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Improving efficiency of hydrostatic steering system used in off-road vehicles using accumulator – a review

Heavy earth moving machines (HEMM) and trackless off-road equipment are extensively used in mining operations. The confined working space in mining operations demand low turning radius for such machines. Therefore, they have articulated bodies steered through hydraulic system for ease of control. The steering operation of the vehicles is usually intermittent and subjected to variable load conditions. Conventional hydraulic systems are difficult to adjust for such load with respect to energy consumptions. This paper describes a review on novel hydrostatic steering control system which turned out to be extensively applicable to heavy earth moving equipment and trackless off-road equipment. In hydrostatic steering system, the steering wheel and steering column are hydraulically connected by pipes and hoses and a variable displacement pump is used that delivers pressurized fluid through hydraulic valves to hydraulic cylinders which in turn moves tools of heavy earth moving machines (HEMM) such as shovels, buckets and steering mechanisms. The paper presents a review on the application of accumulator for improving efficiency of hydrostatic steering system.

Keywords: *Accumulator; HEMM (heavy earth moving machines); hydrostatic steering system; off-road vehicle*

I. Introduction

Present-day vehicles running on road have been making substantial treads in terms of technological advancements emphasizing effective safety systems. However, heavy off-road earth moving machines are lagging behind in this field which needs to be modernized. Vehicle maneuverability, ride opulence and control stability are the main characterizations for the off-road heavy earth moving vehicles. Because of the confined working space in underground mines, trackless off-road vehicles demand low turning radius. As such steering system is among one of the components of the vehicle chassis system that has been inheriting much attention by implementing several mechanical, electrical and electro-hydraulic steering architectures. But, on the other hand, off-road articulated steering vehicles have not fittingly evolved to meet the exigency of off-road equipment manufacturers as well as their end customers. The hydrostatic steering system is system that used to drive or steer the heavy off-road vehicles with very minimal human efforts so that the operator can drive, turn and control the vehicle for a long time with good accuracy [1].

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II. Hydrostatic steering system

Hydrostatic steering controls are generally used in vehicles moving with low-speed normally not exceeding a speed of approximately 60 km/h - such as: trackless off-road machines, construction equipment, fork-lift trucks, agricultural vehicles and others. Hydrostatic steering unit mainly consists of steering valve, metering pump, built-in check valves and there is a provision for a built-in pressure relief valve in the inlet. A separate hydraulic pump is used to supply the pressurized working fluid which is then directed to the steering cylinders by the metering pump. These hydraulic units intensify the torque applied to the steering wheels of the equipment reducing the need of substantive mechanical connection. In general, hydrostatic steering system refers to the system design where a vehicle is steered solely by means of a hydraulic circuit comprising mainly of a hydraulic pump, hose connections, hydraulic fluid, valve, and steering cylinders [2]. Hydrostatic steering system replaces mechanical linkage by a steering unit and steering cylinders along with flexible hoses. This type of steering system is mainly used in heavy earth moving off-road vehicles where directional steering is needed specially in case of underground mining equipment such as off-road vehicles (load haul dump) [3]. All these articulated off-road vehicles adopt hydraulic hydrostatic steering system (HPSS) which is helpful to improve the steering characteristics and to analyze the dynamic characteristics of HPSS that adopts turning spool steering control unit and passing capacities [4]. In fact, the HPSS in off-road vehicles is a control system in which the steering valve controls the steering cylinders. Off-road vehicles especially in underground mines like LHD etc. are operated on uneven terrain surfaces which make the steering very difficult and sometimes lead to failure of hydraulic components of the steering system resulting in idling of the

equipment. One possible solution to keep vehicles steered without any breakdown and difficulty is the incorporation of hydraulic accumulator in the steering unit.

If an accumulator is used in a hydraulic pump unit, intermittent operation of the prime mover for the pump drive is attained by using the pressure holding function of the accumulator which in turn can also lead to an overall reduction in energy consumption. Majority of applications use accumulators to store energy for intermittent duty cycles or to provide a source of emergency power.

A comparative study on energy saved by three different systems, namely a hydraulic pump unit of an inverter control type, pump unit with accumulator and with a variable displacement pump were tested [5]. Within the two limiting pressure the performance of the said systems were analyzed. It was found that pump with the accumulator had the most excellent energy saving effect. Closed loop energy regenerative hydrostatic transmission system with accumulator used in mobile vehicle was analysed [6].

It was found that round trip efficiency of the system in the energy recovery testing varied substantially when the losses of the load are taken into considerations.

This paper denouements a novel scheme of a hydrostatic steering system that incorporates a method of energy saving by using a hydraulic accumulator which supplies stored pressurized fluid in the advent of vehicle engine or primary hydraulic system's component failure, particularly relating more or less to the improvements in the steering system and overall hydraulic system control.

This also eliminates throttling losses in the system by controlling the displacement of a variable displacement pump which is conjoined with the hydraulic control valves.

III. Application of accumulator for enhancing steering efficicency

When compared to heavy earth moving vehicles without hydrostatic steering system, vehicles equipped with hydrostatic steering systems provide an efficient and ease of maneuverability for the off-road vehicle's operator to steer the steering wheels of the off-terrain vehicles with greater torque. Thus, the heavy earth moving off-road vehicles incorporated with hydrostatic steering system are easier to maneuver and control than without hydrostatic steering.

The trackless off-road equipment are extensively used in mining operations. Wheeled rubber tyred vehicles such as load haul-dump (LHD) machine and low profile dump trucks (LPDT) have wide applications in mining operations. The confined working space in underground mines demand low turning radius for such machines. Therefore, they have articulated bodies steered through hydraulic system for ease of control. In hydrostatic steering system, the steering wheel and steering column are hydraulically connected by pipes and hoses.

The steering operation of the vehicles is usually intermittent and subjected to variable load conditions and henceforth, turning a steering wheel without hydrostatic steering system may be very difficult. Also, conventional hydraulic systems are difficult to adjust for such load with respect to energy consumptions. There may also be a chance of failure/breakdown in hydrostatic steering system resulting in the improper functioning of the steering control system. There may be several examples, one among these is, malfunctioning or breakdown of the hydraulic pump unit, improper functioning of the control unit, failure of the engine, or there may be leakages in the hydraulic hoses carrying hydraulic fluid [7].

In order to overcome the problems in the hydrostatic steering system as stated above, one possible solution is to use an hydraulic accumulator in line with the hydrostatic steering system. Hydraulic accumulator is a device which stores fluid under pressure. In case of system failure or breakdown of main supply unit or if there is a sudden drop in pressure from the main hydraulic fluid supply unit, pressurized fluid stored in the accumulator is supplied to the steering unit that can be used as a back-up for the unit to work un-interrupted and smoothly for a certain duration of time.

The hydraulic accumulator used in the system consists of a chamber filled with nitrogen gas called bladder, separating the fluid chamber. Accumulator is generally, precharged at about 80% to 90% of the system pressure [8]. Normally, precharge pressure of the gas filled in the bladder of the accumulator is equal to that of the pressure in the fluid chamber. The gas chamber expands the bladder when the fluid pressure at the accumulator inlet drops below the precharge pressure of the accumulator and the inlet pressure increases. But, when the fluid pressure is more than the gas precharge pressure, gas chamber is compressed.

Typically, a smaller pump can be used in conjunction with a hydraulic accumulator in the system. The accumulator is charged from the pump supply during periods of low demand I the hydraulic unit. This stored energy in the form of pressurized non-compressible fluid is available for instantaneous use which is released during high energy demand or during the time of system failure at a greater rate than that supplied by the hydraulic pump alone in order to get more quick and smooth response to any temporary demand.

Accumulators store energy when hydraulic system pressure is greater than the accumulator pressure and provide hydraulic energy when the accumulator pressure is greater than the system pressure [9]. Hydraulic accumulators store hydraulic fluid under pressure. Pressure is supplied through a bag, diaphragm or piston by either a spring, or pressured gas (most common). This in turn smoothen the maneuverability of the off-road vehicles and allows a vehicle

operator to steer the machine for a short period of time. Accordingly, there is a need for analyzing and designing of an efficient system for charging and/or discharging of steering accumulator [10] (Fig.1).

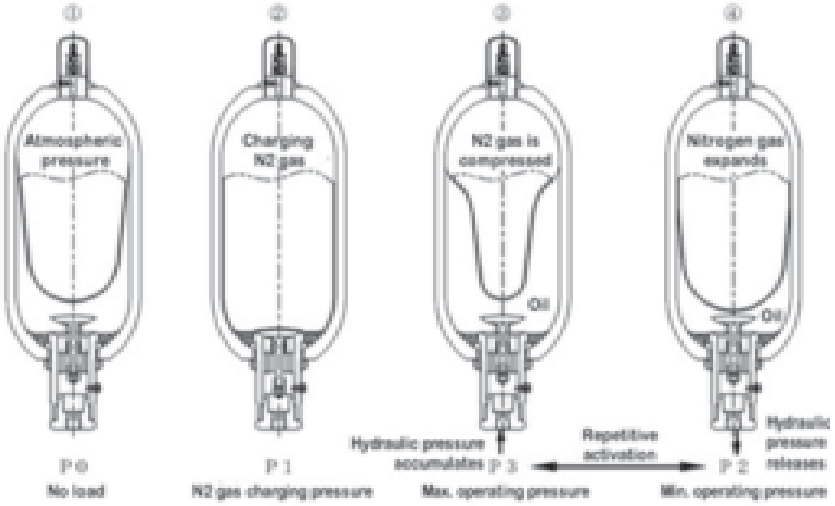

Fig.1 Working of a hydraulic accumulator

A hydrostatic steering system consists of an emergency steering valve which is coupled to a hydraulic accumulator in line with a hydraulic pump supplying fluid to the steering circuit and to a main steering control hydraulic valve. The circuit also constitutes a steering valve spool responding to the steering pressure which normally utilizes a normal or closed center position restraining the fluid flow from the accumulator when the system pressure exceeds a pre-determined minimum operating value.

When the hydraulic system pressure lowers down to the pre-determined minimum value, steering valve spool automatically shifts to an emergency or open position allowing the pressurized fluid to flow from the accumulator to the main steering control valve [11].

The accumulator in HPSS has functions of maintaining pressure, supplementing pump flow, absorbing system shocks, serving as an emergency hydrostatic resource and reducing noise of system [12].

Because the operation time of steering valve is very short, the state of gas (nitrogen) changes very fast, and there is not enough time to exchange heat with the outside when the steering accumulator absorbs pulse flow of system, the gas in steering accumulator changes as adiabatic course given in Eq.1 [13],

$$PV^{\gamma} = C \quad \text{... ... 1}$$

Where; $\gamma = 1.4$, C = Constant

In addition to normal steering working condition, there is abnormal steering working condition in which the engine stops working or oil pump breaks down. The steering accumulator supplies pressurized fluid for steering of off-road vehicles under this condition.

IV. Operation of a hydrostatic steering system using accumulator

Fig.2 shows the basic circuit of a hydrostatic steering system using an accumulator. Various components of the above hydraulic circuit and working is described below [14].

Two pumps are connected in tandem; one is a fixed displacement hydraulic pump (2) and other is a variable displacement pump (1) with a replenishing pump in between. Variable displacement pump (1) supplies flow to the fan motor (A) and from fixed displacement pump (2) through hydraulic valve (5) to the fan pump (B).

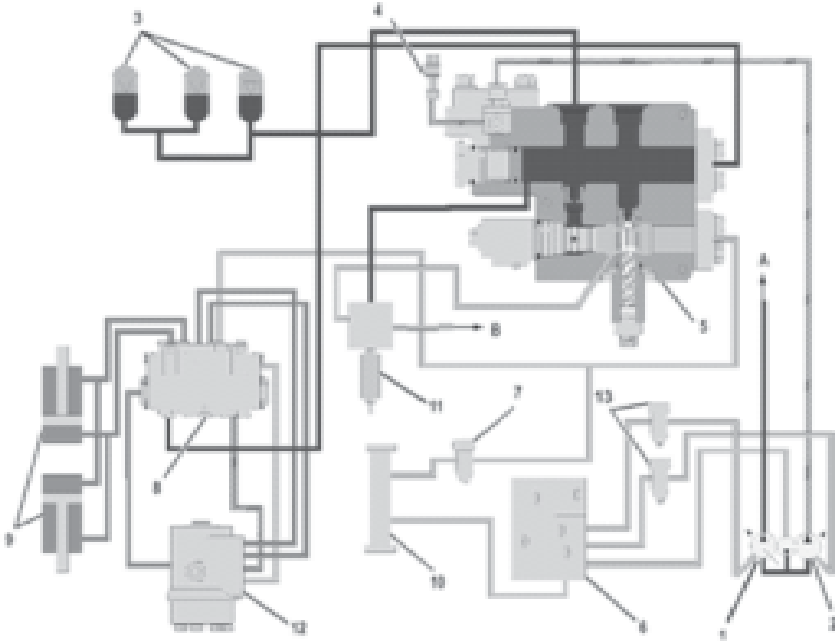

Fig.2 Circuit diagram of a hydrostatic steering system using accumulator [14]

The steering circuit mainly consists of following hydraulic components:

1. Variable displacement hydraulic pump
2. Hydraulic steering pump
3. Steering hydraulic accumulators
4. Pressure sensor for steering pump
5. Pressure relief valve and solenoid valve manifold
6. Hydraulic oil reservoir for steering circuit unit
7. Return line hydraulic oil filter

8. Steering control valve
9. Steering cylinders
10. Pressure reducing valve
11. Oil cooler
12. Hand metering unit
13. Hydraulic oil filters (case drain type)

The circuit shown in Fig.2 is a hydrostatic steering system. The hydraulic steering pump is driven by an electric motor. There is no mechanical linkage between the steering wheels and steering cylinders (9) that steers the front wheels of the vehicle. Variable displacement hydraulic piston pump (1) is the steering piston pump. Hydraulic tank (6) stores the oil for the steering system. Accumulator pressure sensor connected to the hydraulic accumulators (3) sense the pressure of the accumulators and sends the pressure signal to the chassis ECM of the vehicle. The flow of hydraulic oil from the steering pump is controlled by the chassis ECM by energizing the solenoid valve (5).

The steering circuit consists of following hydraulic pumps: Hydraulic piston pump for the fan drive, hydraulic steering piston pump, hydraulic brake pump, gear pump (each for the motor drive for the oil pump of the rear axle and for hoist and brake cooling). Hydraulic pump drive is located on the right-hand side of the vehicle chassis frame rail which is near to the rear of the flywheel housing. Drive shaft drives the pump drive which is connected in between the engine and pump drive. Hydrostatic steering piston pump (2) operates only during the period when the engine is running and steering accumulator (3) is charged by the fluid flow from the hydraulic pump (2) which delivers fluid at high pressure and the pressure increases to the set pressure of the circuit. When the set pressure is compassed, pressure sensor installed in line with the steering accumulator will send pressure feedback to the vehicle chassis ECM (electrically controlled motor). Owing to this, prime mover will then increase the amount of current in accordance with the feedback received, actuating the hydraulic solenoid valve (5) which will move the spool within pressure and flow compensator valve.

During the unloading condition, the steering pump will be de-stroked to standby condition running at a very low pressure thus saving the power consumption. In unloading condition, the steering pump delivers flow which is used normally for lubrication and for the normal internal leakage. Due to the internal leakage in the steering circuit, the fluid pressure in the hydraulic accumulator reduces gradually till the set pressure (cut-in pressure) is achieved. The sensor installed in line with accumulator senses the pressure and sends feedback in terms of pressure signal to vehicle chassis ECM. This in turn decreases the amount of current drawn thereby up stroking hydraulic pump to its maximum displacement. The pressure sensor installed in line with the steering accumulator can have one of the following conditions as mentioned in Table 1.

TABLE 1. HYDROSTATIC STEERING CONDITION AT DIFFERENT PRESSURE RANGE OF THE STEERING ACCUMULATOR

Pressure sensor reading of the steering accumulator	Hydrostatic steering condition at different pressure range of the steering accumulator
Very low	This value shows condition during steering of vehicles in difficult terrains or, during heavy steering.
Low	This value shows condition during steering of vehicles during light steering or during the condition of normal internal leakage in the steering circuit.
High	This value shows condition when the accumulator pressure reaches above the system set pressure. This pressure range is the useful pressure range of the steering accumulator.

When the system pressure reduces below the set pressure, the accumulator will get charged thereby activating the charging system and the steering pump supplies the fluid to the circuit.

The charging of accumulator takes place under three conditions of operation:

- Off mode
- Low mode
- High mode

Vehicle engine output speed has an independent countenance to the steering accumulator charging current for each of the above three charging modes. Accordingly, the steering pump output adjusts itself to deliver higher flow of fluid at lower speed of the vehicle engine.

V. Conclusions

Off-road vehicles are operated on uneven terrain and hence their steering mechanism should be precise and can be done with very less human effort. Hydrostatic steering made vehicle driver smooth and effective driving. In this paper we consider the part of automobile i.e. steering and how it works in terms of performance and values. Addition of accumulator in hydrostatic steering system will ease the steering and enhance the maneuverability of the steering system.

In case of failure of fluid supply necessary for steering from the main supplying unit or if there is a pressure drop from the main hydraulic fluid supply, accumulator will act as a backup device.

Also, if an accumulator is used in a hydraulic pump unit, intermittent operation of the prime mover for the pump drive is attained by using the pressure holding function of the accumulator.

Thus an overall reduction in energy consumption is realized as well. Majority of applications use accumulators to store energy for intermittent duty cycles or to provide a source of emergency power.

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IMPROVING EFFICIENCY OF HYDROSTATIC STEERING SYSTEM USED IN OFF-ROAD VEHICLES USING ACCUMULATOR

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