Dynamic Characteristics Research and Energy Efficiency Analysis of Marine Parallel Gas-Electric Hybrid Power System *

SUN Xiao-jun, YAO Chong, SONG En-zhe, ZHANG Feng-lin, BAI Hui-quan, LI Kang-ning

(College of Power and Energy Engineering, Harbin Engineering University, Harbin 150001, China)

Abstract: The solution of the new marine parallel gas-electric hybrid power system was proposed for the defects of poor power and slow dynamic response of natural gas engines alone. The overall efficiency of ship power was enhanced by the rapid response characteristics of the motor. The dynamic characteristics of the new power system were quantitatively analyzed by design-related tests using the three parameters of rising time, peak time and overshoot. The degree of energy efficiency improvement and the optimal working mode were studied under different operating conditions. The results show that the rise time of dynamic response of marine hybrid propulsion system can be reduced to 1/10 with the addition of a reversible motor. The peak time is shortened to 1/2. The overshoot is stable at 5.5%. It fully shows that the reversible motor can effectively make up for the poor dynamic response of natural gas engine and further verifies the feasibility and effectiveness of the new hybrid power system. Through energy efficiency analysis, the optimal working mode under different working conditions is obtained. It provides theoretical support for energy matching optimization and energy management strategy design.

Key words: Natural gas engine; Hybrid power; Marine; Dynamic characteristics; Energy efficiency

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船舶并联气电混合动力系统动态特性研究与能量效率分析

孙晓军，姚 崇，宋恩哲，张风林，白慧泉，李康宁

（哈尔滨工程大学 动力与能源工程学院，黑龙江 哈尔滨 150001）

摘 要：针对天然气发动机单独使用动力性能较差、动态响应较慢的缺陷问题，提出新型船舶并联气电混合动力系统解决方案，通过电机快速响应特性来提升船舶动力整体效率；设计相关试验，利用上升时间、峰值时间和超调量三个参数对新型动力系统的动态特性进行定量分析，研究不同工况下能量效率提升程度和最优工作模式。研究表明：可逆电机的加入将船舶混合推进系统的动态响应上升时间缩短至1/10，峰值时间缩短至1/2，超调量稳定在5.5%；充分说明可逆电机有效弥补天然气发动机的动态响应差的问题，进一步验证新型动力系统的可行性和有效性；通过能效分析给出不同工况下的最优工作模式，为能量匹配优化、能量管理策略设计等提供理论支撑。

关键词：天然气发动机；混合动力；船舶；动态特性；能量效率

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作者简介：孙晓军，博士生，研究领域为船舶混合动力能量管理。

通讯作者：姚 崇，博士，副教授，研究领域为船舶混合动力系统能量管理系统开发。

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1 Introduction

The shipping industry is under enormous pressure to reduce its environmental impact due to the increasingly stringent environmental regulations[1-2]. Many scholars used exhaust gas recirculation (EGR) and selective catalytic reduction (SCR) to reduce emissions from marine diesel engines, which were difficult to meet during the overall operating cycle[3-5]. The use of clean energy and multi-power source coupling operation of ship power systems has become a new research field. Fan et al.[6] put forward the marine hybrid power system to make full use of the complementary advantages of multi-energy. Energy management enabled the engine to work in an efficient area to achieve energy-saving down drains. The above system used a fast dynamic response motor as the second power source. It was suitable for in-river vessels, such as tugboats and ferries, that were frequently required to propulsion and operate within emission limits[7].

Lebedevas et al.[8] confirmed that tugboats using natural gas instead of diesel fuel could reduce NO_x emissions by 78%. Gokalp[9] proposed exergy to analyze the emission reduction effect on the tugboat, using mixed kerosene fuel. The experimental results show that CO_2 can be reduced. However, high exhaust temperature leads to higher NO_x emissions. Kifune et al.[10] researched the correlation between different control methods and energy efficiency in order to apply energy storage systems to tugboats. It is clearly stated that reducing the energy loss of the clutch helps to improve the efficiency of the hybrid power system propulsion system. Zhu et al.[11] conducted a simulation analysis on the best operating performance of a tugboat equipped with a hybrid power system and a conventional tugboat. Zhen et al.[12] developed an accurate solution method based on the branch price method to plan the operating time of the tug. Krecl et al.[13] analyzed the influence of environmental conditions on the evolution of ferry engine failures. Balestra et al.[14] established an energy transformation assessment model for hybrid ferries equipped with fuel cells and batteries. The validity of the model was evaluated using the actual case. Mannarini et al.[15] researched that ferries were often partially loaded on short-haul routes. The Center for Environmental Research and Technology Engineering at the University of California conducted an emission assessment of hybrid tugboats in 2010. The report points out that diesel-electric hybrid tugs saved 5% of oil compared with conventional tugs[16]. Power system updates were most common for hybrid power systems with energy storage systems[17]. The economy and feasibility of a wide range of hybrid drive systems were analyzed and validated by Völker[18]. It can be concluded from the literature that the economy and emissions of traditional power systems of types such as tugboats are improved by means of clean fuel replacement or multi-power source drive. However, there are few researches on the energy efficiency and energy management of the parallel hybrid power of ships that use the advantages of the engine's clean alternative energy and the rapid response of the motor. To further broaden the research field, the parallel hybrid power system, combined with the natural gas engine and reversible motor, is used as the research object to carry out related research.

A new type of marine parallel gas-electric hybrid power system is proposed to compensate for the shortcomings of the natural gas engine, which alone uses poorer power and slower dynamic response. In order to verify the effectiveness and feasibility of the proposed scheme, the following work is carried out. Firstly, the topological structure and working mode of the new parallel gas-electric hybrid power system are described in detail. Secondly, based on the energy flow simulation model, the dynamic characteristics of the new power system are studied to verify the effectiveness of the motor's poor dynamic response to the natural gas engine and low load emission difference. Finally, in order to quantify the energy efficiency of the marine gas-electric hybrid power system, the optimal working mode under different working conditions is given through the system energy efficiency analysis.

2 Method

2.1 System topology

The marine parallel gas-electric hybrid power system was mainly composed of the natural gas engine, reversible motor, energy storage system, clutch, gearbox, power conversion device, etc. The power conversion device included mostly the DC/DC converter, DC/AC inverter, and AC/DC rectifier. The topological structure of the gas-electric hybrid power system was shown in Fig.1. The main parameters of the power sources were listed in Table 1.

Table 1　Main parameters of power source

Major equipment	Parameter	Detailed
Natural gas engine	Model	YC6K295LN-C30
	Rated power/kW	218
	Rated speed/(r/min)	1500
	Overload power/kW	240
	Overload speed/(r/min)	1548
Reversible motor	Rated power/kW	75
	Rated speed/(r/min)	1500
	Rated torsion/(N·m)	478
	Rated voltage/V	380
	Rated current/A	141.7
Energy storage system	Model	$LiFeO_4$
	Rated power/kW	102.4
	Rated voltage/V	512
	Energy storage/(kW·h)	126.26
	Capacity/(A·h)	250

2.2　Working mode and energy flow path

The marine parallel gas-electric hybrid power system can change the operating conditions of the natural gas engine and improve the system's response speed by adding a reversible motor. According to the demand power and the state of the energy storage system, the marine parallel gas-electric hybrid power system was divided into four working modes, namely mechanical propulsion mode (MP), motor propulsion mode (PTH), mechanical propulsion charging mode (PTO) and hybrid propulsion mode (Boost), as shown in Fig.2.

The MP was shown in Fig.2(a). Clutch 1 was connected, and only the natural gas engine was in the working state. The reversible motor only works when the demand power of the ship changes greatly, which was used to make up for the natural gas engine's dynamic response. A reversible motor gradually stopped working after entering a stable working condition, and the natural gas engine drove the propeller independently. The PTH was shown in Fig.2(b). Clutch 2 was connected. Only the motor worked at this time. The natural gas engine was not working. The reversible motor drove the propeller through the energy storage system. The PTO was shown in Fig.2(c). Clutch 1 and Clutch 2 were connected. Both the natural gas engine and the reversible motor (generator state) were in the working state. The natural gas engine drove the propeller. The reversible motor (generator state) was driven by the natural gas engine's residual power to generate electricity for the energy storage system. The energy storage system was in charging mode. The Boost was shown in Fig.2(d). Both Clutch 1

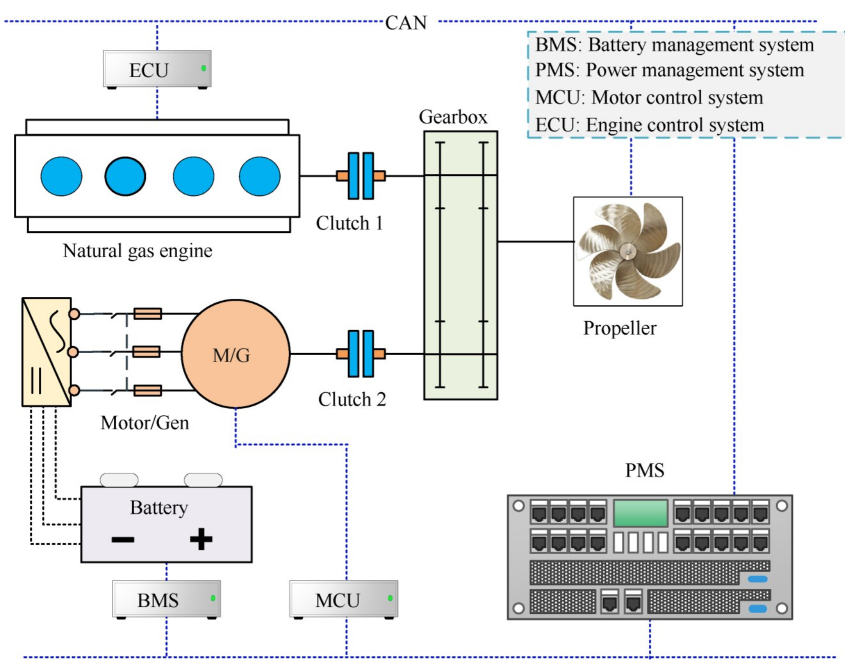


Fig. 1　System topology

and Clutch 2 were connected. Natural gas engine and reversible motor were in operation. Most of the ship's demand power was outside the external characteristic curve of the natural gas engine. The natural gas engine can not meet the demand power of the ship, and the reversible motor compensates the insufficient power. Simultaneously, the reversible motor can also make up for the dynamic response of the natural gas engine in real-time. The energy storage system was in discharge mode. In Fig.2, the green arrow is used to illustrate the process of energy flow in each mode.

3　Results and discussion

3.1　Dynamic characteristics analysis

3.1.1　Experimental design

Aiming at the natural gas engine's defects, such as slow dynamic response and low load efficiency, the compensation effect of the reversible motor on the natural gas engine and its influence on the dynamic characteristics of the power system are analyzed by numerical ener-

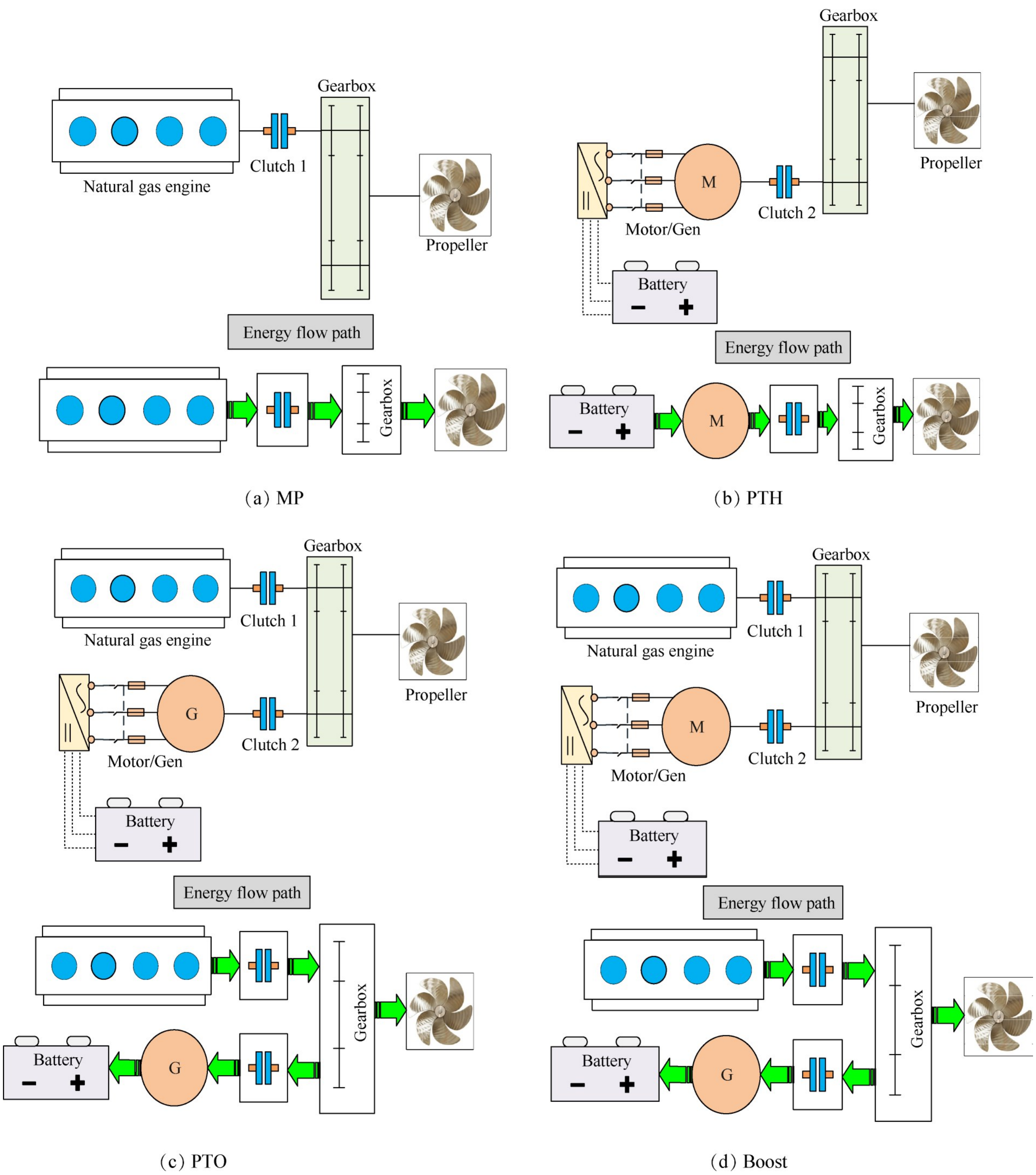


Fig. 2　System working mode and energy flow path

gy flow model.

Georgescu et al.[19] explained the maximum load acceptance of gas engines for maritime applications and set the demand load increment to 30% based on this. Relevant working conditions are designed for research and analysis, as shown in Table 2. In the column of motor participation, 1 means participating and 0 means not participating. The initial power in the Table 2 refers to the current operating output power of the hybrid power system. The target power refers to the working power of the hybrid power system in the following process.

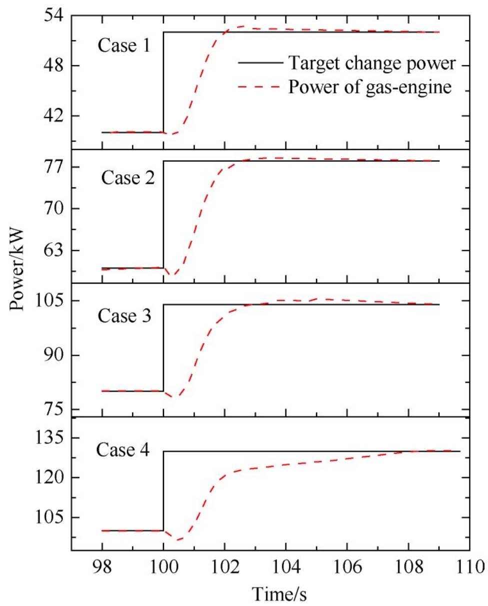
3.1.2 Experimental analysis

The experimental analysis and research are based on the design conditions in Table 2, and the dynamic response changes are shown in Fig. 3~6. When the target power demand of the system suddenly increases, the output power of the natural gas engine will decrease to varying degrees. When the initial working power of the system is higher, the time required for the natural gas engine to reach the preset target output power is longer. After the system comes to the predetermined target power, the power output fluctuation becomes more evident. When the reversible motor is involved, the overall dynamic response speed of the system is significantly improved. When the natural gas engine' s output power cannot reach the predetermined output power value, the reversible motor can accurately compensate through dynamic coordination. From the above analysis, it can be concluded that the high output power fluctuation of the natural gas engine can be well suppressed when the reversible motor is involved. It can eliminate the instability of the natural gas engine at low power output.

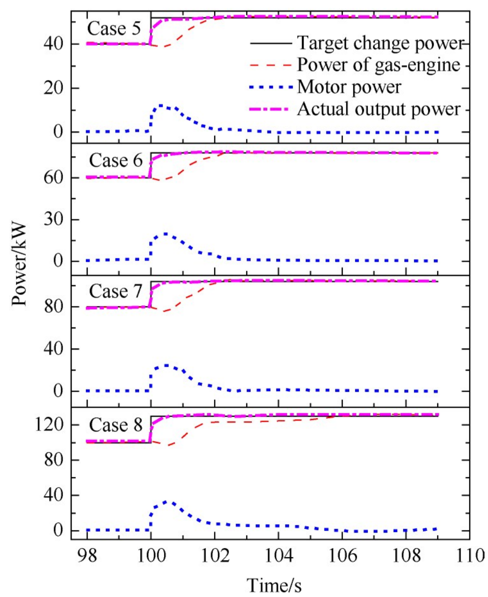
To more intuitively describe the dynamic response characteristics reflected in Fig. 3~6, three parameters, rise time(t_r), peak time(t_p), and overshoot(δ), are adopted to visualize the dynamic characteristics. The t_r refers to the time it takes for the power increase to rise from 0.1 times to 0.9 times. The power increase refers to the difference between the initial power and the target power. The t_p refers to the time from the initial power to

Table 2 Selection of system dynamic response conditions

No.	Initial power/kW	Target power/kW	Speed/(r/min)	Motor participation	No.	Initial power/kW	Target power/kW	Speed/(r/min)	Motor participation
1	40	52	900	0	23	120	156	1300	0
2	60	78	900	0	24	140	182	1300	0
3	80	104	900	0	25	40	52	1300	1
4	100	130	900	0	26	60	78	1300	1
5	40	52	900	1	27	80	104	1300	1
6	60	78	900	1	28	100	130	1300	1
7	80	104	900	1	29	120	156	1300	1
8	100	130	900	1	30	140	182	1300	1
9	40	52	1100	0	31	40	52	1500	0
10	60	78	1100	0	32	60	78	1500	0
11	80	104	1100	0	33	80	104	1500	0
12	100	130	1100	0	34	100	130	1500	0
13	120	156	1100	0	35	120	156	1500	0
14	40	52	1100	1	36	140	182	1500	0
15	60	78	1100	1	37	160	208	1500	0
16	80	104	1100	1	38	40	52	1500	1
17	100	130	1100	1	39	60	78	1500	1
18	120	156	1100	1	40	80	104	1500	1
19	40	52	1300	0	41	100	130	1500	1
20	60	78	1300	0	42	120	156	1500	1
21	80	104	1300	0	43	140	182	1500	1
22	100	130	1300	0	44	160	208	1500	1

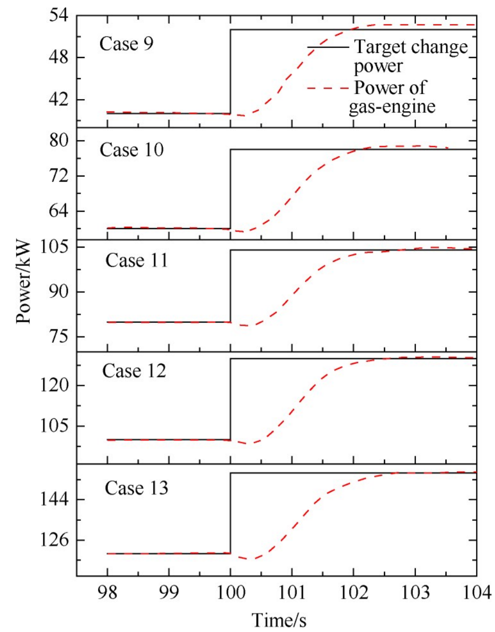


(a) Mechanical propulsion mode

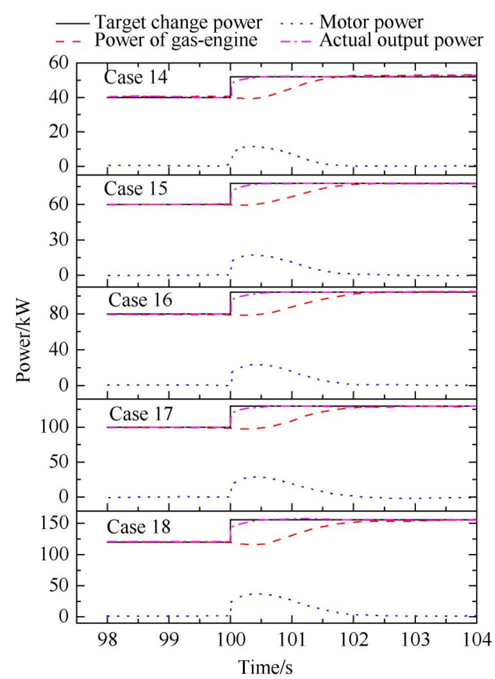


(b) Hybrid propulsion mode

Fig. 3 Dynamic response at 900r/min



(a) Mechanical propulsion mode

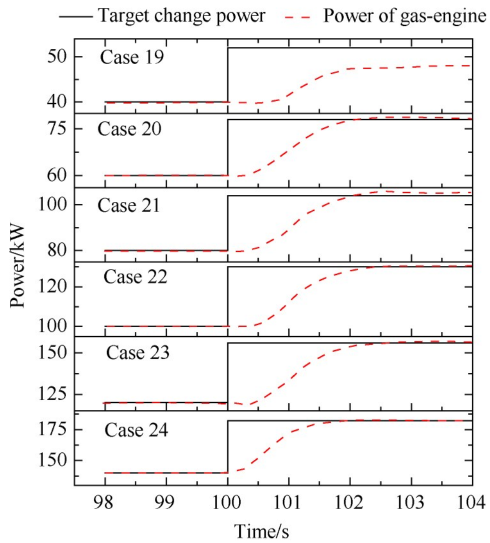


(b) Hybrid propulsion mode

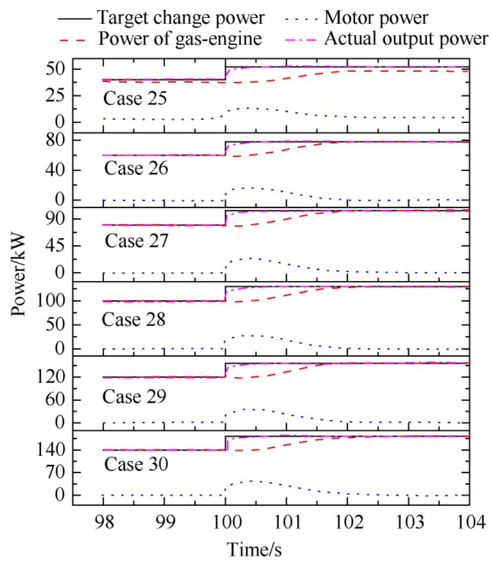
Fig. 4 Dynamic response at 1100r/min

the first peak when the target power is exceeded. The δ refers to the ratio between the maximum power offset and the difference between the initial power and the target power. When the demand power suddenly increases by 30%, the dynamic response performance index of the hybrid power system is shown in Fig.7~9.

The following conclusions are obtained by the t_r of the dynamic response of the system. In the mechanical propulsion mode, t_r is mostly more than 2s. When the speed is 900 r/min and 1100 r/min, t_r increases with the initial power increase. At the speed of 1300r/min and 1500r/min, t_r decreases first and then increases. When the initial power is 40kW, the t_r is abnormal due to the natural gas engine's low efficiency at high speed and low load. The rise time required for unit power increase gradually decreases as the initial power increases. It shows that the greater the initial power of the system at the same speed, the more sensitive it is to resist load disturbances, as shown in Fig.7(a). When the reversible motor is involved, the t_r of the hybrid power system is about 0.2~0.3s, and the duration is shortened to 1/10

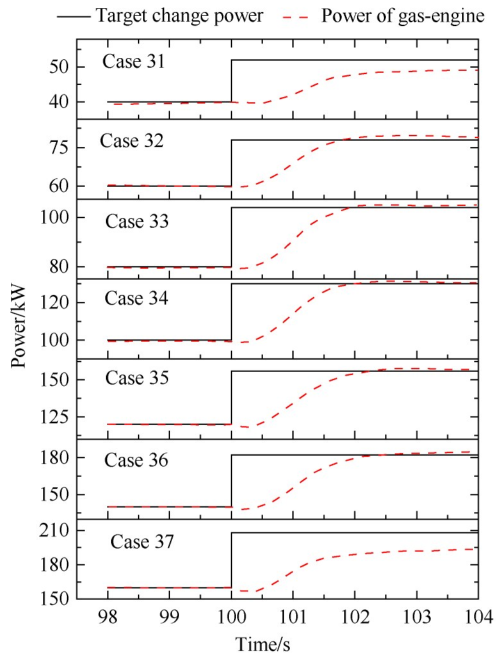


(a) Mechanical propulsion mode

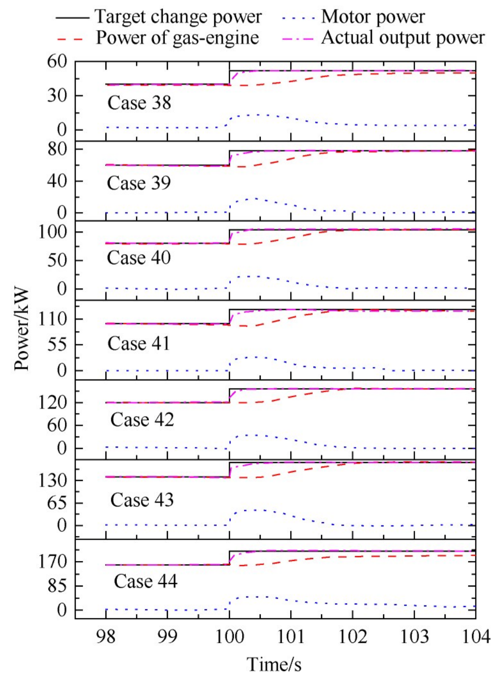


(b) Hybrid propulsion mode

Fig. 5 Dynamic response at 1300r/min



(a) Mechanical propulsion mode



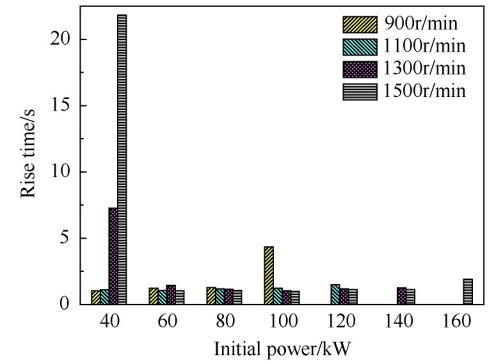
(b) Hybrid propulsion mode

Fig. 6 Dynamic response at 1500r/min

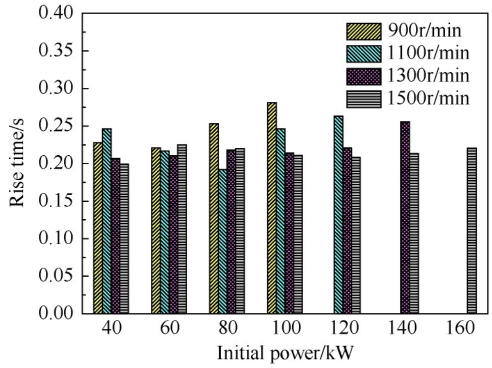
of the original. The t_r of the hybrid power system is not affected by the initial power and system speed, which shows that the reversible motor can make up for the defect of the slow dynamic response of the natural gas engine and improve the sensitivity of the hybrid power system, as shown in Fig.7(b).

The following conclusions are obtained by the t_p of the dynamic response of the system. In the mechanical propulsion mode, the speed and initial power greatly influence the dynamic response peak time t_p. When the dynamic response initial power is 100kW and above, it gradually decreases as the speed increases. The faster the speed, the faster the parallel gas-electric hybrid power system's dynamic response, as shown in Fig.8(a). When the reversible motor is involved, the t_p of the hybrid power system's dynamic response is about 1.1~1.3s, and the duration is shortened to about 1/2 of the original. The dynamic response speed of the hybrid power system is faster, as shown in Fig.8(b).

The following conclusions are obtained by the δ of the dynamic response of the system. In the mechanical propulsion mode, when the initial power is the same, the overshoot increases with the increase of speed,

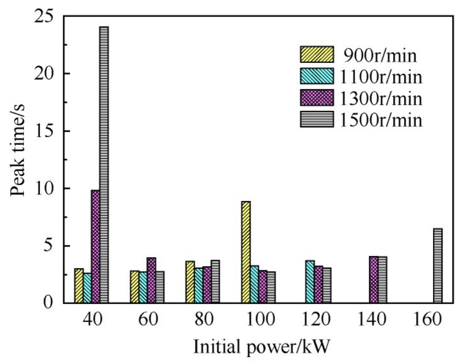


(a) Mechanical propulsion mode

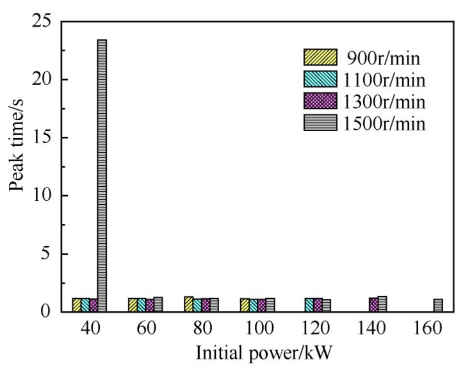


(b) Hybrid propulsion mode

Fig. 7 Rise time of system dynamic response



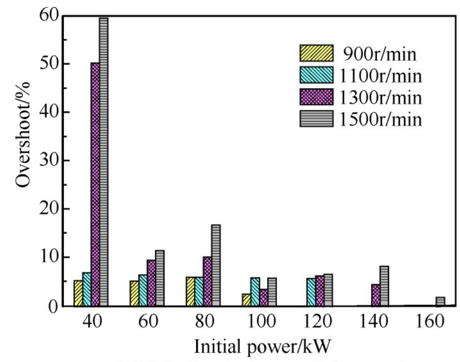
(a) Mechanical propulsion mode



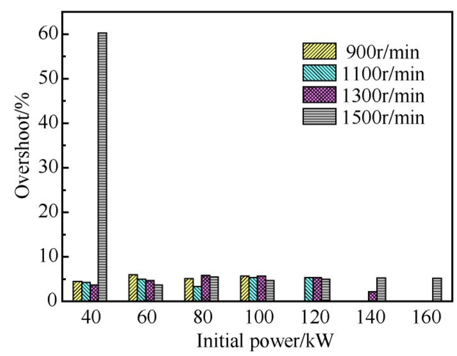
(b) Hybrid propulsion mode

Fig. 8 Peak time of system dynamic response

which indicates that the higher the hybrid power system speed, the lower the hybrid power system stability, as shown in Fig. 9(a). When the reversible motor is involved, the dynamic response overshoot δ of the hybrid power system is mostly concentrated in 5.5%, which indicates that the hybrid power system's stability is enhanced, as shown in Fig.9(b).



(a) Mechanical propulsion mode



(b) Hybrid propulsion mode

Fig. 9 Overshoot of system dynamic response

Through the above dynamic characteristics analysis, it can be concluded that the fast response of the reversible motor can make up for the inadequate dynamic response of the natural gas engine so that the output power of the hybrid power system can quickly meet the demand power. In low load areas, the motor's high-efficiency working area can replace the natural gas engine, which can effectively avoid the defect of poor emission performance of the natural gas engine at low load. Compared with the traditional power mode, it can significantly improve energy utilization efficiency. In order to quantify the marine parallel gas-electric hybrid power system's energy efficiency, the energy efficiency of the system under different working modes is analyzed.

3.2 Energy efficiency analysis

3.2.1 Selection of working conditions

The operating conditions of the natural gas engine and reversible motor are selected to study the energy efficiency change law of each mode of the ship propulsion system, as shown in Table 3 and Table 4.

Table 3 Operating parameters of natural gas engine

Speed/(r/min)	Power of natural gas engine/kW					
1500	218	200	160	120	80	40
1300	—	—	160	120	80	40
1100	—	—	—	120	80	40
900	—	—	—	—	80	40
700	—	—	—	—	80	40

Table 4 Operating parameters of reversible motor

Speed/(r/min)	Power of reversible motor/kW				
1500	75	60	45	30	15
1300	75	60	45	30	15
1100	75	60	45	30	15
900	75	60	45	30	15
700	—	—	45	30	15
500	—	—	—	30	15
300	—	—	—	—	15

3.2.2 Energy efficiency and optimal mode

The energy efficiency distribution under different working modes is analyzed by numerical energy flow model, as shown in Fig.10. In MP, the natural gas engine's energy efficiency is the lowest at low load, and the energy efficiency increases gradually with the increase of output power of hybrid power system. When the demand power is the same, the lower the hybrid power system speed, the higher the energy efficiency is. When the demand power is 120kW, and the speed is 900 r/min, the energy efficiency of the hybrid power system reaches the highest, which is 37.2%, as shown in Fig.10 (a). In PTH, the system's energy efficiency increases first and then decreases with the increase of speed. The maximum efficiency is at a demand power of 30kW. When the output power of hybrid power system is the same, the system's speed is inversely proportional to the energy efficiency, as shown in Fig 10(b). When the system's output power of hybrid power system is the same in PTO, the lower the speed, the higher the energy efficiency. When the speed and output power of the natural gas engine is the same, the more power the ship needs, the higher the energy efficiency of the system, as shown in Fig.10(c). When the output power of the natural gas engine is the same in Boost, the system speed is inversely proportional to the energy efficiency of the system. When the demand power is the same, the natural gas engine's output power is proportional to the high energy efficiency of the system. When the natural gas engine's output power is small, the energy efficiency of the system increases with the increase of the output

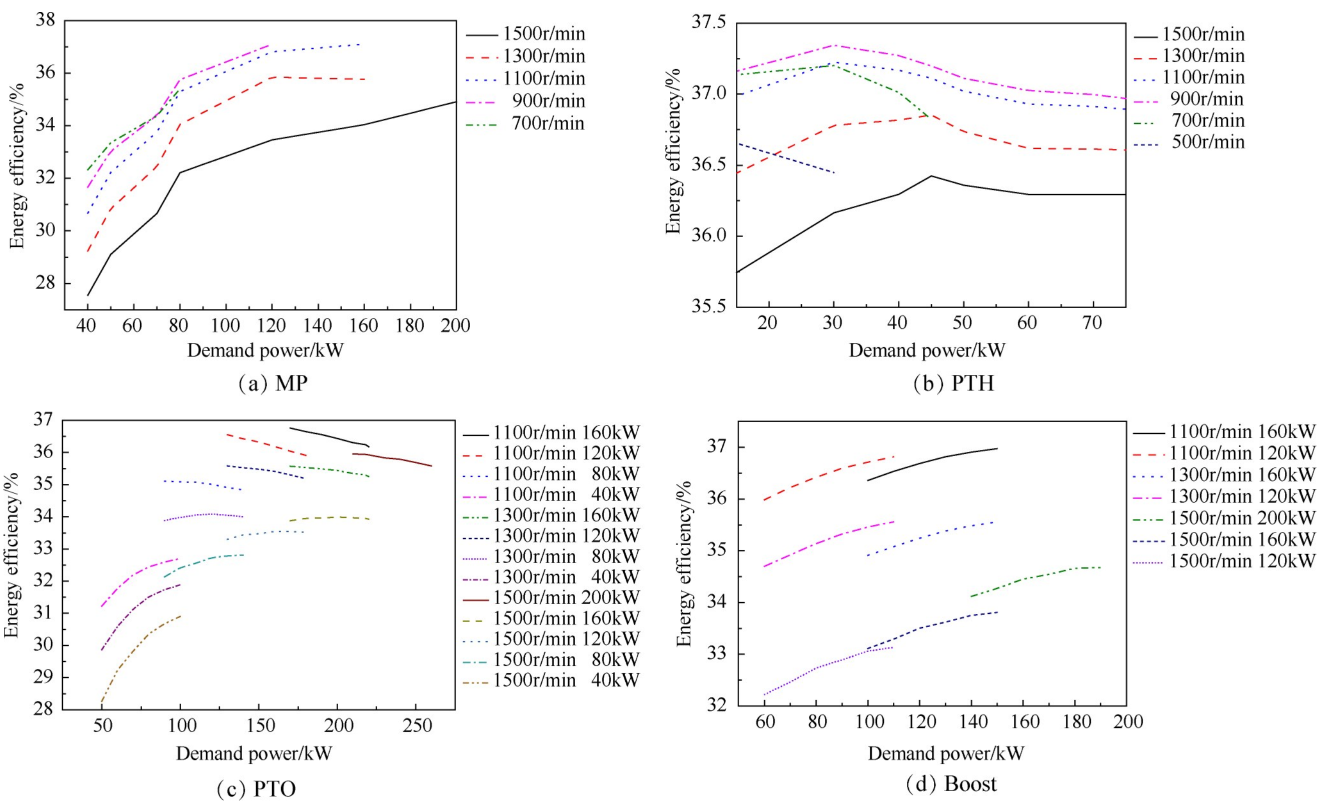


Fig. 10 Energy efficiency of different working modes

power of the reversible motor, as shown in Fig.10(d). In the legend of Fig.10, power refers to the output power of the natural gas engine.

For the sake of more clearly defining the optimal working mode of the hybrid power system under different demand power, the energy efficiency distribution diagram of 1100r/min, 1300r/min, and 1500r/min is analyzed, as shown in Fig.11. Fig.11 shows that the system applies to PTH, PTO, MP, and Boost at lower load, low load, high load, and higher load, respectively. It shows that the marine hybrid power system can avoid the bad condition of the natural gas engine under high speed and low load. In PTH, the working range of 1100r/min is wider than that of 1500r/min. The energy efficiency of hybrid propulsion mode is higher at high speed.

To further describe the effectiveness of the hybrid power system scheme, the dynamic response improvement ability of the hybrid power system compared with the traditional ship is analyzed by combining with the dynamic characteristics research, as shown in Fig.12. It can be seen from Fig.12 that when the demand power is 100kW and the speed is 1300 r/min, the improvement efficiency is low because the natural gas engine is already on the high efficiency external characteristic curve. At this time, the power of natural gas engine has met the demand power. When the demand power is 40kW, the energy efficiency improvement rate of hybrid power system is the highest at 1300 r/min and the lowest at 1500 r/min. At 1300 r/min, the power of the energy storage system is enough to meet the requirements of the reversible motor. At 1500 r/min, the energy of the energy storage system is not enough to support the demand power, and the reversible motor works in part load. Meanwhile, the engine works in the high speed and low load area, and the efficiency is low, which leads to the low efficiency of dynamic response improvement. To achieve the optimal working effect of hybrid power, energy management strategy combined with dynamic response promotion rate distribution is required for comprehensive analysis to give the best operation plan.

Through the analysis of the energy flow of the hybrid power system, the corresponding working mode when the energy efficiency is the best can be obtained, as shown in Table 5. The above analysis further verifies the conclusions of Fig.10~12.

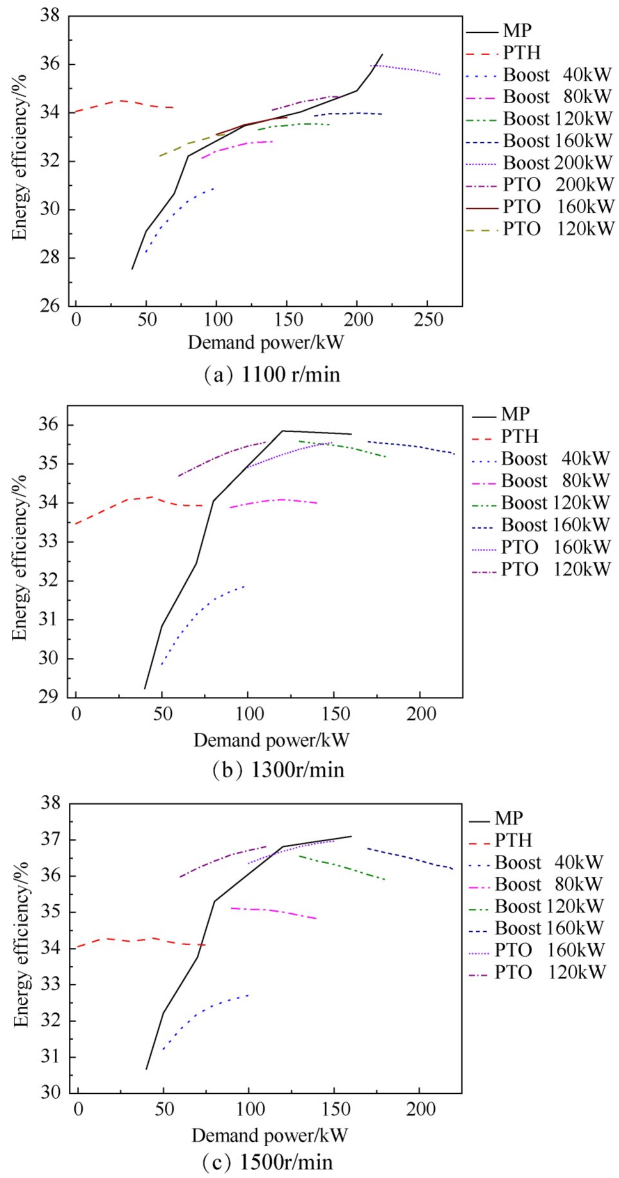


Fig. 11　Energy efficiency distribution of different modes at different speeds

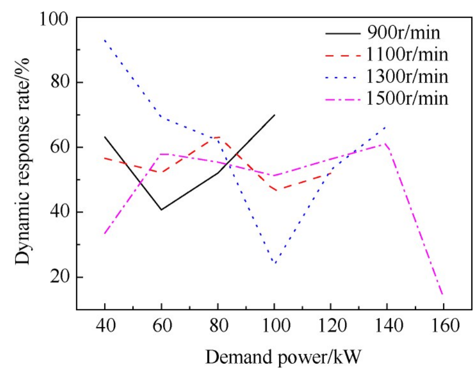


Fig. 12　Dynamic response change graph

Table 5 Optimal energy efficiency of the parallel gas-electric hybrid propulsion

No.	Ship power demand/kW	Working mode	Speed/(r/min)	Output power of natural gas engine/kW	System energy efficiency/%
1	10	PTH	700	0	34.359
2	15	PTH	900	0	34.442
3	30	PTH	900	0	34.612
4	40	PTH	900	0	34.544
5	45	PTH	900	0	34.476
6	50	PTH	900	0	34.396
7	60	PTO	1100	120	35.985
8	70	PTO	1100	120	36.222
9	75	PTO	1100	120	36.321
10	80	PTO	1100	120	36.420
11	90	PTO	1100	120	36.593
12	100	PTO	1100	120	36.713
13	110	PTO	1100	120	36.815
14	120	MP	900	120	37.101
15	130	MP	1100	130	36.885
16	140	MP	1100	140	36.956
17	150	MP	1100	150	37.027
18	160	MP	1100	160	37.099
19	170	Boost	1100	160	36.759
20	180	Boost	1100	160	36.647
21	190	Boost	1100	160	36.555
22	200	Boost	1100	160	36.434
23	210	Boost	1100	160	36.302
24	218	Boost	1100	160	36.240
25	220	Boost	1100	160	36.178
26	230	Boost	1500	196	35.834
27	240	Boost	1500	196	35.786
28	250	Boost	1500	196	35.688
29	260	Boost	1500	196	35.582

4 Conclusion

The following conclusions are presented through research:

(1) Through the research on the dynamic characteristics of marine parallel gas-electric hybrid power system, it is found that the reversible motor can effectively resist external interference and maintain the system stability. The addition of the reversible motor shortens the dynamic response rise time of the marine parallel gas electric hybrid power system to 1/10. The peak time is reduced to 1/2. The overshoot is stable at 5.5%.

(2) Through energy efficiency analysis, the working range of the operating mode is quantitatively optimized. In the case of different output power requirements, the analysis can select PTH in the low load area, Boost in the high load area, MP in the higher load area, and PTO in the lower load area. Avoid low load characteristics of the natural gas engine at low load and reduce the natural gas engine's installed capacity at high load. At low load, if PTO is used, the natural gas engine can work in high-efficiency areas.

(3) The conclusions drawn from the system dynamic characteristics and energy efficiency analysis show that the proposed marine parallel gas-electric hybrid power system solution is effective and feasible, which further provides a theoretical basis for the design of system mode switching and energy management.

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