Fuzzy logic-based energy management strategy for a novel mechatronics-electro-hydraulic power coupling electric vehicle

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Title page

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ORIGINAL ARTICLE

Fuzzy logic-based energy management strategy for a novel mechatronics-electro-hydraulic power coupling electric vehicle

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Abstract: In order to solve the troubles of electric peak torque and enhance the energy efficiency of electric vehicles, a novel mechatronics-electro-hydraulic power coupling electric vehicle (MEH-PCEV) with low energy consumption is proposed. The hydraulic system and the motor are integrated into a device to simplify the structure, taking the pure electric vehicle as a reference. Simultaneously, a fuzzy logic-based optimization method is proposed for real-time adjustment of the electric torque based on the original rule control strategy. Compared with the pure electric vehicle, the proposed methods can substantially enhance energy utilization and the recovery efficiency of electric energy. Ultimately, the actual driving cycle is analyzed using data acquisition capacity, with the authentic speed as the input signal. The verification results on real-world vehicles demonstrate the consumption rate of the battery state of charge and the electric torque are improved by 7.32% and reduced by 22.24%, respectively. Moreover, this research is expected to provide a reference for the development and engineering applications of the mechatronics-electro-hydraulic coupling systems.

Keywords: Mechatronics-electro-hydraulic power coupling electric vehicle • Economic performance • Energy efficiency • Torque characteristic • Fuzzy control

1 Introduction

1.1 Research motivation

With the increase of energy-saving and environmental protection requirements, pure electric vehicles (PEV) are developing rapidly [1-2]. Whereas constrained by battery defects, the frequent start/stop of the PEV generates peak torque [3]. The battery's life and vehicle mileage will be substantially reduced [4]. In recent years, electro-hydraulic hybrid technology has received a lot of attention as a new configuration. The hydraulic system has the advantages of high power density [5-6] and fast energy charging and discharging [7-8].

1.2 Literature review

New energy vehicles are regarded as a promising means of transportation to reduce air pollution and fossil fuel consumptions. Nevertheless, on the one hand, voltage, temperature, and state of charge (SOC) are the essential characterization parameters for various battery faults, and accurate prediction of these parameters is critical for battery safety [9]. On the other hand, battery safety and vehicle mileage are obstacles to the development of electric vehicles [10]. Therefore, pure electric automobile research is far from ample to enhance energy efficiency

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and driving range.

Currently, researchers have done a lot of work on hybrid research. Zhu [11] built a complex multi-energy coupled system to improve the traction power supply system's overall energy efficiency. Liu [12] presented an electro-hydraulic hybrid power system and verified its energy recovery efficiency of up to 50%. The new mechanical-electric-hydraulic dynamic coupling drive system (MEH-DCDS) can combine a conventional permanent magnet motor with a swashplate piston pump/motor to achieve the mutual transformation of electrical, mechanical, and hydraulic energy [13]. MEH-DCDS plays a significant role in supporting the development of electro-hydraulic hybrid technologies, which will gradually improve the production and lifestyle of the human.

For multi-mode hybrid vehicles, the core technology is the design of the control strategy [14]. The rule-based control strategy is highly logical. Whereas the output signal changes in real-time in different environments [16-17]. Yang [18] proposed a novel electro-mechanical-hydraulic coupler. After a theoretical analysis of the system power flow, a rule-based dynamic optimal energy management strategy was established to control energy distribution and the dynamic switching of working modes in real-time. Ultimately, a fuzzy controller was used to optimize the logic threshold control strategy. The motor torque was dramatically reduced and the overall efficiency of the motor operating point was enhanced. Chen [19] proposed a rule-based dynamic optimal energy management strategy for city buses. The outcomes demonstrated that the peak torque was reduced through 36.4%, and the battery consumption was decreased via 33.98% in the new European driving conditions. Xiong [20] used both fuzzy control strategy and parallel drive energy management to control the bus. After verification, the energy consumption was theoretically 30.3% lower than that of conventional buses under driving cycle working conditions. Tirkolaee [21] combined the interactive fuzzy-based solution method with the adaptive artificial fish swarm algorithm, aiming to find the optimal solution for the test object.

Currently, intelligent control strategy has better control effect on nonlinear hybrid drive systems. Therefore, this paper presents a fuzzy logic control strategy for real-time adjustment of the electric torque proportionality coefficient for mechatronics-electro-hydraulic power coupling electric

vehicles (MEH-PCEV). Simultaneously, the actual vehicle data acquisition method is further used to carry out the test verification.

1.3 Challenges and Problems

Hydraulic technology has made great progress in the conversion of mechanical energy into hydraulic energy [22]. Nevertheless, the development of mechatronic technology first faces some challenges that cannot be ignored, mainly reflected in the volume loss and mechanical loss. To continuously expand its field of application to meet future needs, it is vital to begin with the discount of internal stress losses in elements and the use of hydrostatic technology with load sensing systems [23-24]. Second, electro-hydraulic servo-proportional technology as well as computer simulation standardization is the core technology to improve its working reliability [25]. Electro-hydraulic torque coupling and the adoption of a generalized control mechanism are also issues that need to be explored in the future.

Fuzzy control language is simple and robust with high fault tolerance [26]. However, Simple information processing will lead to lower control accuracy and poor dynamic quality. Furthermore, fuzzy controller design lacks systematicity to define control objectives [27].

Currently, there are many studies that use real measurement data to construct vehicle driving conditions. Whereas there are fewer articles that import actual driving cycles into simulation models for validation. Simultaneously, due to incorrect driver operation, vehicle vibration, and road complications, the car generates noise that causes data to appear as a singularity. A giant variety of evaluation strategies nonetheless have many difficulties in smoothing the speed curve. Due to the inherent drawbacks of the method and the above challenges, there are nevertheless sizable difficulties in the sensible mannequin validation [28].

1.4 Contributions of this work

To address the above issues, the main research of this paper has the following points:

- 1) A novel mechatronics-electro-hydraulic power coupling system is proposed.
- 2) A fuzzy logic-based optimization strategy is proposed for real-time adjustment of the electric torque.
- 3) The actual results of driving conditions are analyzed by means of data acquisition and simulation.

1.5 Organization of the paper

The rest of this paper is organized as follows: Section 2 describes the working principle of the MEH-PCEV. Section 3 performs the design and modeling of the fuzzy controller. Section 4 collects real road information for verification. Section 5 summarizes the research of this paper.

2 Working principle of the MEH-PCEV

The specific structure of the MEH-PCEV is given in Fig. 1. MEHC-PCEV is a new vehicle type based on pure electric drive [29-30]. The system includes a high pressure accumulator (HPA), a low pressure accumulator (LPA), safety valves, oil coolers, oil filters, solenoid valves, mechatronics-electro-hydraulic power coupling system (MEH-PCS), clutches, main reducers, differentials, pressure sensors, controllers, power converters, and battery.

To reduce the electric peak torque, the vehicle is customarily started using hydraulic power. In this case, hydraulic energy is converted to mechanical energy. When the vehicle accelerates or climbs a hill, the demand torque must be high enough. Thus, the battery pack begins to provide electrical power. Electric energy is coupled with hydraulic energy through the MEH-PCS, and then mechanical energy is output. The motor provides power when the external load of the vehicle is small relative to the starting and acceleration working conditions. At this time, the solenoid valve switch is closed and the hydraulic system does not work. When the vehicle is braking, the regenerative braking energy is converted into hydraulic energy and recycled into the HPA. The remaining energy is converted into electrical energy through the generator and stored in the battery.

Figure 1 Specific structure of the MEH-PCEV

3 Design and modeling of fuzzy controllers

Fuzzy logic control strategy is also a rule-based control strategy. It does not rely on an exact mathematical model,

and the control rules are mainly based on engineering experience. The strategy has a strong robustness to the parameter changes of the controlled object and a strong ability to exclude the external disturbances. Therefore, fuzzy logic energy control strategies have shown promising applications in the field of hybrid vehicles [31-34]. The control strategy consists of three parts: fuzzification, fuzzy inference, and defuzzification. The composition of the fuzzy controller is demonstrated in Fig. 2.

Figure 2 Composition of the fuzzy controller

3.1 Fuzzification of Precise Quantities

Fuzzy conclusions are generated by reasoning operations on values using fuzzy logic [35]. Therefore, the first step is to convert the exact input quantities into fuzzy values, which is the fuzzification of precise quantities. According to the driving cycle situation and the rule control strategy, the vehicle speed (v) and the pressure difference of the accumulator (Δp) are designed as the system's input variables. Eq. (1) represents the pressure difference equation of the accumulator. First, the input variables of the processing system should be discretized. Second, the linguistic variables are determined. Generally, the symbols "M" and "B" can be used to describe them. In this paper, the fuzzy set of v is {NB, NS, ZO, PS, PB}, and the fuzzy domain is [0, 25]. {NB, NS, ZO, PS, PB} is the fuzzy set of Δp , and [0, 350] is its fuzzy domain. NB represents negative large, NS represents negative small, ZO represents zero, PS represents positive small, and PB represents positive large. Ultimately, this paper chooses the Gaussian shape's affiliation function, which can be expressed by Eq. (2). Fig. 3 and Fig. 4 indicate membership functions of input variables, respectively.

$$\Delta p = \text{PHPA} - \text{PLPA} \quad (1)$$

$$f(x, \sigma, a) = e^{-\frac{(x-a)^2}{2\sigma^2}} \quad (2)$$

where PHPA represents the pressure of the high pressure accumulator. The pressure of the low pressure

accumulator is PLPA. a is used to determine the center of the function and σ is used to determine the width of the curve.

Figure 3 Membership function of “v”

Figure 4 Membership function of “Δp”

3.2 Fuzzy Inference and Rules

Fuzzy control rules are the core of the fuzzy controller [36]. The purpose of fuzzy rules is to achieve conversion between input and output variables. In the process of establishing fuzzy control rules, when the system has a large error, a larger control amount is used to eliminate the error as soon as possible. When a smaller error occurs in the system, an appropriate control amount is used to prevent overshooting and maintain system stability [37]. The development of the rules requires abundant experience. Fig. 5 portrays the output map of the fuzzy inference system.

Figure 5 Output map of the fuzzy inference system

3.3 Defuzzification of Fuzzy Quantities

The output quantity derived from the fuzzy controller is a subordinate function or fuzzy subset which reflects the fuzziness of the original control language. A defuzzification verdict is needed for these fuzzy outputs to transform them into an accurate control quantity. Thus, the role of defuzzification is to map the fuzzy set to a definite point [38-39]. The scale factor of electric torque (T_c) is used as the output variable, and the triangle function is selected as the output variable's membership function, as demonstrated in Fig. 6. Its fuzzy set is {NB, NS, ZO, PS, PB}, and the fuzzy domain is [0,1].

Figure 6 Membership function of “ T_c ”

3.4 Modeling of fuzzy controllers

The model is based on the Fuzzy Logic Controller module in Simulink [40-43]. The article inputs the fuzzy controller file or structural data and outputs the desired value through the fuzzy control box as expressed in Fig. 7.

Figure 7 Fuzzy controller module

When the vehicle enters electrodynamic drive mode (ED mode), the vehicle's external load is relatively low. At this time, the traction force only needs to overcome frictional resistance and gradient resistance. Therefore, the acceleration signal (acc) is multiplied by the external characteristic curve of the motor to obtain the motor torque.

$$T \cdot acc = T_m \quad (3)$$

where T_m indicates the actual torque signal of the motor.

Figure 8 Control strategy of the MEH-PCEV

When the vehicle enters into electro-hydraulic drive mode (EHD mode), electric and hydraulic energy together provide power, and their distribution ratio is set to x and $(1-x)$. The torque of the motor is the acceleration signal multiplied by the motor's external characteristic curve. The motor torque at this point is then calculated as the swashplate angle according to the distribution ratio:

$$\beta = \frac{20\pi \cdot T_m}{V \cdot \Delta p} \quad (4)$$

where Δp is the differential pressure between the inlet and outlet of the secondary element. V is the displacement of the secondary element. β indicates the swashplate opening.

Subsequently, it follows from the above equation that:

$$\beta = \frac{T \cdot acc \cdot x \cdot 20\pi}{V \cdot \Delta p} \quad (5)$$

When the hydraulic power cannot meet the power demand, the electric power will provide the power compensation. Motor torque can be calculated by Eq. (6):

$$T_m = T \cdot acc \cdot (1-x) + \left(T \cdot acc \cdot (1-x) - \frac{V \cdot \Delta P \cdot \beta}{20\pi} \right) \quad (6)$$

The electrical torque signal is fuzzy controlled and then

Figure 9 Test equipments: (a) Test vehicle (b) Data tester

Figure 11 Analysis of experimental results: (a) Hydraulic pressure variation (b) Changes in battery SOC (c) electric torque variation (d) vehicle mileage variation

connected to the mode selection module. The fuzzy control strategy models for ED mode and EHD mode are presented in Fig. 8. As can be seen from the figure, based on the regular control strategy, the electrical torque will be output only after fuzzy adjustment.

4 Validation Under Actual Driving Conditions

Typical cycling conditions must be obtained from traffic data on the vehicle's route. In order to construct a realistic vehicle driving cycle, representative roads in Qingdao were selected for further study in this study. By analyzing the utilization rate of each road, geographic information characteristics, and traffic flow of each road, this paper selected representative routes in urban and suburban areas,

mainly passing through densely populated residential areas and densely populated vehicle lots [44-45].

After the route is determined, it is essential to select the appropriate test equipment and check communication status to ensure the accuracy of data collection. Test equipment include GPS sensor, laptop, AM-2600 tester, signal connection cables, stopwatch, and power supply, as demonstrated in Fig. 9.

Table 1 Basic parameters of the MEH-PCEV

Components	Parameters	Value
Vehicle basic parameters	Loaded mass (m)	1206kg
	Frontal area (A)	2.28 m ²
	Rolling resistance coefficient (f)	0.0135
	Coefficient of air resistance (C_D)	0.32
	Wheel width (D)	290mm
	Transmission efficiency (η)	0.85
High pressure accumulator	Work pressure (P)	35MPa
Low pressure accumulator	Volume (L)	35L
	Work pressure (P)	18MPa
	Volume (L)	35L
Battery	Voltage (V_b)	310V
	Maximum power (P_b)	35kW
	Pack capacity (C)	65Ah
Secondary component	Displacement (V)	30ml/r
	Swash-plate opening (β)	$-1 \leq \beta \leq 1$
Motor	Rated power (P_t)	30kW

During data collection, the car will generate noise due to the driver's incorrect operation, vehicle vibration, and the road conditions, which will cause singularities in the data and affect the accuracy of the final experiment. Therefore, for a large amount of data, this paper intercepts 680s of them for analysis. The basic parameters are illustrated in Table 1.

Path following curves are depicted in Fig. 10. After analysis, it can be seen that the actual vehicle speed curve of the MEH-PCEV basically overlaps with the control speed curve. The result illustrates that the strategy is highly reliable in the actual cyclic mode.

Fig. 11 (a) accentuates the oil pressure curves of the high and low pressure accumulators. The pressure curve changes continuously, and the PHPA decreases whilst the PLPA increases. The simulation effects demonstrate that hydraulic power can play a full position in the process of vehicle operation.

Figure 10 Comparison of the vehicle speed

The battery state of charge is a basic indicator of the remaining battery power and plays an essential role in the battery's optimal operation [46-47]. Fig. 11 (b) displays the variation curve of the battery charge. The SOC of the car with an embedded fuzzy control strategy was 86.74%. The battery SOC of pure electric vehicles is 85.70%. 86.69% is the battery SOC based on rule-based control strategy. The vehicle consumes 7.32% less battery than a pure electric vehicle after fuzzy control. Compared with the rule-based control strategy, the fuzzy control strategy reduced the vehicle's battery consumption rate by 1.51%.

The validation results portray that this strategy can substantially improve energy efficiency.

Fig. 11 (c) displays the comparison of electric torque in 3 modes. As can be seen from the figure, both the rule control strategy and the fuzzy control strategy can substantially reduce the vehicle's peak torque. And it can increase the power recovery in a large proportion. In addition, the effect is even more obvious after fuzzy control. The maximum electric peak power is 22.24% lower after fuzzy control compared to pure electric vehicles. Therefore, this strategy can effectively reduce the peak torque and increase the utilization of electrical energy.

Fig. 11 (d) presents the graph of vehicle mileage. The mileage of the vehicle after optimization is 7.53118km. Compared to pure electric vehicles, fuzzy control strategy can effectively increase the vehicle mileage.

5 Conclusion

The article proposed a novel low-energy mechatronics-electro-hydraulic power coupling electric vehicle (MEH-PCEV), which combines a conventional motor and a piston pump/motor into a single unit that converts electrical, mechanical, and hydraulic power into a single unit.

Firstly, a fuzzy logic optimization strategy was proposed for the MEH-PCEV configuration, by taking the electric torque as reference. The state of charge, differential pressure, and energy storage of the battery are monitored in real-time, with the desired speed as the manipulate input signal. Based on the real-time control of the velocity threshold and differential pressure threshold, the fuzzy strategy ensures that the output torque meets the vehicle torque necessities. Electrical torque can be adjusted in real-time during operation in accordance to the scaling coefficient.

Secondly, to verify the accuracy and authenticity of the method, the GPS dynamic data acquisition instrument was assembled on the automobile for data acquisition. Through the verification experiment of actual data, the actual speed curve of MEH-PCEV essentially coincides with the control speed curve, indicating that the path

following accuracy is higher. The energy consumption of the battery charging state diminished via 7.32%, and the electric torque decreased by 22.24%. The results demonstrated that the fuzzy logic strategy can effectively reduce the peak torque and amplify the energy utilization rate.

This technology provides ideas for the future development and optimization of electro-mechanical-hydraulic power coupled electric vehicles. The future work will focus on two areas: a further verification of the MEH-PCEV's management strategy will be unfolded thru the dSPACE platform; a MEH-PCS device will be embedded into the complete vehicle for operational research of the actual vehicle.

6 Nomenclature

Δp	The pressure difference of the accumulator
v	The vehicle speed
a	The center of the function
σ	The width of the curve
T	The motor torque
T_e	The electric torque
T_m	The actual torque signal
acc	The acceleration signal
br	The brake signal
β	The swashplate angle
V	The displacement of the secondary element
f	The rolling resistance coefficient
m	The loaded mass
A	The frontal area
D	The wheel width
C_D	The coefficient of air resistance
η	The transmission efficiency
P	The work pressure of accumulator
L	The volume of accumulator
V_b	The battery voltage
P_b	The battery maximum power
C	The battery pack capacity
P_t	The motor rated power
NB	Negative large
NS	Negative small
Z0	Zero
PS	Positive small
PB	Positive large
NB	Negative large
MEH-PCS	Mechatronics-electro-hydraulic coupling system power
MEH-PCEV	Mechatronics-electro-hydraulic coupling electric vehicle power
PEV	Pure electric vehicle
HPA	High pressure accumulator
LPA	Low pressure accumulator
PHPA	Pressure of the high pressure accumulator
PLPA	Pressure of the low pressure accumulator
EHD	Electro-hydraulic drive
HD	Hydrodynamic drive
MB	Mechanical brake
ERB	Electric regenerative braking
HRB	Hydraulic regenerative braking

ED	Electrodynamic drive
SOC	State of charge
HPA	High pressure accumulators
LPA	Low pressure accumulators

6 Declaration

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Availability of data and materials

The datasets supporting the conclusions of this article are included within the article.

Authors' contributions

The author's contributions are as follows: Tie-Zhu Zhang, Hong-Xin Zhang, and Ji-Chao Hong were in charge of the whole trial; Jian Yang wrote the manuscript; Qing-Hai Zhao and Ze-Wen Meng assisted with sampling and laboratory analyses.

Competing interests

The authors declare no competing financial interests.

Consent for publication

Not applicable

Ethics approval and consent to participate

Not applicable

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