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Constant-Power Hydraulic Drive and Dynamic Volume-Compensated Leakage Detection for a Grain Silo Sweep Auger

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Abstract. A constant-power hydraulic drive and a leakage-detection method based on dynamic volume compensation are developed for a grain silo sweep auger to address insufficient torque under low-speed heavy-load conditions and false flow-balance alarms caused by rapid pressure variations. A variable-displacement axial piston pump and a load-sensing circuit provide adaptive pressure-flow regulation. A flow residual is established from the supply, return, and motor case-drain flow rates, and dynamic volume compensation attenuates the effects of fluid compressibility, line elasticity, and accumulator charging and discharging. Within the constant-power envelope, the drive extends the low-speed heavy-load operating range by trading rotational speed for torque. The compensated residual suppresses transient flow disturbances during load variations while retaining the imbalance caused by sustained external leakage. At 45 kW, the predicted torque reaches 6900 N·m at approximately 62.3 r/min, or 2.10 times the rated torque of the original electric drive. Leakage decisions additionally require residual persistence and agreement with reservoir-level trends to separate hydraulic faults from sensor failures.

Keywords: grain silo sweep auger, constant-power hydraulic drive, load-sensing control, hydraulic leakage, dynamic volume compensation

1. Introduction

Silo cleanout is the final stage of bulk-grain discharge. The sweep auger must continuously convey residual grain toward the central discharge sump while withstanding abrupt loads caused by compacted grain and occasional foreign objects. The output of a conventional electric drive is constrained by the motor rated torque and a fixed transmission ratio; consequently, its torque reserve is insufficient under low-speed heavy-load conditions, leading to stall. Hydraulic drives offer high power density, a wide speed range, and high torque at low speed. However, hoses, fittings, and seals are exposed to sustained vibration and pressure shocks, which increases the likelihood of leakage. Because the interior of a silo is a confined space, hydraulic leakage causes power loss and grain contamination and increases the need for personnel to enter the silo for inspection. Current guidance for sweep-auger operation emphasizes isolation of hazardous zones, external observation, and

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emergency stopping [1]. The hydraulic system must comply with the general safety requirements of GB/T 3766-2015 and ISO 4413:2010 [2, 3].

Constant-power control of a variable-displacement pump reallocates pressure and flow as the load changes without increasing installed power, thereby enabling a transition between high-speed low-load operation and low-speed heavy-load operation. A load-sensing circuit adjusts the pump outlet pressure in response to the highest load pressure, reducing unnecessary throttling losses and improving flow sharing among parallel actuators [4-6]. Flow-balance leakage detection is physically interpretable under steady conditions. During startup, reversal, and abrupt load changes, however, fluid compression, elastic expansion of the lines, and accumulator exchange produce substantial transient storage flow. Direct use of the supply-return flow difference therefore causes false alarms during these transients [7]. This study integrates a load-adaptive constant-power hydraulic drive with a leakage residual that accounts for dynamic volume changes. The shared pressure measurements support both drive regulation and leakage monitoring.

2. Constant-power hydraulic drive and control principle

The drive system comprises two auger-drive circuits and two travel-drive circuits, as shown in Figure 1. A 45 kW electric motor drives a variable-displacement axial piston pump. A load-sensing directional valve bank distributes pressurized fluid to four parallel circuits, and proportional flow-control valves regulate the inlet flow to the low-speed high-torque motors. The highest load pressure is fed back to the pump regulator through the load-sensing line so that a prescribed pressure margin is maintained between the pump outlet and the highest load. A relief valve limits the maximum system pressure, and an accumulator attenuates rapid pressure pulsations. This arrangement allows the pump delivery to track actuator demand and implements constant-power regulation.

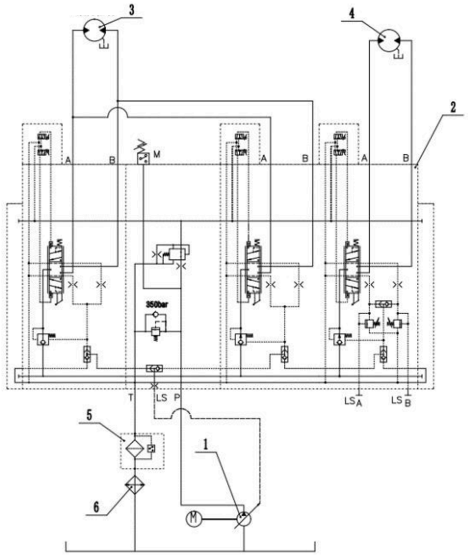


Figure 1. Hydraulic circuit of the constant-power sweep-auger drive

The hydraulic output power of the variable-displacement pump is determined by the pump outlet pressure p and flow rate Q. The corresponding constant-power torque-speed characteristic is described by the following governing relations:

$$P = pQ/60 \quad (1)$$

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$$T = 9550P/n \tag{2}$$

where P is the transmitted power in kW, p is the pressure in MPa, Q is the flow rate in L/min, T is the torque in N·m, and n is the rotational speed in r/min. For the 45 kW rated drive, Eq. (2) gives the torque-speed relationship under constant-power regulation. At low load, the pump maintains a relatively large displacement to provide the required speed. When the load pressure reaches the constant-power setting, the regulator reduces the swashplate angle so that pQ remains within the permissible motor-power range. Simultaneously, the load-sensing circuit adjusts pump outlet pressure according to the highest load, the proportional metering orifices determine circuit flow demand, and the pressure-limiting circuit constrains extreme loads. As the auger penetrates compacted grain and load pressure rises, reduced flow and speed produce higher torque. When the load decreases, pump displacement and motor speed recover. The resulting characteristic is bounded jointly by rated power and maximum pressure.

3. Leakage detection based on dynamic volume compensation

The monitoring boundary in Figure 2 prevents normal motor case-drain flow and transient storage flow from being classified as external leakage. Flowmeters are installed in the pump discharge line and the main return line, while the case drains from all motors are collected in a separate line and measured by a third flowmeter. Pressure transducers are installed in the valve-bank and actuator circuits, and the reservoir is equipped with temperature and level sensors. The programmable logic controller (PLC) acquires these signals synchronously for pressure-transient identification, residual calculation, and fault confirmation. The resulting control volume encloses the valve bank, actuators, and connecting lines, with normal case-drain flow treated as a measured outflow.

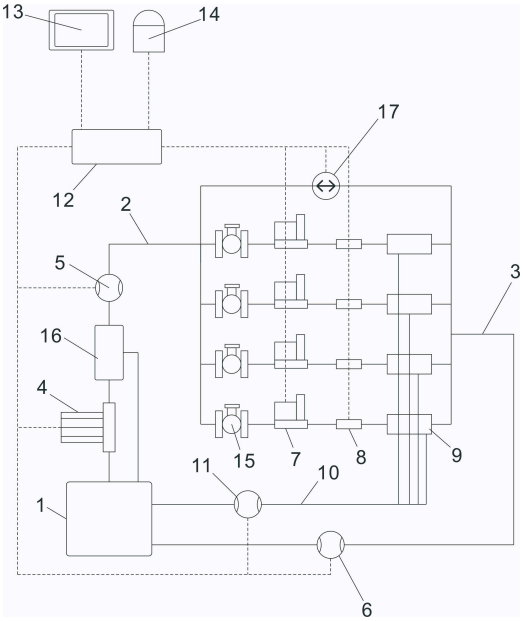


Figure 2. Hydraulic leakage-monitoring circuit with dynamic volume compensation

The control volume extends from the pump discharge measurement point to the main return measurement point. Let Q_1, Q_2, and Q_3 denote the supply, return, and case-drain flow rates, respectively. The uncompensated flow imbalance is

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$$\Delta Q(t) = Q_1(t) - Q_2(t) - Q_3(t) \tag{3}$$

Under steady operating conditions, ΔQ is governed primarily by external leakage. During rapid pressurization or depressurization, fluid compressibility, line elasticity, and accumulator charging or discharging produce a transient change in the volume stored inside the control volume. This effect generates a component of ΔQ that is unrelated to leakage. Physically, the compensation flow depends on the equivalent hydraulic capacitance and the pressure rate. For controller implementation, a dynamic volume-compensation map Qc(t, Δp) is obtained under leak-free conditions from the time histories of instantaneous flow imbalance associated with different pressure-step amplitudes. The compensated leakage residual is

$$r(t) = \Delta Q(t) - Qc(t, \Delta p) \tag{4}$$

where Qc(t, Δp) represents the time-varying equivalent storage flow for a specified pressure-change amplitude. Compensation attenuates the reversible flow deviation induced by a pressure transient, whereas the net flow loss caused by sustained external leakage remains in the residual. The pressure signal determines the occurrence time and amplitude of the transient. Temperature is used to correct the flow-measurement state and identify abnormal operating conditions, while reservoir-level change independently confirms sustained leakage.

Leakage classification combines residual persistence with consistency among operating-state indicators. The three flow signals are first synchronized and filtered, after which the applicable compensation profile is selected from the measured pressure change. A leakage fault is declared when the compensated residual remains above its threshold for the specified duration. Open-circuit, out-of-range, and synchronization faults in the flowmeters are classified separately as monitoring faults so that sensor failures are not confused with leakage. Coincident residual exceedance and rapid reservoir-level decrease raise the fault severity and initiate a shutdown interlock. During shutdown, proportional-valve openings and pump displacement are reduced progressively before the drive motor is disconnected, thereby limiting continued release of high-pressure fluid and reducing additional pressure shocks.

4. Results and discussion

As illustrated in Figure 3, at 45 kW, the output torque at 130 r/min is 3306 N·m. A torque of 6900 N·m corresponds to a constant-power speed of approximately 62.3 r/min, which is 2.10 times the rated torque of 3288 N·m for the original electric drive. Both the hydraulic drive and the leakage detector use pressure measurements, but for different purposes. The drive controller uses load pressure as feedback to regulate pump displacement and supply pressure, whereas the detector uses the pressure-change amplitude to select the dynamic volume-compensation profile. A normal control transient caused by an abrupt load change produces an instantaneous flow imbalance, but it does not form a persistent leakage residual after compensation. Leakage is identified only when the supply flow remains inconsistent with the sum of the return and case-drain flows for the specified duration. Separating drive dynamics from fault signatures at the residual level reduces false alarms under variable-load operation.

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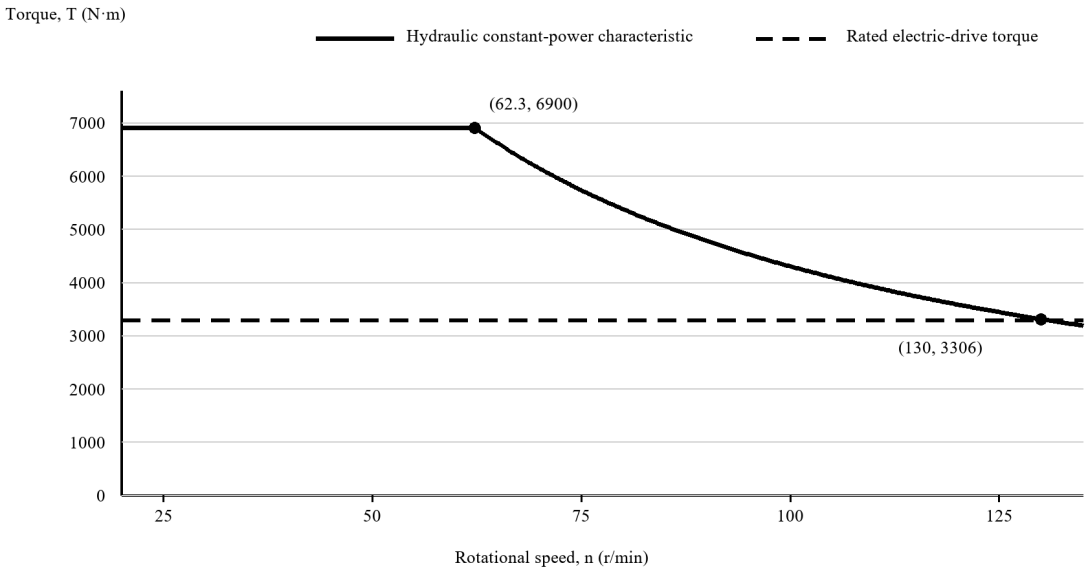


Figure 3. Torque-speed characteristics of the 45 kW constant-power drive

5. Conclusions

(1) A constant-power hydraulic drive comprising a variable-displacement axial piston pump, a load-sensing valve bank, and low-speed high-torque motors was established for the grain silo sweep auger. At 45 kW, a torque of 6900 N·m corresponds to approximately 62.3 r/min, which is 2.10 times the rated torque of the original electric drive. Constant-power regulation therefore extends the low-speed heavy-load operating range by exchanging speed for torque.

(2) A three-flow balance was formulated over a control volume extending from the pump discharge to the main return measurement point. Supply, return, and motor case-drain flows were combined with the dynamic volume-compensation term Qc(t, Δp) to separate the transient flow imbalance caused by fluid compression, line elasticity, and accumulator exchange during pressure steps.

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