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Simulation of Electrically Powered Hydraulic Steering System in Electric Vehicles

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Abstract

As concerns about global and local pollution have grown, stricter and stricter environmental legislations are enforced. A fuel cell city bus was developed in the last year, which is supported by Ministry of Science and Technology in China. The simulation of an electrically powered hydraulic steering system used in the developed fuel cell city bus is studied. The layout of the steering system is introduced. Resistive force of the steering tire originating from the vertical load and lateral force of tire is computed, and then the resistant force of hydraulic cylinder can be determined. The DC motor is used to drive the hydraulic vane pump and dynamic equation of the system is established. Simulation is performed with the help of Simulink of MATLAB. Relationships between hydraulic pressure and forward speed, voltage of armature of motor are simulated, respectively, which is helpful to determine parameters of hydraulic vane pump, DC motor in electrically powered hydraulic steering system in electric vehicles.

Keywords

fuel cell city bus, electrically powered hydraulic steering system, steering resistive torque, simulation

1. INTRODUCTION

In recent years, concerns about global and local pollution have intensified. In some countries, they have already led to stricter and stricter environmental legislation. Transportation is thought of as a source of every major pollutant except sulfur dioxide. CO emissions from automobiles are responsible for two-thirds of total CO emissions. Carbon dioxide concentration in the air is about 25 percent higher than it was before the industrialization [Rajashekara, 2000]. Amid the worldwide calling for environmental protection, demand for the development of cleaner vehicles with less pollution has increased. Electric vehicles, including pure electric vehicles, hybrid electric vehicles and fuel cell vehicles, have been paid more and more attention. The power sources in electric vehicles are different from conventional ICE vehicles. In the transport sector, some countries have already taken or will take measures to lower vehicle emissions, aiming at a reduction of air pollution. Some countries have also set up goals for the reduction of greenhouse gases. Many city bus demonstration projects have been started in some countries, including US Clean Air Act, Montreal Urban Hythane Bus Project, and China Clean Vehicle Act.

Fuel cells produce electricity through an electrochemical process combining hydrogen and oxygen (Fuel cells do not utilize combustion). Because electrical energy is generated without combusting fuel, fuel cells are extremely attractive from the view of environmental protection. We developed a fuel cell city bus supported by Ministry of Science and Technology in China. The specifications of the bus are listed in Table 1. Figure 1 is the photo of the fuel cell city bus, which uses an electrically powered hydraulic steering (EPHS) system. In the steer-

Table 1 Specifications of the developed fuel cell city bus

Parameters (Unit)	Value
Gross weight (kg)	15500
Length×Width×Height（mm）	11070×2490×3420
Number of passengers	50
Ratio of gearbox	i_{g1}=3.002, i_{g2}=1.862
Ratio of final drive	i_0=6.83
Type of storage battery	Li-ion battery
Rated voltage (V)	384
Maximum speed (km/h)	65
Gradeability (%)	>15
Accelerating time (0-50km/h) (s)	<40

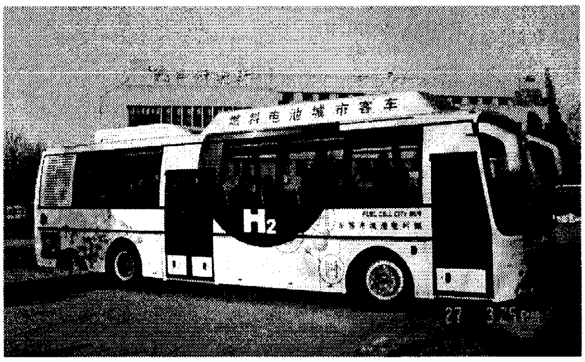


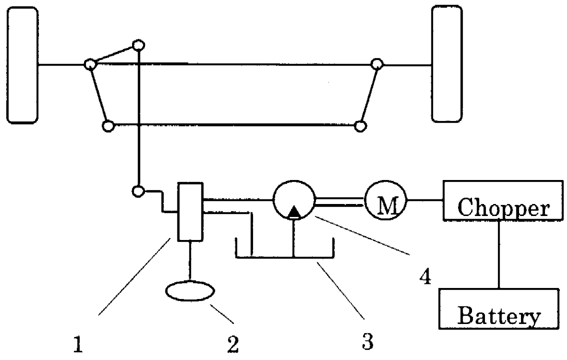
Fig. 1 Photo of the developed fuel cell city bus

ing system, the hydraulic pump is driven by a motor rather than directly by the conventional engine. In conventional ICEVs, the hydraulic pump in a power steering system is directly driven by the engine. Since the hydraulic pump always runs in proportion to the engine speed, there will be wastage of energy when the vehicle runs straightforward at high speeds. The corresponding energy consumption has been found to be about 3% of the total engine fuel [Chan, 2002]. In order to minimize the energy consumption of a power steering system for the bus, the power consumption of the hydraulic pump in the power steering system should be adjusted according to the need of steering cases.

The variation of steering resistance is considered because it directly affects the power consumption of the hydraulic pump, and then determines operating cases of the PMDC motor. Determination and control of power of the PMDC motor is very important because the motor consumes the energy of storage batteries onboard, which affects range of the vehicles. The determination of the power of the PMDC motor is different from that of the conventional vehicle in which resistance is considered as peak value when the speed of the engine is idled. In the developed powered steering system, based on the need of turning the front wheels, the controller adjusts the current in armature of the motor. So, energy required to drive the hydraulic pump can be reduced according to the requirements of different operating cases. After simulations in different cases are performed with the help of Simulink of MATLAB, many important parameters in the system, such as the power of motor, the displacement of hydraulic pump, can be understood.

2. LAYOUT OF THE ELECTRICALLY POWERED HYDRAULIC STEERING SYSTEM

The electrically powered hydraulic steering system in the developed fuel cell city bus consists of a PMDC motor, a controller or chopper, a hydraulic vane pump and steering linkage system. The steering gear is identical to the conventional hydraulic power steering unit. An auxiliary battery (384V, 100Ah) provides the power source for the PMDC motor through a chopper. The power steering system is an integral system, in which the control valve and the power piston are integral parts of the steering gear. A recirculating ball steering gear is used. The layout of the steering system is depictured in Figure 2.



1- Integral steering gear
2- Steering wheel
3- Oil pan
4- Hydraulic vane pump

Fig. 2 Layout of electrically powered hydraulic steering system

3. DETERMINATION OF STEERING RESISTANCE OF THE HYDRAULIC PUMP

3.1 Vehicle model and steering torque of the front tires

The lateral force of a tire is proportional to its sideslip angle, and varies the steering torque. Sideslip angle can be determined by vehicle model originating from vehicle dynamic equations. The vehicle model used in this paper is the simplest model, or the two degrees of freedom bicycle model. This model combines left and right wheels, lumping them together at the front and rear of the vehicle. The model uses vehicle lateral motion and vehicle yaw as degrees of freedom. The equation of motion for the linear model can be written in the following matrix form [Zhisheng, 1990]:

$$\begin{Bmatrix} \dot{v} \\ \dot{r} \end{Bmatrix} = \begin{bmatrix} \dfrac{C_{\alpha f}+C_{\alpha r}}{mu} & \dfrac{aC_{\alpha f}-bC_{\alpha r}-mu^2}{mu} \\ \dfrac{aC_{\alpha f}-bC_{\alpha r}}{I_z u} & \dfrac{a^2C_{\alpha f}+b^2C_{\alpha r}}{I_z u} \end{bmatrix} \begin{Bmatrix} v \\ r \end{Bmatrix} - \begin{bmatrix} \dfrac{C_{\alpha f}}{m} \\ \dfrac{aC_{\alpha f}}{I_z} \end{bmatrix} \delta \qquad (1)$$

In the above matrix, m denotes the mass of the body, I_z the yaw moment of inertia of the vehicle, a and b the distances from the center of gravity to the front and rear wheel axle respectively, $C_{\alpha f}$ and $C_{\alpha r}$ equivalent cornering stiffness of the front and rear tires, respectively, u the forward vehicle speed, v the lateral velocity, r the yaw rate, δ equivalent steering angle of the front wheels. The front sideslip angle is

$$\alpha_f = \frac{v+ar}{u} - \delta \qquad (2)$$

where the small angle assumption for sideslip angle has been made. The front sideslip angle and the tire cornering stiffness determine the resulting lateral forces.

$$F_{yf} = C_{\alpha f}\alpha_f \qquad (3)$$

3.2 Steering resistive torque of the front tires

Generally speaking, the highest steering torque in a steering system takes place when the wheels are turned with the car stationary. In the ICE vehicle, the above-mentioned steering torque is computed when the vehicle is stationary. A formula describes the approximate value of the static torque to turn a non-rolling tire [Bastow, 1993], which is usually used to determine stress level of steering system parts.

However, the torque imposed on the front tires varies in different operating cases. So the torque on the front tires in simulation differs from that in the ICE vehicle. Assuming that the vehicle is symmetric about longitudinal centerline, load transition on the left and right tire during cornering, camber and toe-in are all neglected, so vertical load and tractive force on left and right wheels are considered to be equal. Referring to Thomas [1992], we can get the resistive torques on the front steering tires resulting from vertical load and lateral force.

The steering resistive torque T acting on the front steering tires can be written as follows,

$$T = T_V + T_L \tag{4}$$

where T_V and T_L are torque originating from vertical force, lateral force on the front wheel, respectively.

According to wheel alignment, we can gain

$$T_V = -F_{zf} d \sin 2\lambda \sin \delta \tag{5}$$

where F_{zf} is vertical load on front axle, d lateral offset at the ground, λ lateral inclination angle of the kingpin.

$$T_L = F_{yf}(r_r \tan\gamma + e) \tag{6}$$

where F_{yf} is lateral force, r_r is tire radius, γ caster, e pneumatic-trail generated by tire.

3.3 The pressure in the hydraulic fluid

Steering resistance of the wheel acts on the hydraulic pump through steering linkage sector shaft, drop arm steering nut-follower, piston and hydraulic fluid.

The force acting on the piston in the power cylinder through steering linkage and steering gear can be written as follows,

$$F = \frac{T}{l}\frac{1}{i_s} \tag{7}$$

where l is the effective length of the steering arm, i_s the ratio of the ball nut rack in the steering box to the steering arm. So the pressure in the power cylinder is

$$p = \frac{F}{A} + \Delta p \tag{8}$$

where A denotes the effective area of the piston, $\triangle$p is the pressure loss in hydraulic pipeline, which can be determined by experiment.

3.4 Time to respond to steering

When steering the front wheels takes place, the volume variation in the powered cylinder due to movement of the piston is

$$V = \frac{A\delta l}{i_s} \tag{9}$$

so, the time to perform the steering demands is determined by the following formula,

$$t = \frac{V}{q_0} \tag{10}$$

where q_0 is displacement of the vane pump. Generally speaking, the time to respond to steering demand is less than 2.3-3s, and the speed at which a driver turns the steering wheel is less than 1.5 revolutions per second.

4. DYNAMIC EQUATION OF THE DC MOTOR

Based on the specifications of the PMDC motor, the dynamic equation of the PMDC motor and the flow of fluid of the oil pump can be established. In the structure, the vane pump is connected to the output shaft of the DC motor directly.

Dynamic equation of the DC motor is as follows,

$$C_M \phi \frac{U_a - C_E \phi n_M}{R_a} - T_R = 2\pi J \frac{dn_M}{dt} \tag{11}$$

where U_a is armature voltage. Φ is permanent magnetic flux. C_M and C_E are torque constant and voltage constant, respectively. n_M is rotational speed of the motor. J is sum of rotors of the motor and that of the vane pump. T_R is resistance torque can be determined by the following formula,

$$T_R = \frac{1}{2\pi} p q_0 \frac{1}{\eta_m} \tag{12}$$

where p, q_0 and η_m are operating pressure, displacement of the pump and mechanical efficiency of the pump, respectively.

5. SIMULATION OF ELECTRICALLY POWERED HYDRAULIC STEERING SYSTEM

Simulation of electrically powered hydraulic steering system is performed with MATLAB/Simulink. The simulation model is depicted in Figure 3. In the simulation, feedback control is used in the controller to adjust the armature current of the DC motor, which is helpful to reduce the energy consumption of the DC motor. Simulations are performed at different steering angles and different velocity.

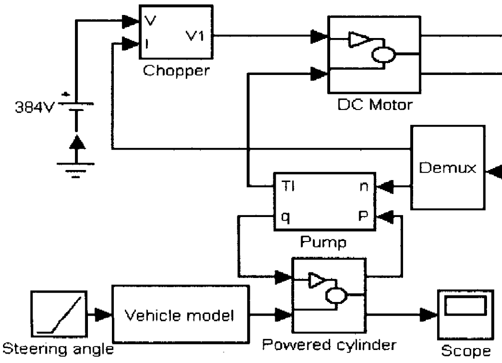


Fig. 3 Simulation model

The front wheel alignments in the developed fuel cell city bus are listed in Table 2.

Table 2 Wheel alignment

King-pin inclination (deg)	7
Caster (deg)	2
Camber (deg)	1
Toe-in (mm)	0-2

Simulations of the city bus are performed in two cases, one is stationary, and the other is that the bus is running at the speed of 45km/h.

5.1 Simulation of the stationary vehicle

When the bus is stationary and the front wheels are turned, the turning angle of the front wheels, the pressure in pipeline, speed of the motor and current in armature are depicted in Figure 4 to Figure 7.

5.2 Simulation of the running bus

Simulation is carried out when the bus runs at a speed of 45km/h. The turning angle of the front wheels, the pressure in pipeline, speed of the motor and current in armature are depicted in Figure 8 to Figure 11.

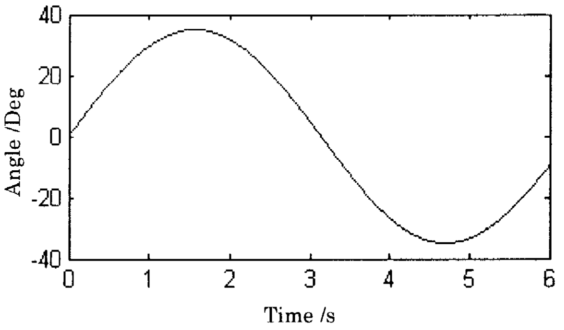


Fig. 4 Turning angle of the front wheels

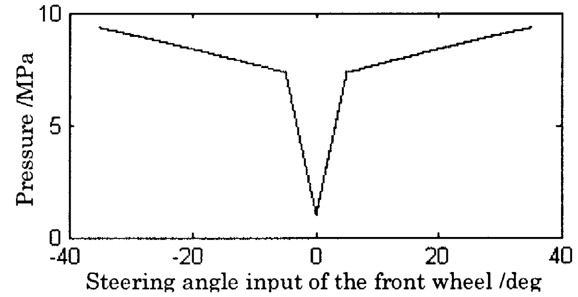


Fig. 5 Pressure in pipeline

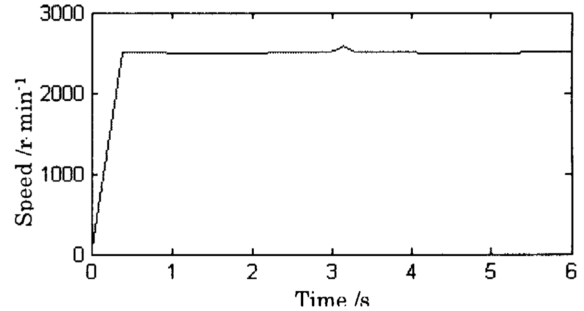


Fig. 6 Speed of the motor

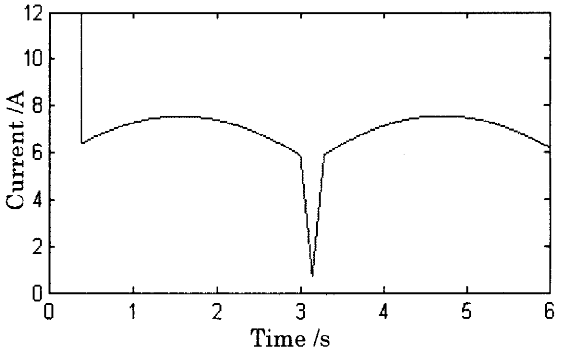


Fig. 7 Current in armature of the motor

6. CONCLUSIONS

The results of simulation show that the purpose of reduction of energy consumption is reached and can satisfy the requirements of all cases. Due to the reduction

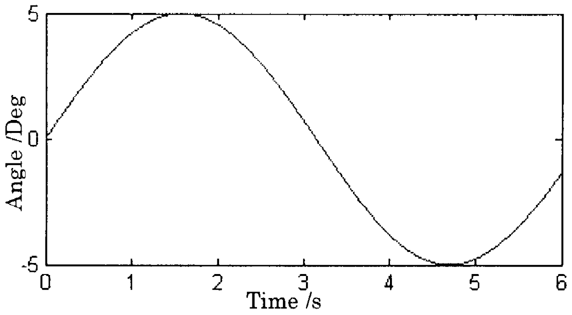


Fig. 8 Steering angle input of the front wheels

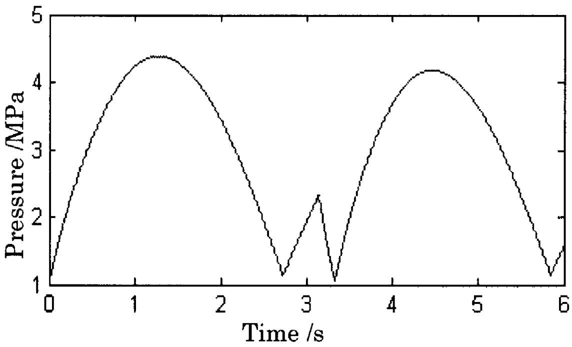


Fig. 9 Pressure in pipeline

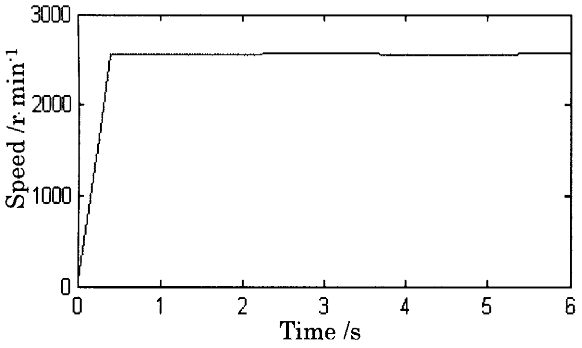


Fig. 10 Speed of the motor

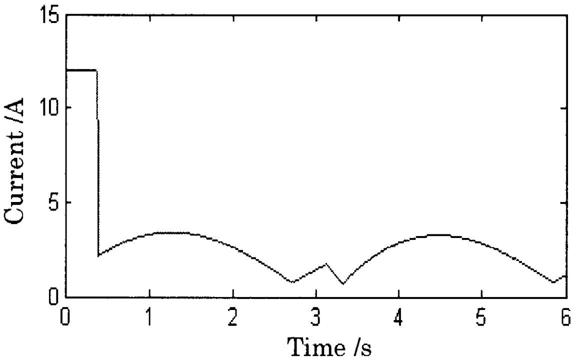


Fig. 11 Current in armatures of the motor

of sideslip of the front wheels when the vehicle is running, the steering resistive torque will decrease. With the help of the simulation results, one can determine displacement of the powered pump, the power of the motor, steering linkage and steering gear.

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