ENERGY-SAVING HYDRAULIC POWER SOURCE USING INVERTER-MOTOR DRIVE

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ABSTRACT

From a view point of saving energy, power losses in hydraulic systems including power sources should be minimized as small as possible. In conventional hydraulic power units, the output power is adjusted by controlling a displacement of variable displacement pump to avoid a waste of excess power. In this study, it is proposed for adjustment of the output power that rotating speeds of a fixed displacement pump is controlled by making use of a inverter-motor drive. We apply a digital control scheme to the energy-saving hydraulic system. A pressure feedback control system and an estimated pressure feedback control system are discussed and the results are experimentally verified. Experimental results demonstrate that the studied systems are effective to save energy for constant pressure power sources.

KEYWORDS

energy saving, electro-hydraulic servo system, fixed displacement pump, inverter-motor drive, accumulator

NOMENCLATURE

\( C_1, C_2 \): coefficient of delivery flowrate
\( f \): frequency of electric AC supply [Hz]
\( f_c \): inverter command frequency [Hz]
\( f_i \): inverter frequency [Hz]
\( G_f \): feedback gain
\( K_1, K_2, K_3 \): coefficient of total efficiency
\( N \): rotational speed of motor [rad/s]
\( P_s \): setting system pressure [MPa]
\( p_s \): system pressure [MPa]
\( q_s \): pump delivery flowrate [cm³/s]
\( q_l \): quiescent flowrate [cm³/s]
\( r \): reference input [rad]
\( v \): load velocity [rad/s]
\( W_e \): supply electric power [kW]
\( \eta \): total efficiency

INTRODUCTION

Electro-hydraulic servo systems have been widely used for automatic control applications requiring high power and rapid response. Conventional valve controlled electro-hydraulic servo systems are usually powered by a constant pressure power source shown in Fig.1a, where the system pressure is controlled by a relief valve. In this type of hydraulic power units, the power losses are inevitable because of the existence of the relief flow maintaining the system pressure at a certain constant value. From a view point of saving energy, power losses in hydraulic systems including power sources should be minimized as small as possible. In conventional energy-saving hydraulic power units, the output power is adjusted by controlling a displacement of pump to avoid a waste of excess power. It has been well known that
a so-called pressure compensated variable displacement pump\(^1\) is used for an energy-saving power source shown in Fig.1b. However this type of power sources was not suitable for electrical remote control of pump delivery flowrate adapting to the change of operating conditions so far. On the other hand, an intelligent variable displacement pump\(^2\) equipped with a pressure sensor, a tilt angle sensor, a control actuator and an electric amplifier is recently developed, but this variable displacement pump consists of many mechanical parts in need of maintenance and is usually more expensive than a fixed displacement pump.

In order to minimize power losses in a hydraulic power source, two of the authors have proposed a new type of energy-saving power source\(^3\) shown in Fig.1c. In this power source, the delivery flowrate is controlled by change of rotating speed of a fixed displacement pump instead of changing a pump displacement. The rotating speed of the fixed displacement pump is controlled so as to supply the necessary amount of oil to the servo system and to maintain the system pressure at a certain constant level without making use of a relief valve. The speed control method by the inverter-motor drive is adopted to change the speed of the induction motor which drives the fixed displacement pump.

In a previous paper\(^4\), the system pressure was directly measured by a sensor and fed back to the analogue controller. The inverter-motor was controlled to keep the system pressure at a constant value by the analogue controller. The present research gives a digital control scheme by using a microcomputer. Then a tentative duty cycle of the servo system is given as an example and investigated to confirm the effect of the digital control system for energy saving. It is also discussed that the pump pressure and flowrate are indirectly estimated by the state variables of the inverter-motor. These estimated variables are used for the digital feedback control system.

**INVERTER-MOTOR DRIVE**

Electric AC induction motors are generally used for prime movers in hydraulic power sources. AC induction motors offer the advantage of maintenance free, lower initial cost and simple structure, but it is a demerit in a sense that their speeds are determined by the frequencies of the commercial electric supply. It was formerly difficult for AC induction motors to change the speeds. Recently, a variable speeds AC motor drive can be achieved by advances in power electric devices and microprocessors.

\[
N = \frac{4f\pi(1-s)}{p}
\]

where \(N\) is a rotational speed of motor, \(f\) is a frequency of the electric AC supply, \(s\) and \(p\) are a slip and the number of poles of the motor respectively. The speed of AC motors is nearly proportional to the frequency under the small slip conditions. Then the speed of AC motors can be controlled by varying a frequency of electric
AC supply. These variable frequencies are provided by a so-called inverter which is able to transform the frequency of electric AC supply from the standard frequency to an arbitrary frequency.

In this study, we use a pulse width modulation (PWM) type transistor inverter shown in Fig.2, which is one of the high efficient frequency converter. This transistor inverter can change the frequency of AC electric power within the range of 0 to 80 Hz which corresponds to the rotational speed range 0 to 251 rad/s given by Eq.(1) in the four-poles AC motor. The advantage of the inverter drive is that the speed control of AC motors can be easily realized in low cost, high efficiency and wide speed range.

**EXPERIMENTAL APPARATUS**

An experimental hydraulic circuit used in this study is shown in Fig.3. It consists of an electro-hydraulic position control servo system and a hydraulic power source. The servo system is composed of a nozzle flapper type electro-hydraulic servo valve, an axial piston motor (geometric displacement 1.55 cm³/rad) and an inertia load (polar moment of the inertia 6.0×10⁻⁴ kgm²). The load position and velocity are measured by a potentiometer and a tachometer, respectively.

The hydraulic power source consists of a 1.5kW squirrel-cage three-phase induction motor controlled by a 2.5kVA transistor inverter, a gear pump (geometric displacement 0.56 cm³/rad) and a bladder type accumulator.

Fig.4 shows static characteristics of the pump delivery flowrate in the studied hydraulic power source, where the system pressure p<sub>s</sub> is kept at 7 MPa and the flowrate is measured by a volumetric flowmeter. It is clear that the delivery flowrate q<sub>s</sub> is nearly proportional to the inverter frequency f<sub>i</sub>.

![Fig.3 Experimental hydraulic circuit](image)

![Fig.4 Pump delivery flowrate](image)

In a transient condition, the pump can't supply the sufficient amount of oil to the servo system, because the AC induction motor has so large rotational inertia that the motor can't respond rapidly comparing with the servo system. A typical transient response of inverter-motor drive is shown in Fig.5, where f<sub>c</sub> is a command frequency to the inverter, f<sub>i</sub> is an inverter frequency which corresponds to the speed of the AC motor. A rotational inertia or an output torque limits a maximum acceleration and deceleration of the AC motor to 50 rad/s² and 84 rad/s² respectively.

![Fig.5 Transient response of inverter drive](image)

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1 50 Hz or 60 Hz is the standard frequency for commercial AC supply in Japan.
To avoid an imbalance of oil flow between supply in the power source and demand in the servo system, a short delivery is supplemented by the transient flow from the accumulator. The accumulator is recharged by the excess delivery of the pump during a dwell time of the servo system.

Total efficiency of the hydraulic power source is defined as follows:

\[ \eta = \frac{p_s \times q_s}{W_e} \]  

where \( p_s \) and \( q_s \) is a system pressure and a pump delivery flowrate respectively and \( W_e \) is a supply power from the electric source to the inverter. Fig.6 shows the experimental relationship between the inverter frequency \( f_i \) and the total efficiency \( \eta \), where the system pressure is kept at 7 MPa. In the frequency range 10 to 20 Hz, the values of the total efficiency is markedly low. This is attributed to the inherent characteristics of the pump and the AC motor, so we must avoid to drive the AC motor continually in this frequency range. The hydraulic power source always has to supply the sufficient amount of oil which corresponds to a quiescent flow in the servo valve. From this reason, the pump is driven in the frequency range higher than 30 Hz which corresponds to the necessary flowrate for compensation of the quiescent flow.

PRESSURE FEEDBACK CONTROL

In the studied system, a pressure feedback control was adopted. In the previous paper \(^4\), the authors made use of an analogue controller to maintain the system pressure at a constant. An analogue system is, however, inconvenient for changing system parameters. On the contrary, a digital control is flexible for the change of system parameters, e.g. the setting pressure, the quiescent flow and the duty cycle of the servo system.

Digital Feedback Control

A schematic diagram of the pressure feedback control system used in this study is shown in Fig.7. The system pressure \( p_s \) is directly measured by the pressure transducer and feedback to the microcomputer through the A/D converter. The microcomputer calculates the inverter command frequency \( f_c \) in order to maintain the system pressure at a constant value. In this digital control system, one microcomputer simultaneously reads data of the system pressure and calculates both the reference input to the servo system given periodically and the command frequency to the inverter. If a cycle time of the servo system is controlled by a software, the CPU is used for a time controller over the cycle time and can't afford to calculate the inverter command frequencies in a pressure feedback control.
loop. Therefore data of the reference input to the servo system given in advance are stored in memories of the microcomputer system and periodically transferred from the memories to the servo system through the D/A converter by the interrupt signal of PTM (Programmable Timer Module). Its cycle time is given in a control register in the PTM beforehand. The PTM in place of the CPU is used for the cycle time controller of the reference input to the servo system.

Fig. 8 shows a block diagram of the pressure feedback control system, in which a pressure transducer (P.T.) senses the system pressure. A pressure feedback gain $G_c$ is selected to an optimal value by computer simulation tests. The reference input to the servo system is given to the control path in a sense of the feedforward control to get necessary pump speed. The extra signal for the compensation of the quiescent flow $q_i$ described in the previous section is also added to the control path.

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**Duty Cycle**

In order to illustrate energy saving of the studied system, a tentative duty cycle for the servo system shown in Fig. 9 is investigated. In these figures, $r$ is a load displacement, $v$ is a load velocity, $q$ is a necessary flowrate and $W$ is a necessary power. The system pressure is kept at a constant (7MPa). The necessary power is nearly proportional to the necessary flowrate as given by Eq.(2). In a constant pressure power source using a relief valve shown in Fig. 1a, a pump delivery flowrate must be greater than or equal to the maximum necessary flowrate for the servo system. Therefore the energy requirement of the servo system for one duty cycle is calculated to be $2.4\text{kW} \times 20 \text{ sec} = 1.33 \times 10^{-2} \text{kWh}$ and the energy not required by the servo system is wasted at a relief valve as shown by the cross-hatched area in Fig. 9.

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**Results and Discussion**

Fig. 10 shows experimental results of the transient responses of the pressure feedback control system for three duty cycles. In these figures, $r$ is the reference input, $v$ is the measured load velocity, $f_i$ is the inverter frequency nearly equal to the pump delivery flowrate, $p_s$ is the system pressure and $W_e$ is the supplied electric power from an electric source to the inverter.
Corresponding to the magnitude of the reference input, the speed of the AC motor is controlled by the inverter and the pump changes the delivery flowrate. Since the shortage of the delivery caused by the response lag of the AC motor is supplemented by the flow from the accumulator, the system pressure is almost exactly maintained within a permissible range. Even if the actuator of the servo system is at a stand still, the AC motor continues the rotation in order to recharge the accumulator until the system pressure rises up to the setting pressure.

System energy is measured to be $5.89 \times 10^{-3}$ kWh during one duty cycle in Fig.10. Thus the use of the inverter-motor drive increases saving energy to:

$$\frac{1.33 \times 10^{-2} - 5.89 \times 10^{-3}}{1.33 \times 10^{-2}} \times 100 = 56 \%$$

by eliminating relief flow.

PRESSURE ESTIMATION

Hydraulic power sources transform electric energy into hydraulic energy, therefore system pressures may be estimated by state variables of an electric AC motor.

From Eq.(2), the system pressure may be written as:

$$p_s = \frac{\eta W_e}{q_s}$$

Namely, the electric power, the pump delivery flowrate and the total efficiency must be determined by the state variables of the AC motor in order to estimate the system pressure.

The electric power $W_e$ can be directly measured at the electric AC supply by a watt meter or an ammeter and a voltmeter.

The pump delivery flowrate $q_s$ is nearly proportional to the speed of the AC motor, i.e. the inverter frequency $f_i$. From the experimental results in Fig.4, the pump delivery flowrate $q_s$ is approximately given by the inverter frequency $f_i$ as follows:

$$q_s = C_1 f_i + C_2$$

where $C_1$ and $C_2$ are constants shown in Table 1.

The total efficiency $\eta$ markedly varies with the change of the AC motor speed, so the total efficiency expressed as a function of the inverter frequency $f_i$.

$$\eta = K_1 f_i^2 + K_2 f_i + K_3$$

where $K_1$, $K_2$ and $K_3$ shown in Table 1 are determined by the experimental results in Fig.6. The dependence of the delivery flowrate and the total efficiency characteristics on the change of system pressure can be neglected.

<table>
<thead>
<tr>
<th>Parameter values for Eq.(4),(5)</th>
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<tbody>
<tr>
<td>$20 \leq f_i \leq 40$</td>
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<tr>
<td>$C_1$</td>
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<tr>
<td>$C_2$</td>
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<td>$K_1$</td>
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<td>$K_2$</td>
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<td>$K_3$</td>
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From Eq.(4),(5), the system pressure $p_s$ given by Eq.(3) is rewritten as follows:

$$p_s = \frac{(K_1 f_i^2 + K_2 f_i + K_3) W_e}{C_1 f_i + C_2}$$

Fig.11 shows a relationship between the values of the system pressure $p_s$ and the electric power $W_e$ as a function of the inverter frequencies $f_i$. The estimated values of the pressure given by Eq.(6) agree with the output values of the pressure sensor. Then the estimated pressure can be used for the digital pressure feedback control system.

A schematic diagram and a block diagram of the pressure feedback system without sensing the system pressure are shown in Fig.12 and Fig.13 respectively. The state variables of the inverter-motor, i.e. the inverter frequency and the supply electric power, are measured to estimate the system pressure. The measured electric power is delayed by a little time lag of
the watt meter. The estimated pressure $\hat{p}_s$ is incorrectly calculated by the delayed electric power and the undelayed inverter frequency, so the closed loop to calculate the inverter command frequency $f_c$ becomes unstable. To prevent the inverter command frequency from being unstable, the measured inverter frequency $f_i$ is delayed by using memories as a retardation element in the microcomputer system. In the control loop, it took 150 ms to calculate Eq.(6) including many multiplications. In order to allow a high speed operation of Eq.(6), the relations between the measured state variables of the inverter-motor and the values of the system pressure are tabulated in advance on memories of the microcomputer system. As a result, the estimated value of the pressure is obtained at every 200 µs by referring to the table in memories of the microcomputer system.

Fig.13 Block diagram of estimated pressure feedback system

Fig.14 shows typical results obtained from the experimental system. The duty cycle is the same example as the pressure feedback system shown in Fig.10. The system energy is measured to be $6.05 \times 10^{-3}$ kWh during one duty cycle. Comparing to
the results in Fig.10, the inverter frequency changes slowly because of the time delay.

CONCLUSIONS

This paper describes the energy saving hydraulic power source using the inverter-motor drive. The AC motor which drives the fixed displacement pump is controlled by the inverter, so that the pump delivers the necessary flowrate for the duty cycle of the servo system. The digital control scheme is applied to the pressure feedback system. In addition, the system pressure is estimated by the state variables of the AC motor. The estimated pressure feedback control system without sensing the system pressure is developed. It is experimentally clarified for the other duty cycles that the both digital control systems using the microcomputer are quite effective to save energy for the constant pressure power source.

REFERENCES