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A compromise solution for energy recovery in vehicle braking

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Abstract

A combined regenerative-dissipative brake system for a city bus is considered. The regenerative component consists of a fixed displacement hydraulic pump/motor discharging into or receiving high pressure fluid from a hydropneumatic accumulator. The braking force provided by the pump is determined by the pressure in the accumulator. It is brought into action only when a greater total braking force is required, in which case the conventional dissipative brake provides the difference. From a preliminary analysis using probability data for acceleration, an estimated 45% of the total kinetic energy absorbed in braking could be channeled through the hydropneumatic component. The system was conceived as a practical alternative to a more costly fully regenerative system employing a variable displacement pump.

1. Introduction

Regenerative braking in vehicles using a variable displacement hydraulic pump/motor together with a hydropneumatic accumulator has attracted considerable interest during the last 20–25 years. Such a system is particularly suitable for application in city buses, as these vehicles make frequent stops and generally permit an unobstrusive installation of the required hardware. Indeed, some rather successful examples may be cited: a 30–35% reduction in fuel consumption was achieved with a Volvo Flygmotor hydraulic accumulator bus operating in Stockholm [1]. A round trip energy recovery efficiency of 45% for the cycle from braking to acceleration is reported for the M.A.N. "hydrobus" [2]. Fuel savings resulting from the installation of a hydro-pneumatic system in a Leyland Panther bus exceeded 20% as measured during service in Brisbane, Australia [3].

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Ref. 4 describes an experimental setup in which energy was transferred back and forth between a hydropneumatic accumulator via a pump/motor and a flywheel with round trip efficiencies of 61 to 89%. A proposal to further improve fuel economy consists of stopping the vehicle's engine in lieu of idling whenever there is no power demand and restarting it using part of the stored energy in the hydropneumatic accumulator [5].

Despite the significant gains in the efficient use of energy that can be brought about by hydropneumatic regenerative braking, its use has not attained great popularity. The added cost, which may represent 10–15% of the total for the vehicle, is undobtedly a deterrent. In this paper, the possibility of combining conventional dissipative braking with a modest hydropneumatic regenerative unit utilizing a fixed displacement pump/motor is considered. The dissipative and regenerative elements contribute variable and fixed braking force components respectively. When the total braking force required is less than that which the hydropneumatic system would provide, only the dissipative brake is brought into action; when higher, the dissipative component would complement the part provided by the hydropneumatic system. During acceleration, the total propulsive force is similarly constituted with the engine providing the variable component in this case. This concept is a variation of the one previously described in reference to a battery powered electric bus [6]. In that instance, the variable braking force is provided by the electric traction motor operating as generator, so that electric as well as hydropneumatic regeneration takes place resulting in reduced peak battery charge and discharge currents.

2. Combined regenerative-dissipative brake system

Fig. 1 is a schematic diagram of the proposed arrangement combining regenerative and dissipative braking in the manner described above. A three position directional control valve determines the operation mode of the hydraulic pump/motor, which is directly coupled to the vehicle's trans-

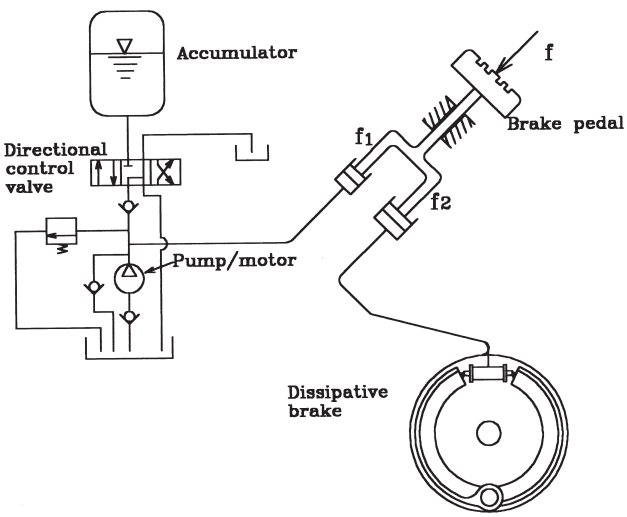

Fig. 1. Schematic diagram of combined regenerative-dissipative brake system.

mission. The central position of the valve, as shown in the diagram, corresponds to neutral. Pump and motor modes correspond to the displaced positions to the right and to the left respectively. In general, a force, f, applied to the brake pedal is resisted by a force, f_1, resulting from the pressure existing on the discharge side of the pump/motor plus a force, f_2, resulting from the pressure in the dissipative brake system. The pedal mechanism is so designed that a given value of f_1 or f_2 gives rise to the same braking force on the vehicle. It is emphasized that Fig. 1 is a schematic representation. Thus, the usual booster mechanism of the dissipative system is omitted. It is also understood that appropriate linkages may be introduced as required to conveniently satisfy the previously stated condition of equivalence of forces f_1 and f_2. Because of such a condition, the vehicle's response when the brake pedal is depressed is not affected by the relative contributions of the regenerative and dissipative brake components. The total braking force on the vehicle arising from those two components is:

$$F = \mathrm{K}f = \mathrm{K}(f_1 + f_2) \tag{1}$$

where K is a constant.

The system is controlled in the following manner: when the pedal is depressed, the applied force, f, is detected by means of a load cell. f is then compared to the force f_1 which would arise if the control valve were to be displaced to the right. f_1 is proportional to the accumulator pressure, which is measured by means of a pressure transducer. Then, if $f<f_1$, the valve is maintained in the neutral position and the full force on the pedal is transmitted to the dissipative braking system, so that $f_2=f$. If, however, $f\geq f_1$, the valve is displaced to the right causing the hydropneumatic system to become active and f_2 to adjust to the value $f-f_1$. This action would be impeded by the opening of an overriding, normally closed, pressure switch if the accumulator reached a fully charged condition.

Acceleration of the vehicle is controlled by an accelerator pedal coupled to a displacement transducer. This displacement, together with the engine speed, are fed as inputs to the controller. Then, from stored data of the engine characteristics, the torque, T, that would develop if the accelerator pedal were connected in the usual manner to a throttle mechanism is determined. This torque is compared to the torque, T_1, that would be available from the hydraulic pump/motor (motor in this case), if activated. If $T<T_1$, the directional control valve of the hydropneumatic system is maintained in the neutral position and an actuator sets the throttle precisely in the position that results in an engine torque $T_2 = T$. On the other hand, if $T \geq T_1$, the directional control valve is displaced to the left, bringing the hydraulic motor into action, and the engine throttle is set in a position to produce a torque $T_2 = T - T_1$. Displacement of the directional control valve from the neutral position would be prevented if the accumulator is totally discharged. This is possible by the insertion of a normally open pressure switch in series with the solenoid controlling such displacement.

3. Potential for energy recovery

In order to maximize the recovery of energy when braking, attention must be given to the size of the pump/motor. A criterion for its selection is based on a consideration of the probability distribution of the required braking force. A very small pump/motor providing a correspondingly small braking force would have a high probability of being activated when the vehicle is required to decelerate but in general would only recover a small fraction of the kinetic energy available.at the beginning of such deceleration On the other hand, a very large pump/motor providing a large braking force would seldom be activated. It is recognized that a meaningful probability distribution of the required braking force should be obtained on the basis of operating conditions as specific as possible, such as the particular route and perhaps even the individual driver.

For illustration purposes, the particular data in Ref. 3 will be used. Figure 1 of this reference is a map of the cumulative probability of bus acceleration at various vehicle velocities for a particular route in the city of Brisbane. From this figure one may obtain the probability, P, for a given velocity, V, that a given acceleration, a, or lower, will occur. A range of acceleration between -3 and $+2$ ms^{-2} essentially covers all possibilities. The probability density, p = dP/da, multiplied by a differential increment in acceleration, da, represents the probability that the acceleration be within the interval da. It must be emphasized that this probability is with respect to time. If, on the other hand, one is interested in the probability that a change in kinetic energy, $mVdV$, occur in that particular interval, the factor $mVdV/dt = mVa$ must be applied. Thus, the probability density in an energy-wise sense rather than a time-wise sense is

$$p = \mathrm{C}mV(dP/da)a = \mathrm{C}mVa\mathrm{p}, \tag{2}$$

where C is an appropriate constant. It is seen that, for a given velocity, the transformation from a time-wise probability density to an energy-wise one is obtained by application of a weight factor proportional to the acceleration.

During deceleration, part of the decrease in kinetic energy is the result of tire rolling and other losses. To isolate this effect from the brake action, one can assume that the losses account for a deceleration of say, 0.1 ms^{-2}, and correct the previously mentioned map of cumulative probability by shifting by that much the acceleration axis in the negative direction. This was done for a velocity of 20 km/hr, and only negative acceleration was considered. The resulting energy-wise probability density curve is shown in Fig. 2. The area under it multiplied by a small velocity decrement, ΔV, is a measure of the kinetic energy available for recovery due to that decrement. That area was made equal to unity by an appropriate choice of the vertical scale or, equivalently, of the constant C.

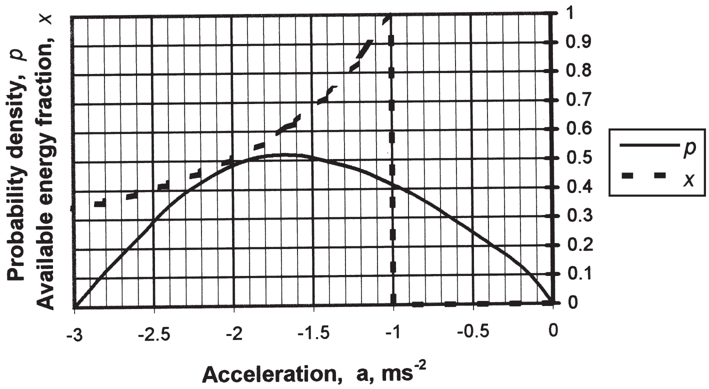

Fig. 2. Energy-wise probability density corresponding to 20 km/hr and available energy fraction for $a_1 = -1$ ms^{-2}.

The threshold of braking force for activation of hydropneumatic braking corresponds to a certain equivalent negative acceleration, a_1. This threshold varies somewhat with the state of charge of the accumulator. To simplify the analysis, a fixed, average value will be considered. The fraction of the braking energy that can be captured by the hydropneumatic system, x, would be

$$\begin{aligned} x&=0, \quad |a|<|a_1| \\ &=a_1/a, \quad |a|\geq|a_1|. \end{aligned} \tag{3}$$

As an example, a plot of x for $a_1 = -1\ \mathrm{ms}^{-2}$ is shown superimposed on the probability density curve of Fig. 2. If the ordinates of these two curves are multiplied by each other, the area under the resulting curve represents the expected overall fraction, X, of the energy that may be recovered when the brakes are applied at 20 km/hr. By varying a_1, it is found that X attains a maximum value of 0.45 corresponding to $a_1 = -1.1\ \mathrm{ms}^{-2}$.

The procedure was repeated for a velocity of 40 km/hr. In that case the maximum value of X turns out to be 0.48 corresponding to $a_1 = -0.94\ \mathrm{ms}^{-2}$. At both velocities considered, the value of X is quite insensitive to variations in a_1. In the range of $-1.2 \geq a_1 \leq -0.8\ \mathrm{ms}^{-2}$, X varied less than 6%. Although these results are based on a specific bus route, the shape of the probability density curve should, in general, be quite similar to that of Fig. 2.

A more accurate evaluation of the potential for energy recovery would be possible using joint probability density data with respect to acceleration and velocity. There again, the transformation of the probability density from a time-wise to an energy-wise basis would be given by Eq. (2). Then, with the same definition of x given by Eq. (3), the expected overall energy fraction, X, available for recovery, would be

$$X=\left(\int xVap\ da\ dV\right)/\left(\int Vap\ da\ dV\right) \tag{4}$$

The above analysis is based on the assumption of a level road. If one wished to take into account the effect of grades, probability data incorporating the slope as an additional variable would be necessary. The interchange between kinetic and potential energies corresponding to this variable would have to be suppressed from the formulation by subtracting out that part of the acceleration due to the slope.

4. Conclusions

A vehicle braking system combining an on-off hydropneumatic regenerative component with a conventional dissipative component may offer a practical alternative to a more costly regenerative system employing a variable displacement hydraulic pump/motor. From the calculations presented in this paper it is estimated that, in the proposed system, about 45% of the total kinetic energy absorbed in braking could be channeled through the hydropneumatic component. Thus, an efficiency roughly one half that of a system with a variable pump/motor could be expected. Considering the substantial fuel savings that have been reported with the latter, the proposed solution appears to be an attractive compromise. It is also significant to point out that, in order to have a fully regenerative system, not only a variable displacement pump/motor is required but, at maximum capacity, it must be able to provide the braking force corresponding to the maximum deceleration expected, so that a considerably bigger machine is implied which, furthermore, would operate most of the time at partial load and consequently, reduced efficiency.

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