FULL POWER HYDRAULIC BRAKE ACTUATION, CIRCUIT DESIGN CONSIDERATIONS FOR OFF-HIGHWAY VEHICLES AND EQUIPMENT

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ABSTRACT

The intent of this paper is to create a clear understanding of full power hydraulic brake actuation system design as it relates to off-highway vehicles and equipment. The paper is divided into four main sections. The first section outlines six design prerequisites used for selecting the service brakes and the full power brake actuation system. The second section, Brake Actuation Systems, includes advantages of a full power brake system and a brief description of reverse modulation brake systems. Section three is a discussion of open center, closed center and load sensing hydraulic systems and the integration of a full power brake actuation system into these systems. Section three also explains the operation, related components and some common problems to be avoided in the actuation system design process. The fourth section describes reverse modulating brake actuation and how it differs from full power hydraulic brake actuation.

The actual selection of the service brakes is beyond the scope of this paper. However, it is assumed the vehicle's brakes have been properly sized and are fully operational. The brakes are referred to throughout to emphasize the importance of their relationship to the brake actuation system.

DESIGN PREREQUISITES

The goal of the brake actuation system designer is to select the proper components to provide optimum brake performance for a given application. To do this the designer must start at the vehicle service brakes and “work backward” to the method of actuation. Specific design prerequisites for the vehicle brakes as well as the brake actuation system must be identified. The six key prerequisites that will be discussed are: (1) vehicle stopping parameters, (2) the resultant brake torque and kinetic energy required, (3) service brake capacity, (4) brake line pressure, (5) brake volume and (6) operator input effort.

STOPPING PARAMETERS - The stopping parameters are identified as performance attributes associated with stopping the vehicle. They will include, but are not limited to, the deceleration rate, stopping distance, percentage of grade for operation and vehicle velocity. Information used in determining these properties can be procured from professional organizations, government agencies and the vehicle designer.

Professional organizations such as the International Standards Organization (ISO) and the Society of Automotive Engineers (SAE) can provide recommended vehicle brake system performance specifications. Information on laws that regulate vehicle brake performance can be obtained from Federal, State, and Provincial Government agencies. Actual vehicle performance is determined by the vehicle designer. It will be the vehicle designer's responsibility to insure a proper testing program is defined and conducted to insure validation of the components selected for use in the brake actuation system.

BRAKE TORQUE AND KINETIC ENERGY REQUIREMENTS - The brake torque and kinetic energy required to stop the vehicle is calculated based on the desired stopping parameters and the vehicle specifications. Vehicle specifications include, but are not limited to, the gross vehicle weight, vehicle velocity, static loaded radius of the tires, gear reductions between the brake and the ground, the number of braked wheels, the number of brakes to be used and the road surface. Of the specifications mentioned, vehicle velocity will have the greatest impact on the brake torque and kinetic energy. For example, if vehicle velocity is doubled, the magnitude of the kinetic energy is multiplied by a factor of four. Where as, an increase in vehicle mass will result in a directly proportional increase in kinetic energy, reference 1.

There are many sources for formula's used to calculate brake torque, kinetic energy and the factors that affect them, two of which are given in references 2 and 3.

SERVICE BRAKE CAPACITY - Identifying the service brake capacity is the process of matching the service brake(s) to the vehicle stopping parameters and brake torque requirements. The available brake torque is expressed at a given brake line pressure which allows the designer to identify the proper amount of brake line pressure required to match the vehicle torque requirements. The service brake capacity information is acquired from the brake and or axle manufacturer and the torque versus pressure relationship is generally a linear function.

To avoid the pitfalls of either under-braking or over-braking it is important to calculate the actual required torque for the application. **Do not assume** that the manufacturer's specified maximum brake line pressure is the same as the required brake line pressure.

This can be demonstrated in the following examples; one in which the vehicle brake torque requirement is **above** the torque limitations of the service brake. In the other, the vehicle torque requirement is **below** the torque capacity of the service brake.

Consider a vehicle that requires 680 Nm of brake torque. The torque limitation of the service brake is 450 Nm at a **maximum pressure** of 70 bar. Supplying the maximum 70 bar and consequently generating 450 Nm of brake torque, does not stop the vehicle as required. The vehicle is under-braked.

Conversely, consider if the torque requirement is now 110 Nm and the brake is rated for 450 Nm at 70 bar. Supplying the maximum 70 bar will stop the vehicle immediately (too severely). In this example, the torque requirement is satisfied with 25% of the available pressure resulting in aggressive, oversensitive brakes.

These scenarios will change in magnitude depending on the method of actuation that is selected (reference 4) and the type of brakes on the vehicle.

Through proper brake actuation and circuit design the designer can match the actuation circuit to the service brakes and avoid poor performance characteristics.

BRAKE LINE PRESSURE - The brake line pressure, as previously mentioned, is determined by matching the brake torque requirement to the service brake capacity. By examining the brake torque versus brake pressure relationship, the designer can extrapolate the brake line pressure required to attain brake performance matched to the vehicle stopping parameters. The brake line pressure will also used in selection of the hydraulic system pump, determining the system relief valve pressure setting, accumulator dry nitrogen precharge, accumulator charge valve (in open center systems), and the brake modulating valve pressure setting.

REQUIRED VOLUME - The brake volume requirement is critical in determining the method of brake actuation to be used and in component selection. The designer needs to know the minimum, nominal, and maximum volume of fluid required. Different types of actuation components are used in various ranges of brake volume displacements.

The brake volume is also used to determine the capacity of the accumulators and the accumulator charge valve charge rate with respect to the desired number of power-on and power-off stops. In open center and load sensing applications that use an accumulator charging valve, power-on stops are defined as the number of brake applications that can be attained between the high and low accumulator charge limit settings. Power-off stops are defined as the number of stops that can be attained between the low accumulator charge limit setting and the maximum brake line pressure with the energy source disconnected.

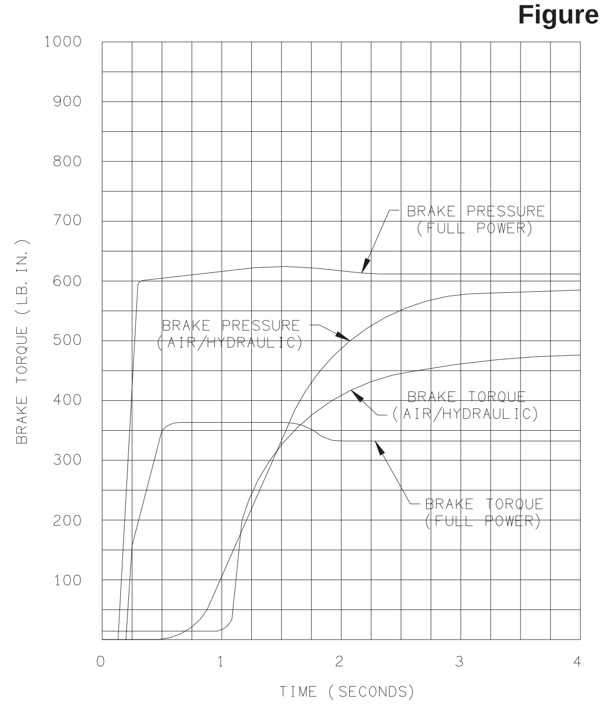
OPERATOR INPUT EFFORT - Input pedal force required by the operator is generally expressed as the maximum force allowed to generate the desired maximum brake line pressure or maximum desired brake torque. Again, there are directing organizations and agencies that make recommendations to assist in identifying this value, references 5 and 6. More importantly, the pedal effort must comply with the operator's ability to effectively control the machine.

BRAKE ACTUATION SYSTEMS

The system designer can accomplish brake actuation in different ways. One method is the classical method of brake actuation which uses fluid pressure to actuate the braking means. Full power hydraulic brake actuation is a direct means of supplying hydraulic pressure to the brakes. This method uses fluid pressure and flow generated by the pump of a hydraulic system and directs this energy to the service brakes.

FULL POWER HYDRAULIC BRAKE SYSTEM ADVANTAGES - The full power hydraulic brake system has several advantages over traditional brake actuation systems. These systems are capable of supplying fluid to a range of very small and large volume service brakes with actuation that is faster than air brake systems. Figure 1 represents a time comparison between a typical air/hydraulic and full power hydraulic brake actuation system.

Figure 1



Response Time

Full Power Brake Actuation
-VS-
Air/Hydraulic Brake Actuation

Full power systems can supply significantly higher brake pressures with relatively low reactive pedal forces. The reactive pedal force felt by the operator will be proportional to the brake line pressure being generated. This is referred to as brake pressure modulation. Another key design feature of full power systems is the ability to control maximum brake line pressure. In addition, because these systems operate with hydraulic oil, filtration can be utilized to provide long component life and low maintenance operation.

Because these systems are closed center, by using a properly sized accumulator, emergency power-off braking that is identical to power-on braking can be achieved. These systems can be either dedicated, where the brake system pump supplies only the demands of the brake system, or non-dedicated, where the pump supplies the demands of the brake system as well as some secondary down stream hydraulic devise. Another important note is that all seals within these system must be compatible with the fluid medium being used.

REVERSE MODULATING BRAKE ACTUATION - Another method of hydraulic brake actuation is reverse modulation or as it is sometimes referred to, negative braking. The term “reverse modulating” is used because pressure is decreased to actuate the brake from a preset pressure that keeps the brake fully released. Reverse modulation uses hydraulic pressure to release a brake that is mechanically applied by springs. Maximum torque is produced when hydraulic pressure is absent either intentionally or due to system failure. Section four of this paper discusses the concept of reverse modulation in further detail and compares it to full power hydraulic apply brake actuation.

OPEN CENTER, CLOSED CENTER AND LOAD SENSE SYSTEM INTEGRATION

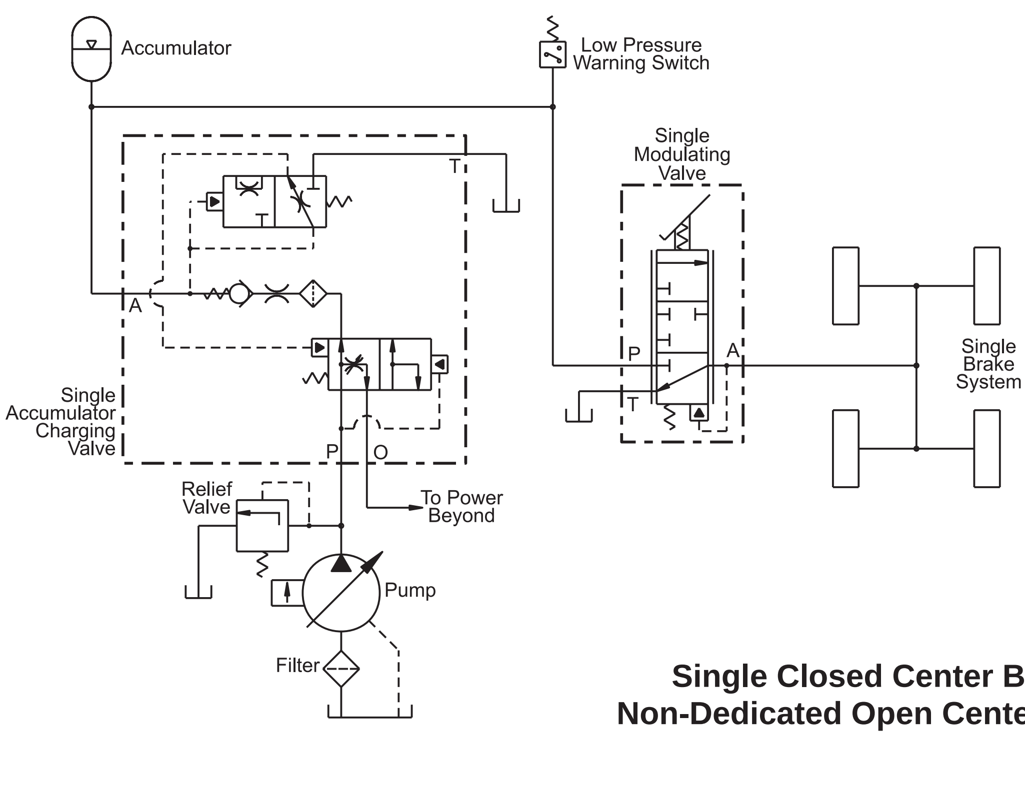
Full power hydraulic brake actuation systems will vary in sophistication with the various types of hydraulic systems available today; open center, closed center, and load sensing.

OPEN CENTER SYSTEMS - For the purposes of this paper, open center systems are considered systems where pump flow circulates to the reservoir at low pressure while the system controls are in a neutral position. Actuation of the system controls will then allow pressure to build as a function of resistance within the hydraulic system.

Full power hydraulic brake actuation circuits that are used in open center hydraulic systems will contain as a minimum; a hydraulic pump, a relief valve positioned between the pump and an accumulator charging valve, an accumulator, a low pressure warning switch, a brake modulating valve, and the service brakes, see system schematic 1. As is the case with any full power hydraulic brake actuation system, it is possible to use either a dedicated brake pump or divert oil from other hydraulic sources on the machine, referred to as a non-dedicated pump.

Depending on the requirement, these systems can be either single, dual or variations thereof. This paper discusses single and dual circuits, only to mention the components that differ between the two.

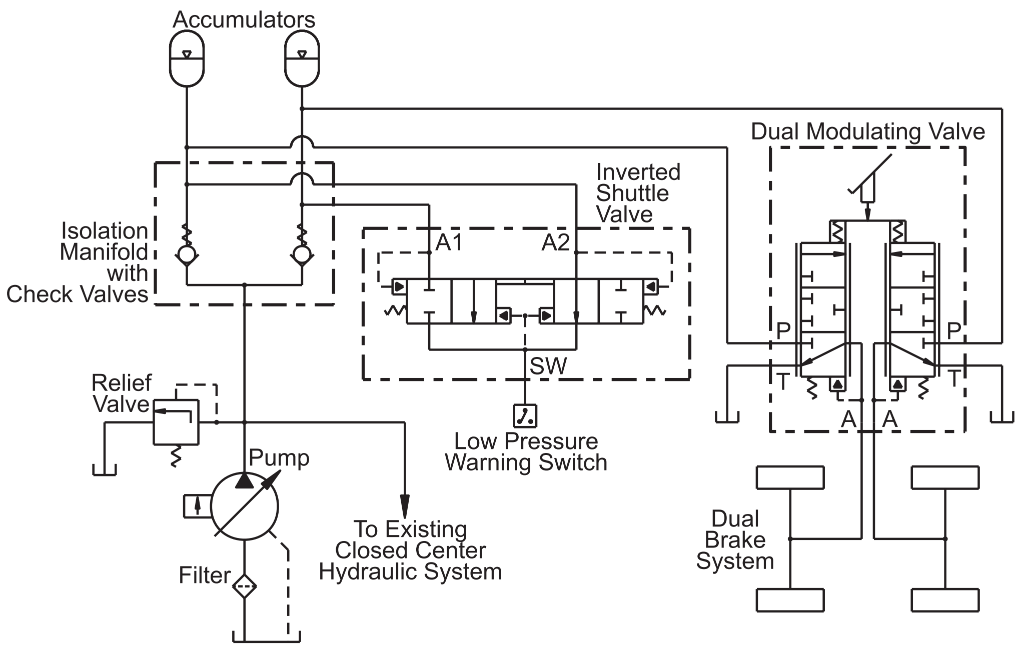
System Schematic 1



Single Closed Center Brake Circuit in a Non-Dedicated Open Center Hydraulic System

CLOSED CENTER SYSTEM - Defined as systems where the fluid is static at full system pressure until the system controls are actuated at which time the closed center system will allow fluid flow to be initiated at load induced pressure. The full power hydraulic brake circuit that is incorporated in a closed center hydraulic system is usually a non-dedicated circuit. The pressure compensated pump that supplies fluid to the brake system will almost always supply fluid to some other system requirement as well. In these circuits the brakes will operate off of the pump displacement and the accumulators will act as the energy source for the power-off braking requirements. Pressure compensated systems may include an isolation check valve in place of the accumulator charging valve, see system schematic 2. The check valve will prevent accumulator pressure loss in the event of an energy source failure. It is important in closed center systems to be sure the pump can fulfill all of the volume demand requirements. The recovery rate of the brake system must be considered under full flow demands on the pump, references 5 and 6. The pump should be sized so that it can satisfy the recovery rate of the brake system accumulators as well as the secondary system requirements. The brakes should never suffer a lack of fluid.

System Schematic 2



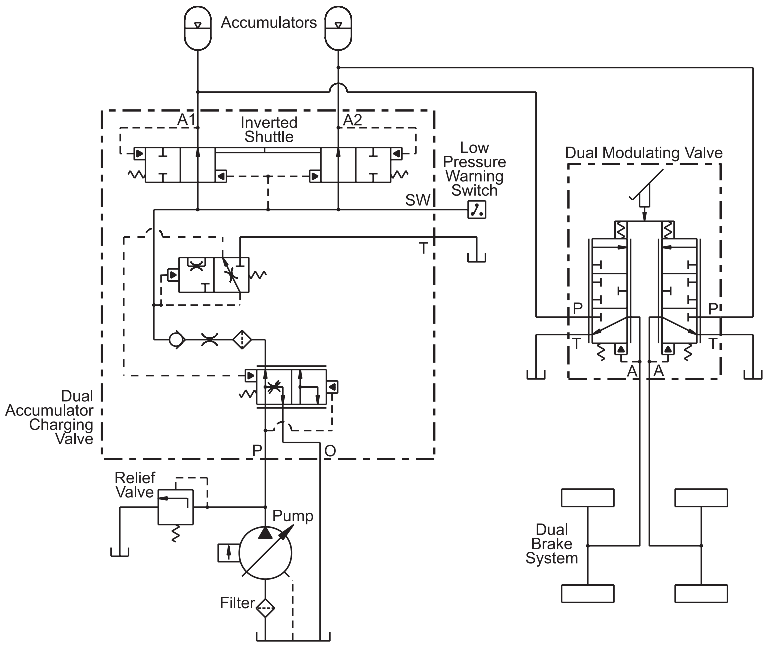
Dual Closed Center Brake Circuit in a Non-Dedicated Closed Center Hydraulic System

If the designer elects to use a dedicated closed center system then consideration must be given to the frequency of brake actuation. The concern is the potential of a pressure compensated pump to operate at design speed while in a zero stroke condition, displacing little or no fluid for the time interval between brake actuations. In these conditions the pump may fail due to heat generated due to a lack of cooling flow.

LOAD SENSING SYSTEMS - By definition the load sense systems are very similar to the closed center system because fluid is static when the system controls are in a neutral position. One exception is that the load sense system is at a significantly lower stand-by pressure in neutral as compared to the higher compensated pressure of the closed center system.

Load sense systems are similar to the open center systems with respect to the components they require for integrating brake actuation systems. In both the open center and load sense brake systems the accumulator acts as the primary fluid source for brake actuation. The accumulator also provides the fluid source for power-off brake actuation. The difference comes in the form of the pump and the charge valve that is used, see system schematic 3. The load sense system will operate as a flow and pressure on demand system. The control section of the load sense accumulator charge valve sends a pilot signal to the pump when fluid is required. Since load sense hydraulic pumps are generally high efficiency piston equipment, the concern over low speed operation is not as great.

System Schematic 3

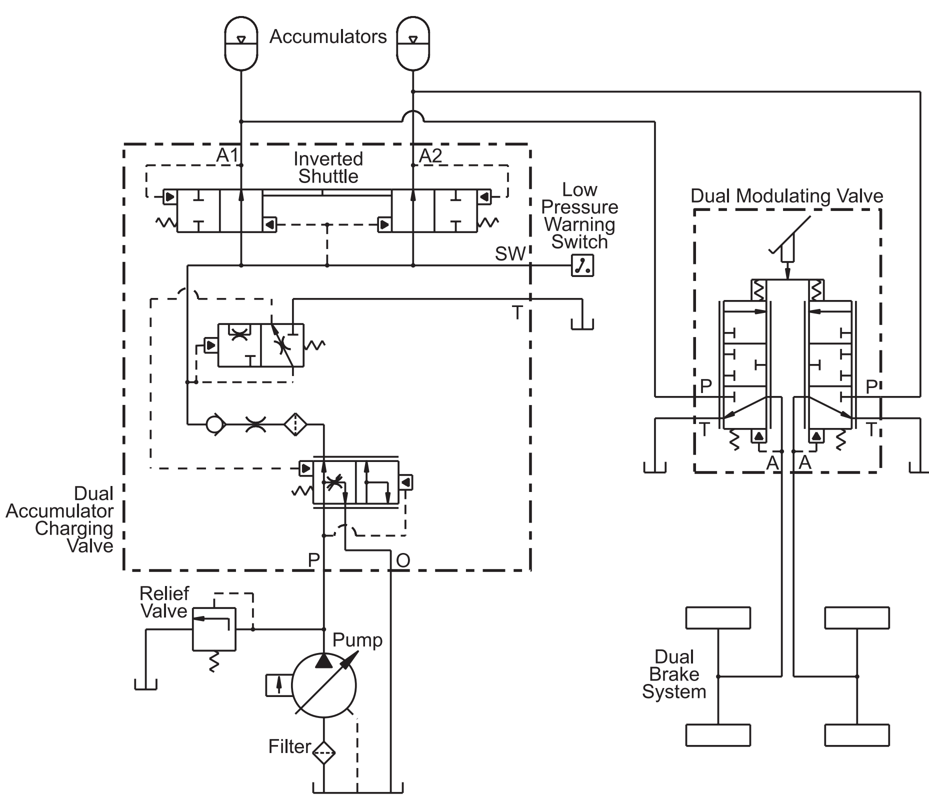


Dual Closed Center Brake Circuit in a Non-Dedicated Load Sense Hydraulic System

OPERATION, RELATED COMPONENTS, AND ASSOCIATED PROBLEMS - In the open center hydraulic system an accumulator charging valve, either single or dual, is used in conjunction with an accumulator and a modulating brake valve. The valve automatically halts charging when the accumulator pressure reaches its high limit. When the accumulator pressure reaches its low limit, the charging valve diverts a small amount of fluid from the main open center hydraulic system to charge the accumulator. However, in a non-dedicated system if the downstream open center circuit causes the hydraulic system pressure to rise over the high accumulator charge limit, the accumulator will be charged to this higher value. This must be taken into consideration when the designer specifies the accumulator(s) to be used in the system.

The dual accumulator charging valve performs essentially the same functions as the single charging valve. When the dual accumulator charging valve is used in a dual hydraulic brake system each individual axle is controlled separately by a modulating valve and an accumulator. One dual charging valve charges both accumulators, see system schematic 4. The primary advantage of the dual charging valve over the single charging valve is that if half of the brake system fails the remaining half will continue to function.

System Schematic 4



Dual Closed Center Brake Circuit in a Dedicated Open Center Hydraulic System

The charged accumulator supplies pressurized fluid to the brake modulating valve. These can also be either single or dual depending on the application. Modulating power brake valves of closed center design are used for controlling output pressures to the brake system. The valves are considered closed center because they block the fluid at the pressure port of the modulating valve while in the brake release position. Fluid remains static at accumulator pressure until the operator depresses the brake pedal. This action causes the brake valve to modulate fluid out to the brakes and provide the braking means. The operator can modulate pressure in the brake system by increasing or decreasing pressure as required in proportion to the input force on the brake pedal. As previously mentioned in this text the maximum brake line pressure can be adjusted and controlled to prevent over-pressurizing the system.

Low pressure warning switches are used to sense accumulator pressure and warn the operator through some audible or visual device in the event the pressure in the accumulator decays to an unsafe operating level. These switches are typically set at a pressure below the low accumulator charge limit yet higher than the pressure required to satisfy the secondary stopping requirements. This value is defined by the directing organizations and agencies that regulate the brake system recovery rate, the number of power-off stops, and operator warning devices, references 5 and 6.

Because the full power hydraulic brake system is dependant on accumulated volume and pressure, the power-off stopping confines of the system must be considered to assure the operator can stop safely in the event the energy source (engine or pump) fails.

The number of power-off stops is determined with the energy source off or disconnected. To determine the number of power-off stops in an open center system, lower the accumulator fluid pressure to the pressure that equals the low limit of the accumulator charging valve. While counting the number of applications, apply the brakes fully and release, repeatedly, until the point where the accumulator fluid pressure is no longer sufficient to supply the pressure required to attain the maximum brake line pressure. The number of brake applications between the low limit of the charge valve and maximum brake line pressure is considered the power-off stopping capacity of the system. The charge rate of the accumulator charge valve is determined by the desired recovery rate of the application. The low charge valve limit is determined by the maximum brake line pressure and the number of power-off stops that are desired. The high limit of the charge valve is determined by the pressure differential band widths available from the accumulator charge valve manufacturer. The minimum relief valve pressure setting is determined by the high charge valve limit. Relief valves must be incorporated into the system to protect the pump and other controls from over-pressurization. The relief valve must be capable of handling the full pump displacement and the required pressure for the actuation system.

The number of power-off stops can be varied by changing the accumulator size, dry nitrogen pre-charge, fluid pressure in the accumulator, or by increasing the pressure differential between the low accumulator charge limit and the maximum brake line pressure.

The accumulator has two purposes in the full power hydraulic brake actuation systems: (1) To provide reserve oil for power-off controlled braking and (2) when used in an open center or load sense system with a charging valve, the accumulator provides the reserve volume and pressure necessary for pump unloading. The accumulator should be of adequate size to accommodate the volume and leakage conditions of the brake system. It is necessary that the accumulator have sufficient oil volume between the high and low limits of the charging valve to minimize the charging cycles. Accumulator oil capacity, dry nitrogen precharge pressure, and the initial oil pressure are also evaluated to limit charge cycle frequency, thus reducing heat and enhancing pump life, references 7 and 8.

The advantages and disadvantages of various pump designs are beyond the scope of this paper. It is important however, that brake system designers be informed about various pump capabilities while evaluating methods of supplying oil to brake actuation circuits.

Most pumps can deliver constant flow and pressure capable of sustaining a full power brake system while rotating at a constant high speed. It is recommended that pump efficiency be strongly considered when used in variable RPM, engine driven mobile equipment.

In dedicated brake systems the pump supplies only the demands of the brake system. Typically, long periods of time can elapse between brake applications. As previously discussed there are concerns over using a dedicated pressure compensated pump in a closed center brake actuation system.

In the non-dedicated closed center brake system where the pressure compensated pump supplies fluid to both the brake circuit and some secondary requirement, this concern is not as great. The secondary requirement will usually allow the pump to function from zero stroke to full stroke and cycle more frequently.

By using the pressure compensated pump with an accumulator charge valve in an open center circuit, the charge valve will unload the pump allowing the pump to displace fluid at low pressure differential. This combination of components works especially well for the variable RPM mobile equipment application.

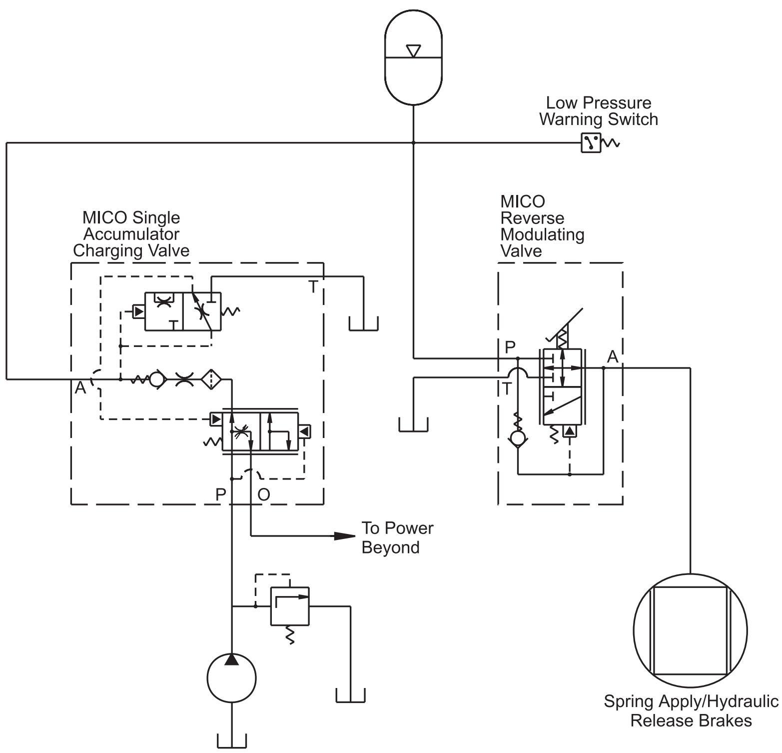
REVERSE MODULATING BRAKE ACTUATION

Although a non-traditional method of braking a vehicle, spring applied hydraulic release brakes are becoming increasingly important to off-highway equipment designers, and engineers. For this reason it is important to understand the difference between the conventional full power hydraulic apply brake actuation system and the spring applied hydraulic release brake actuation system. To obtain brake performance as recommended by the many accepted brake standards (references 5 and 6), a conventional hydraulic brake actuation system may require independent service, secondary and parking brake circuits. These circuits provide braking in the event of any single failure in the service brake system. Service brake actuation systems are commonly split to add redundancy to a system. In addition, parking functions typically require an independent brake and a separate method of actuation. The complexity of such systems will be apparent when the designer considers the number of valves, switches, hoses and connectors that are involved.

Spring applied hydraulic release brake systems, on the other hand, may consist of a single circuit, providing service, secondary and parking functions with a common brake(s). The actuation circuit used to control this brake will require limited control hardware and plumbing. Consequently, this brake system will be easy to maintain, troubleshoot and is cost effective.

In each of the system schematics 5, 6, and 7, the brake actuation circuits will differ only relating to the charging of a brake accumulator.

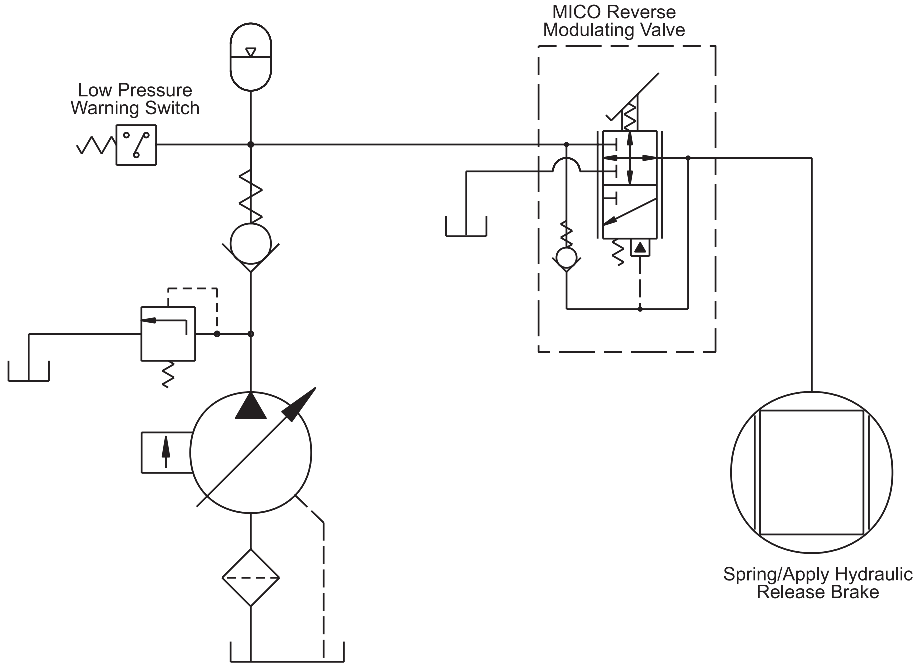
System Schematic 5



Closed Center Actuation Circuit/Open Center Charging System

This is relative to the type of system they are integrated with. As shown in these schematics the brake actuation circuit is considered as closed center. Closed center because the fluid pressure is supplied to the brake which maintains a brake release condition. When the operator applies the brake valve, pressure from the accumulator is blocked in a closed center condition while fluid in the brake is exhausted to the reservoir.

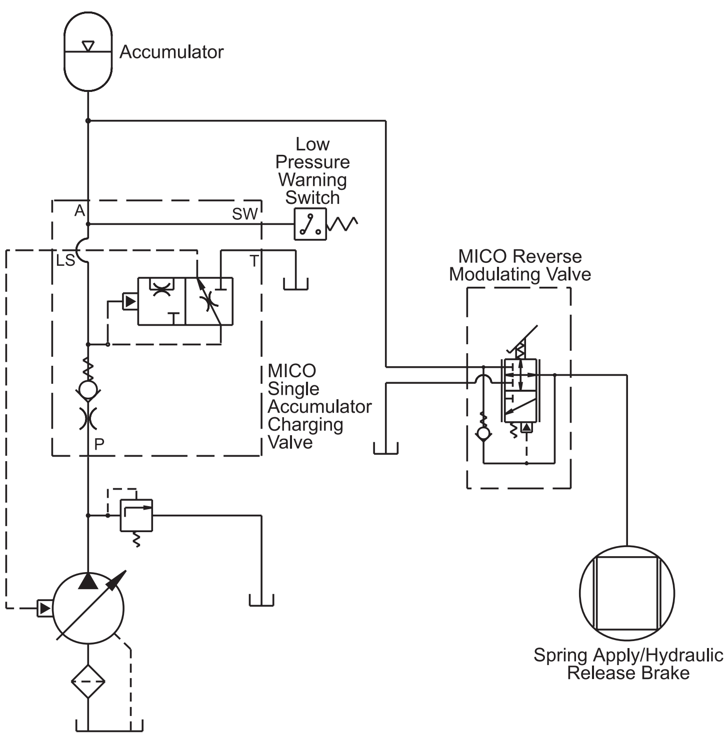
System Schematic 6



Closed Center Actuation Circuit/Pressure Compensated System

In a spring applied hydraulic release brake actuation circuit the primary purpose of the accumulator is to provide power-off controlled braking in the event the energy source becomes disabled. The charged accumulator supplies pressurized fluid to the reverse modulating brake valve. The reverse modulating power brake valve is used for modulating the pressure in the brake system by increasing or decreasing pressure in the brake system in direct proportion to the input force from the operator via the brake pedal.

System Schematic 7



Closed Center Actuation Circuit/Load Sense Charge System

Further detailed explanation of reverse modulation and spring applied hydraulic release brakes can be gained through additional technical papers, references 9 and 10.

COMPARING DESIGN PREREQUISITES - To effectively design the actuation portion of the spring applied hydraulic release brake circuit, the same design prerequisites used in the conventional full power hydraulic brake actuation systems must be known. However, there may be differences in the interpretation of these criteria: (1) vehicle stopping parameters, (2) the resultant brake torque, (3) service brake capacity, (4) pressure requirement of the brake, (5) volume requirement of the brake, and (6) input pedal force requirement. Additionally, the designer must also consider (7) actuation (response) time, and (8) secondary and parking requirements.

Stopping Parameters - The stopping parameters will be identical to the parameters previously discussed for the conventional full power systems. This is because they are defined for the vehicle and not for the method of actuation.

Brake Torque and Kinetic Energy Requirements - Torque and energy requirements that are calculated to satisfy the specifications of the application will again be based on the stopping parameters and vehicle specifications as previously discussed.

Service Brake Capacity - Considerations for matching the service brake to the vehicle requirement are for the most part the same. However, because the spring applied hydraulic release brake relies on the forces generated in the springs to provide the braking means, the selection and flexibility found in hydraulic apply brakes may not be as plentiful. In these types of applications the need to over-brake may be required.

Pressure Requirements - As the name implies, the spring applied hydraulic release brake is mechanically actuated by springs and is dependant on hydraulic pressure to keep it released. Therefore, the brake actuation circuit, in a normal released mode, must maintain sufficient pressure to allow the spring applied hydraulic release brake to fully release. The reverse modulating brake valve regulates this pressure to a safe level above the "full release pressure" of the brake. The brake, in a full release condition, has maximum running clearance between the rotating and stationary plates. "Initial release pressure" refers to the brake condition where the rotating and stationary plates make initial contact and minimal torque is developed. "Full apply pressure" suggests a maximum brake applied condition, normally occurring at zero pressure. The full release pressure, initial release pressure and full apply pressure must be determined prior to design of the brake actuation circuit. Because this brake design is dependant on the forces of the springs to discharge fluid from the brake, it is desirable to have a high full release pressure to work with. This allows the designer a wider pressure range to modulate, thus providing better quality pressure modulation and brake performance.

Volume Requirements - The oil volume capacity of the brake must also be determined prior to brake actuation circuit design. Volume requirements may be referred to in terms of maximum (worn) brake and normal (new) brake displacement. As the brake lining material wears, piston travel increases. As piston travel increases volume increases. Brake system components such as the accumulator, hoses, and valves will be sized according to this brake volume requirement.

Pedal Force - As is the case with the hydraulic apply brake actuation, input pedal force may be expressed as a maximum value required to generate the maximum brake torque. This again is dictated by the application, the operators ability to safely control the vehicle and the organizations and agencies that make recommendations to assist in identifying this maximum value.

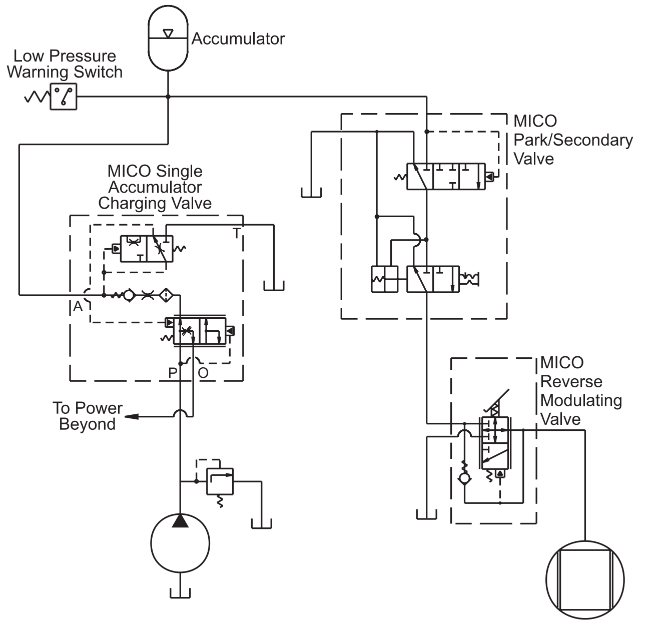
Response Time - Response time or actuation time with respect to a spring applied hydraulic release brake system, is a time interval initiated by pedal movement, resulting in a full brake application. This is directly related to oil volume capacity and full release pressure of the brake. Physical plumbing size, hose, fittings and adapters will affect the response time of the brakes. Oil must be exhausted quickly from the brake and the actuation circuit to reduce the response time and optimize braking performance.

Secondary / Parking - The secondary (emergency) and parking features of the brake actuation circuit must be reviewed. In the case of emergency braking, a "failure mode analysis" will help determine component selection; for example, if the energy source became disabled, and there were no provisions to maintain brake system pressure, the brakes will be energized and bring the machine to an uncontrolled stop. However, by using an accumulator, reserve oil stored in the accumulator will be available so the operator can bring the machine to a controlled stop.

System schematic 8 illustrates a MICO park/secondary control valve which has been incorporated to provide two functions: (1) A two position three way valve for manual park actuation of the brake; this could be a modulated valve or the on/off valve as shown. When this valve is shifted to the apply position the brake is opened to the tank and the pressure supply is blocked. In this apply position, the brake may remain actuated for an indefinite period of time, with or without supply pressure from the accumulator. (2) A trigger valve to allow an automatic emergency actuation of the brake system when accumulator pressure drops below a predetermined level. Although brake actuation is a direct response to a loss of pressure, there are certain government regulations that may require this feature due to stopping time restrictions, reference 11.

Parking and emergency functions may be easily integrated into a spring applied hydraulic release brake actuation system. A typical solenoid or manual two-position three-way directional valve may be used to control parking functions.

System Schematic 8



NOTE:
This diagram depicts a braking system which may be claimed in United States patent no. 4,893,879 which is neither owned nor licensed by MICO, Inc.

Closed Center Actuation Circuit with Park Secondary Valve/Open Center Charge Ststem

SUMMARY

This paper reviewed basic concepts involved in designing full power hydraulic brake actuation systems for off-road vehicles and equipment. The design process is challenging and complex with operator safety being the primary concern. The reliability and economy of the design depends directly upon the quality of the data and the accuracy of the system designer.

Designing a brake actuation circuit involves many factors including analyzing design prerequisites, determining brake system needs based on vehicle specifications, integrating actuation circuits into existing hydraulic systems, being aware of potential problems in the brake actuation design and many other variables. It is the vehicle designer's responsibility to insure a proper testing program is defined and conducted to insure validation of the components selected.

It is essential to have a thorough understanding of not only components and circuits but also the many laws, organizations and agencies that regulate vehicle braking and system design. The importance of planning cannot be overemphasized.

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