The Johns Hopkins University, Applied Physics Laboratory, Jan. 26, 1952.

Improves of Hydraulic Servos

Hydraulic servos have been widely used in applications where good dynamic performance at high power levels is required. Power sources for such systems are often oversized to provide good transient load capability, at the expense of system efficiency for the average load duty cycle. A system concept is reported in this paper, which attempts to match the required input power to the servo as a function of actual load demand. Such a system has potential improved power efficiency. Tests performed on an experimental model have shown encouraging results.

This latter requirement and other system considerations often lead the designer to choose one of the simplest hydraulic power configurations, that is, the constant-pressure system.

Implementing this system in its simplest form is generally accomplished by employing a constant-rpm motor driving a fixed-displacement pump to deliver a constant flow rate. To maintain a fixed pressure level for the system, a relief valve is used to bleed off flow not commanded by the servo. Such a pressure source is sometimes referred to as a fixed-displacement-pump/constant-pressure system. This hydraulic power source operates at 100% pressure and flow at all times and thus can be quite inefficient for many applications. This system,

however, enjoys widespread usage because of its simplicity and inherent reliability.

Recent work at APL has shown that system improvements in efficiency without sacrificing performance may be possible in a fixed-displacement-pump/constant-pressure system by using a hydraulic-load feedback loop around the servo actuator and hydraulic pump. This technique is predicated on the use of a unitized hydraulic servo in which the hydraulic power and servo elements for each servo application are packaged into self-contained servo power packs. Such a system allows a load sensor to be used to sense and control the system pump pressure as a function of the instantaneous external load on the servo. The servo-valve pressure drop remains constant for all load conditions under this arrangement; hence, the servo closed-loop bandwidth and performance is made independent of the variable system pressure operation.

Feasibility studies of this concept have been conducted on an experimental model of the unitized hydraulic package developed under subcontract to APL by the Kearfott Company. This model employs a simplified two-pressure-level system that was designed to check basic feasibility of the concept under dynamic operating conditions. All experimental data discussed in this paper are for this simplified system.

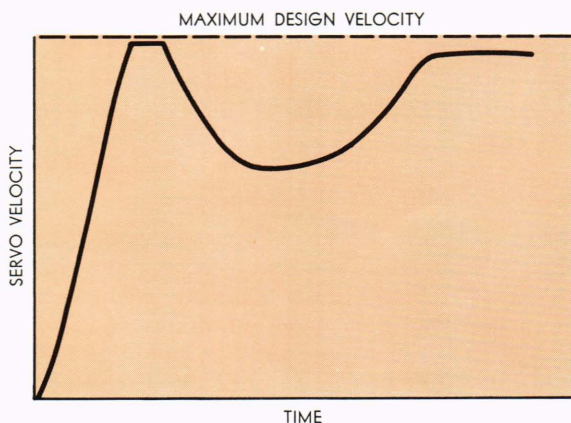


Fig. 2—Typical flight velocity-time history for an anti-aircraft-missile control servo.

The Servo Load Environment

A quantitative definition of the servo load environment is one of the more difficult parameters to pin down in many servo applications. Maximum design loads may be readily calculated, but the

frequency of peak loading or load-duty-cycle profile is often difficult, if not impossible, to predict. A servo application in a missile control system, for example, has a load duty cycle that is a function of the exact flight conditions for each particular flight. The torque load requirements generally reach a maximum during an early portion of the flight and may drop to a moderate or even negligible value for the remainder of the flight. Such a variable load environment requires that this type of a system be designed to handle peak loads at any time during flight.

The minimum power requirements for a given servo are dictated by the servo-torque-load duty cycle and the actuator velocity requirements for its particular mission. Typical plots of instantaneous load and velocity requirements versus time for the anti-aircraft missile control servo are given in Figs. 1 and 2. The maximum required power for such a system would be the product of these two curves. The average required power, however, is considerably less than the maximum value since it is dependent on the time duration of peak load demands. Most actual systems have load duty cycles such as shown in Fig. 3, which result in average power requirements typically 20 to 30% of peak system requirements. The problem then becomes one of a design trade-off to provide the instantaneous peak power as required, and yet consume average power proportional to the actual duty cycle in an effort to keep the system efficiency high.

A common approach taken in some hydraulic system designs is to provide a motor pump, sized to provide the average load duty cycle and to include

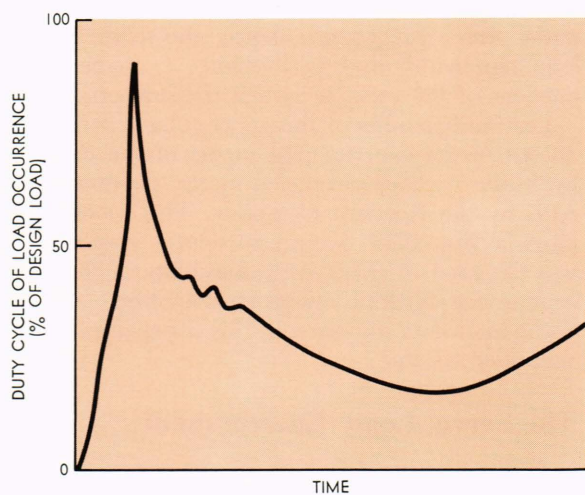


Fig. 3—Typical load duty cycle as a function of time for an anti-aircraft-missile control servo.

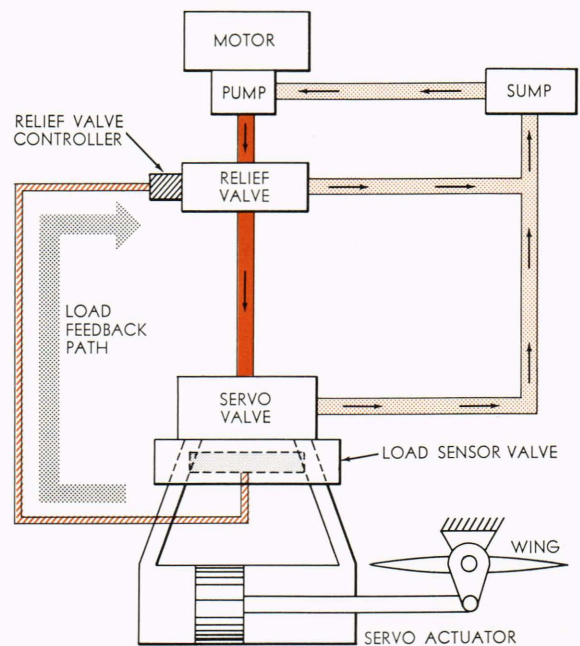


Fig. 4—Schematic diagram of a servo power system with load-sensing variable-pressure control. (Different color values indicate variations in pressure.)

a hydraulic air-oil accumulator for short-term peak-power demands. Although accumulators have been in widespread use for a number of years, missile applications have pointed up many problems, particularly in regard to the long-term storage of high-pressure air. The incorporation of an accumulator in a missile control system may require that the user perform field service maintenance on the equipment. The objections to the accumulator may be overcome by use of a variable displacement pump in lieu of the accumulator; however, this will result in additional system complexity and cost. This paper addresses the problem of how the system efficiency can be improved for a low-duty-cycle system *without* the complexity of *stored energy elements* or a variable-displacement pump.

Load Sensor Feedback

An efficiently designed power system for an application such as a missile control servo would be one whose input power is directly a function of the actual load duty cycle. Theoretically this implies that both flow and pressure should be varied as a direct function of output load. The problem is somewhat simplified for the typical system described in Figs. 1, 2, and 3 by noting that the servo velocity demand is relatively high throughout the flight period, and that a system that simply modu-

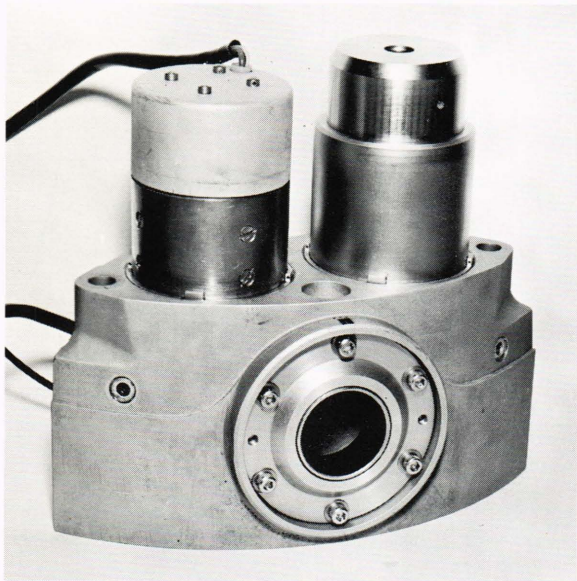


Fig. 5—Unitized hydraulic actuator modified with a load-feedback sensor.

lates input power as a function of torque demands can offer appreciable power savings for the system. Such a system is, of course, a load-controlled variable-pressure system.

Instrumentation of a load-controlled variable-pressure system in a flight-control servo appears feasible by providing each hydraulic servo with its own individual hydraulic power source. This packaging concept is sometimes referred to as a unitized hydraulic servo package; it allows the flexibility of individual pressure control for each servo by sensing its load and controlling the pressure accordingly. A conventional, single, hydraulic power source arrangement, where one pressure source is used for several servos, does not appear feasible for this type of load sensing because of possible conflict of load requirements from each servo.

Instrumentation of a load-controlled variable-pressure system may be accomplished as shown in the system diagram, Fig. 4. In this hydraulic system the relief valve is set at a minimum pressure level for the system when no external load is applied to the servo actuator. Upon encountering a load, the servo actuator will develop a differential pressure to sustain the load. A feedback path is employed to send back a signal to the relief valve to cause it to go to a higher value proportional to the encountered load. This will result in a hydraulic pressure source whose output is controlled by the actual load seen by the servo actuator. An important secondary benefit of the system is that the pressure drop across the servo control valve remains constant, independent of load. This is due to the fact

that the incremental rise in supply pressure is equal to the load demand. This constant pressure drop across the servo valve tends to keep the servo valve gain constant and independent of load. This provides for a constant bandwidth servo system over the load operating range.

Experimental Model Design

In order to study experimentally the basic feasibility and dynamic characteristics of the load-feedback/variable-pressure system, a unitized hydraulic actuator package, shown in Fig. 5, has been modified with a load-feedback sensor. The instrumentation scheme chosen for this first model included a differential pressure load sensor and a two-level pressure-relief valve controlled by the load sensor. This simplified system was designed to determine possible dynamic interaction of the load feedback loop and servo dynamics. The load sensor and relief-valve mechanization employed in the experimental model are shown in Fig. 6. The load sensor valve is a spool-type valve whose displacement from null is a function of the magnitude of the external load on the servo. The metering ports across the spool have a controlled dead zone before pressure is allowed to be connected to the actuation piston of the relief valve. The relief valve is held at its lower pressure setting of 1500 psi by a mechanical stop. When the external load exceeds 400 in.-lb for either direction of load, system pressure of 1500 psi is connected by the load sensor valve to the relief valve actuation piston to force it to the mechanical stop corresponding to the

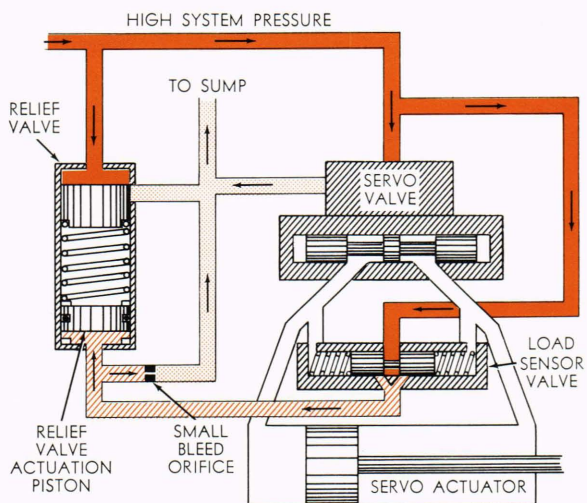


Fig. 6—Schematic diagram of a two-pressure-level system used in an experimental model.

high-pressure, 3000-psi setting. The system pressure will remain at this setting until the high load demand is removed from the servo.

The two-level pressure system in the experimental model operates at a 60% input-power level for loads up to 400 in.-lb and at 100% rated power at loads up to the design maximum of 1500 in.-lb. This power saving of 40% can be appreciable when we consider the basic size and weight of the primary power source.

Experimental Model Results

In order to exercise the load feedback characteristics of the system, the servo power package was operated against a torsion bar load. The servo bandwidth was set up to give 45° phase lag across the servo at approximately 45 cps to determine if there were any serious dynamic effects in a typical high-bandwidth system. The experimental model had its load feedback system set up with the following parameters:

- | | |
|---------------------------------|---------------------|
| (a) No-load pressure | 1500 psi |
| (b) No-load motor current | 12 amps at 56 volts |
| (c) Torque-load switching point | ± 400 in.-lb |
| (d) High-load pressure | 3000 psi |
| (e) High-load motor current | 20 amps at 56 volts |

The servo was operated in this mode for approximately 10 hr of test time. The transition from a small-load to a high-load condition appeared smooth for a variety of input signal conditions.

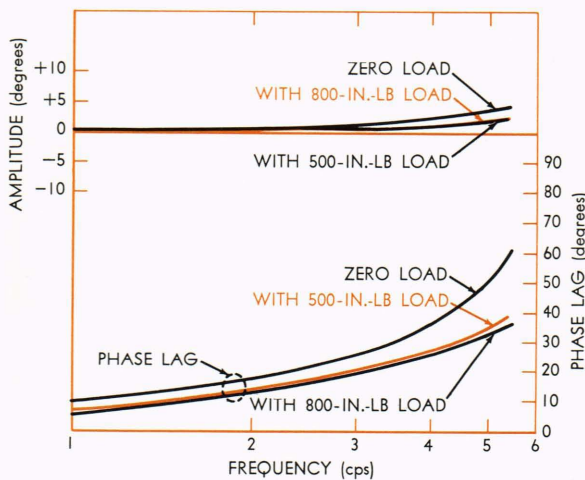


Fig. 7—Unitized actuator frequency-response characteristics with power-matching pressure-control system.

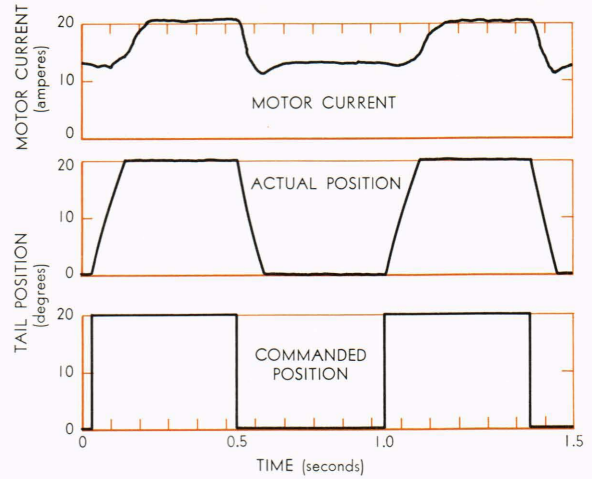


Fig. 8—Unitized actuator step-response characteristics with power-matching pressure-control system. Torsion-bar load is 37 in.-lb per degree.

Servo transfer characteristics were measured at no load, 500-in.-lb, and 800-in.-lb loadings, and are given in Fig. 7. These data show that the bandwidth actually increased as the load was increased above the load sensor switching point. Increasing the torque load switching point to a higher value will reduce this over-compensation of servo gain with increasing load.

In order to insure that the load feedback mechanism would work properly during transient inputs, a step command was applied to the servo. This test yielded typical system performance of Fig. 8. This and other tests with various command signals have not shown any evidence of dynamic instability associated with the load feedback scheme.

Conclusions

The satisfactory demonstration of the experimental model of a hydraulic power servo with load sensor feedback has indicated that this technique is sufficiently promising to warrant additional studies. The model operated at 60 and 100% power levels as a direct function of the load, showed no evidence of dynamic instabilities, and introduced no undesirable transients into the servo. The additional hardware complexity was small and is not expected to affect long-term reliability for missile applications.

A linear load feedback sensor has not been designed as of this date, but it is of interest since it offers the promising possibility of complete power matching to the actual load requirements. Such a system would allow the designer to use the high performance of hydraulic servos and retain high efficiency as well.