Parameter Design for the Energy Regeneration System of Series Hydraulic Hybrid Bus

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Abstract: This paper simplifies the energy recovery process in the series hydraulic hybrid bus' energy regeneration system into a process in which the main axle's moment of inertia drives the secondary element variable delivery pump/motor and brings hydraulic oil from the oil tank to the accumulator. This process enables braking of the vehicle and also allows recovery of energy to the accumulator. Based on the flow equation for the secondary element variable delivery pump/motor and the torque equilibrium equation for its axle, the force equilibrium equation for vehicle braking and the pressure variation and flow continuity equations for the accumulator, simulation studies are conducted to analyze the effects of various system parameters, such as accumulator capacity, displacement of the secondary element variable delivery pump/motor, initial operating pressure of the system, etc. on system performance during regenerative braking.
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1. Introduction

With technology advancements and improvements in our standard of living, automobile as a convenient, efficient means of transportation plays an increasingly important role in our work and daily life, and even in a country's economic development. As a result, the massive use of automobile has led to problems about energy and environmental pollution to be urgently addressed. Thus the hybrid automobile with a regenerative braking system emerges as the times require. However, as conventional hybrid electric vehicles are unable to recover the huge kinetic energy generated in braking quickly and efficiently due to the limited energy storage elements and energy conversion modes in their regenerative braking system, the

conventional electric-energy-storage regenerative braking system has a low efficiency of energy recovery, in particular in urban areas where vehicles have to start up and brake frequently, which amplifies its disadvantages [1-3]. By contrast, the hydraulic hybrid vehicle featuring high power density of accumulator and quick conversion of energy is attracting more and more attention from governments and research organizations. Japan and some European countries have developed and tested various hydraulic energy storage systems in buses, proving that such systems cut fuel consumption and CO₂ emissions by 30 %-50 % [4-6].

The energy regeneration system of the series hydraulic hybrid bus studied in this paper is series-connected to engine when used as a driving system, which includes the original braking system of

automobile in addition to the regenerative braking system. The energy regeneration system of the series hydraulic hybrid bus consists of main gearbox, hydraulic accumulator and secondary-element variable delivery pump/motor (hydraulic motor/pump), as shown in Fig. 1. The hydraulic accumulator is the principal energy recovery device that provides the braking torque for the regenerative braking [7]. The fixed delivery pump connected to engine is used as a power element. The secondary-element variable delivery pump/motor is

bi-directionally reversible. When the vehicle starts up or runs normally, the variable delivery pump/motor works as a motor that serves as the wheel drive actuator. When the vehicles brakes, the variable delivery pump/motor as a pump to recover inertia energy, store it in the form of hydraulic energy in the accumulator and release it at the time of vehicle startup or acceleration to supplement the power output of fixed delivery pump connected to engine, thereby enhancing the power and fuel efficiency of the vehicle.

Fig. 1. Schematic diagram of the energy regeneration system of series hydraulic hybrid bus.

As the energy regeneration system works as part of the driving system during the non-braking mode operation and, as a braking system, it also integrates the vehicle's original braking system, it should be the original braking system that completes the braking operation when regenerative braking is impossible.

Therefore, the energy regeneration system of the hydraulic hybrid bus is a complicated system. The system should enable braking and recovery of braking energy, effectively integrate two braking systems and also drive the vehicle to run with recovered braking energy. Based on analysis and creation of the system's mathematical model, this paper also studies effects of different system parameters on braking and energy regeneration during regenerative braking.

2. Creation of the Mathematical Model for Braking of the Energy Regeneration System

2.1. Force Equilibrium Equation of Vehicle

The forces applied during vehicle braking are illustrated in Fig. 2. According to the figure, the force

equilibrium equation for the vehicle should be as follows:

$$(m + \frac{I_{w1} + I_{w2}}{r^2}) \frac{dv}{dt} = \frac{T_z}{r} + F_f + F_w, \quad (1)$$

where I_{w1} and I_{w2} are the moment of inertia of front and rear wheels, respectively, kg/m^2 ; T_z is the braking resistance torque, N.m ; F_f is the vehicle rolling resistance, N ; F_w is the vehicle head resistance, N ; m is the full loaded weight of vehicle, kg ; v is vehicle velocity, m/s ; r is the radius of wheel, m .

The moment of inertia of wheels and the transmission shaft is much smaller than the moment of inertia of vehicle, and thus may be ignored. The bus works in urban areas, running and braking at a low speed, so rolling resistance and head resistance can be set at fixed values relating to the vehicle. The resultant force of the two resistances is F_z .

In addition, $T_z = iT_L$, i is the gear reduction ratio of main gearbox, and T_z is equivalent braking resistance torque in the variable delivery pump/motor.

Fig. 2. Forces applied during vehicle braking.

$V=r\omega/i$, V is the pump speed of the variable delivery pump/motor; when the vehicle is at the deceleration stage, its velocity is a negative value. Therefore, Equation (1) can be simplified as follows:

$$-m \frac{r}{i} \frac{d\omega}{dt} = \frac{iT_L}{r} + F_z, \quad (2)$$

2.2. Force Equilibrium Equation of Secondary-element Variable Delivery Pump/Motor

$$V_g \Delta P + J_p \frac{d\omega}{dt} + B_p \omega = T_L, \quad (3)$$

where V_g is the displacement of variable delivery pump/motor, /rad; ΔP is the suction-discharge differential pressure of variable delivery pump/motor, Pa; J_p is the moment of inertia of variable delivery pump/motor, kg; ω is the rotation speed of variable delivery pump/motor, rad/m²; B_p is the equivalent viscous damping efficient of variable delivery pump/motor, kg/s; T_L is the equivalent braking resistance torque of variable delivery pump/motor.

2.3. Flow Equilibrium Equation of Secondary-element Variable Delivery Pump/Motor

$$Q_p = V_g \omega - C_{ip} \Delta P - C_{ep} \Delta P, \quad (4)$$

where Q_p is the output flow of variable delivery pump/motor, m³/s; C_{ip} , C_{ep} are the internal and external leak coefficients of variable delivery pump/motor.

As the leak of variable delivery pump/motor is as small as ignorable, equation (4-5) can be simplified as follows:

$$Q_p = V_g \omega \quad (5)$$

2.4. Pressure Variation Equation of Accumulator [8-10]

$$p_0 - \Delta P = \frac{1}{A_a^2} (m_a \frac{dQ_a}{dt} + B_a Q_a), \quad (6)$$

where p_0 is the inflation pressure of accumulator, Pa, the inflation pressure of accumulator in the model equals to the initial operating pressure of accumulator; m_a is the equivalent mass of hydraulic oil in energy chamber of accumulator, kg; B_a is the equivalent viscous damping coefficient of accumulator, kg/s; A_a is the equivalent sectional area of fluid chamber of accumulator.

2.5. Flow Continuity Equation of Accumulator

$$Q_a = -\frac{dV_a}{dt}, \quad (7)$$

where V_a is the volume of gas chamber of accumulator corresponding to accumulator pressure ; Q_a – mass of input hydraulic oil of accumulator.

Assume that there is no flow loss in the system, then $Q_p = Q_a$.

According to the Boyle's gas law:

$$p_1 V_1^n = p_a V_a^n, \quad (8)$$

where p_1 is the initial operating pressure of accumulator, Pa; V_1 is the volume of gas in corresponding accumulator; n is the air polytropic exponent; p_a is the transient pressure of accumulator, Pa.

Taylor-expand equation (8) around and neglect higher-order terms:

$$\frac{dp_a}{dt} = -\frac{np_1}{V_1} \frac{dV_a}{dt} \quad (9)$$

As , substitute Equations (9) and (7) into equation (6):

$$\Delta P = \frac{1}{A_a^2} (m_a \frac{dQ_p}{dt} + B_a Q_p) + \int \frac{np_1}{V_1} Q_p dt + p_1 \quad (10)$$

3. Simulation Analysis of Braking Process

With equations (2), (3), (5) and (10) for models described in Section 2, the MATLAB/Simulink is

used to simulate the impact of accumulator pressure, vehicle velocity changes and torque changes of the variable delivery pump/motor on system performance.

The Bus SWB6106HG manufactured by Shanghai Sunwin Bus Corporation is used as the simulation bus in this paper. Model parameters are calculated and enumerated in Table 1.

Table 1. List of model parameters.

Full loaded weight of bus	m	16500 kg
Radius of wheel	r	0.53 m
Gear reduction ratio of main gearbox of bus	i	4.875
Resultant force of resistances	F_r	2500 N
Moment of inertia of variable delivery pump/motor	J_p	$0.1 \text{ kg} \cdot \text{m}^2$
Equivalent viscous damping coefficient of variable delivery pump/motor	B_p	0.238 kg/s
Equivalent viscous damping coefficient of accumulator	B_e	300 kg/s
Equivalent mass of hydraulic oil in energy chamber of accumulator	m_a	3 kg 6.74 kg
Equivalent selectional area of fluid chamber of accumulator	A_a	0.0377 m^2 0.0700 m^2
Initial air volume of accumulator	V_i	40 L 63 L
air polytropic exponent	n	1.25
Initial velocity of vehicle	v	40 km/h

According to equations for models described in Section 2, a Simulink model can be created for braking of the energy regeneration system of the vehicle, as shown in Fig. 3.

3.1. Effects of Accumulator Capacity

With the displacement of the secondary-element variable delivery pump/motor being 100 ml/r and the system operating pressure being 20 MPa, select accumulators NXQL40 (with a capacity of 40 L) and NXQL63 (with a capacity of 60 L) for braking simulation of the energy regeneration system. Curves of changes in output vehicle velocity, changes in accumulator pressure and changes in torque of the secondary-element variable delivery pump/motor are illustrated in Fig. 4 – Fig. 6 respectively.

As shown by simulation results in Fig. 4 – Fig. 6, a larger accumulator capacity will lead to slower braking, but the effects are not obvious; but a smaller accumulator capacity will result in markedly accelerated rise in the accumulator pressure during braking of the energy regeneration system, even causing the pressure to easily exceed the permissible maximum pressure, and a smaller accumulator capacity will lead to a significant change in the torque of the secondary element during braking. Therefore, if the bus chassis space permits, accumulator with a larger capacity should be used.

Fig. 3. Simulink model during vehicle braking.

Fig. 4 Vehicle velocity changes during braking.

Fig. 5. Accumulator pressure changes during braking with different accumulators.

Fig. 6. Changes in the torque of the secondary-element variable delivery pump/motor during braking with different accumulators.

3.2. Effects of the Displacement of Secondary-element Variable Delivery Pump/Motor on the System

With the accumulator NXQL63 (with a capacity of 60 L) and system operating pressure being 12 MPa, select the secondary-element variable delivery pumps/motors with a displacement of 100 ml/r, 150 ml/r and 200 ml/r respectively for braking simulation of the energy regeneration system. Curves of changes in output vehicle velocity, changes in accumulator pressure and changes in torque of the secondary-element variable delivery pump/motor are illustrated in Fig. 7 – Fig. 9 respectively.

As shown by simulation results in Fig. 7 – Fig. 9, the displacement of the secondary-element variable delivery pump/motor has a large impact on the torque of the variable delivery pump/motor during braking. A larger displacement of the secondary-element variable delivery pump/motor will result in a larger torque of the secondary-element variable delivery pump/motor, and also a larger change in torque. The displacement also has an obvious impact on braking speed, with a larger displacement corresponding to quicker braking. The displacement has less impact on system pressure. With an overall consideration of the impact on torque and braking speed, therefore, a medium-sized displacement of variable delivery pump/motor may be selected.

3.3. Effects of Initial Operating Pressure on the System

With the displacement of the secondary-element variable delivery pump/motor being 200 ml/r and the accumulator model number being 20 MPa, select the system's initial operating pressures 12 MPa, 15 MPa and 18 MPa braking simulation of the energy regeneration system. Curves of changes in output vehicle velocity, changes in accumulator pressure and changes in torque of the secondary-element variable delivery pump/motor are illustrated in Fig. 10 – Fig. 12 respectively.

As shown by simulation results in Fig. 10 – Fig. 12, the initial operating pressure of the system has an impact on deceleration. A higher initial pressure will result in faster deceleration, but the impact is insignificant and ignorable. The initial pressure has a significant impact on the torque of the secondary-element variable delivery pump/motor. As shown in the figure, the final pressure of accumulator at an initial system pressure of 15 MPa is lower than that at an initial system pressure of 12 MPa, while the final pressure of accumulator at an initial system pressure of 18 MPa is too high.

Fig. 7. Vehicle velocity changes during braking with variable delivery pumps/motors with different displacements.

Fig. 8. Accumulator pressure changes during braking with variable delivery pumps/motors with different displacements.

4. Conclusion

This paper simplifies the energy recovery process in the series hydraulic hybrid bus' energy regeneration system into a process in which the main axle's moment of inertia drives the secondary element variable delivery pump/motor and brings hydraulic oil from the oil tank to the accumulator. This process enables braking of the vehicle and also allows recovery of energy to the accumulator. Based on simulation study on effects of different system

parameters on system performance in the system's mathematical model, the author arrives at the following conclusion.

The accumulator capacity has an insignificant impact on the braking speed of vehicle, but has a significant impact on changes in accumulator pressure during braking. A smaller accumulator capacity will lead to significantly faster rise in accumulator pressure during braking, easily pushing the pressure up to reach or even exceed the permissible maximum pressure.

The displacement of the secondary-element variable delivery pump/motor has an insignificant impact on system pressure, but has a relatively large impact on the torque and braking speed of the variable delivery pump/motor during braking. A larger displacement of the secondary-element variable delivery pump/motor will lead to a larger torque of secondary-element variable delivery pump/motor, large changes in torque and faster braking.

The initial operating pressure of system has an insignificant impact on the braking speed of vehicle, but has a significant impact on changes in accumulator pressure during braking. However, when the initial operating pressure of system rises within a band of low pressures, changes in the final accumulator pressure will become less significant.

Fig. 9. Changes in the torque of the secondary-element variable delivery pump/motor during braking with variable delivery pumps/motors with different displacements.

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Fig. 10. Vehicle velocity changes during braking at different initial operating pressures.

Fig. 11. Accumulator pressure changes during braking at different initial operating pressures.

Fig. 12. Changes in the torque of the secondary-element variable delivery pump/motor during braking at different initial operating pressures.

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