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DEVELOPMENT OF "4E" LEVELRIVER-SEA-GOING SHIP

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ABSTRACT

In order to effectively promote the construction of the Yangtze River economic belt, it has become China's national strategy to vigorously develop the river-sea-going transportation. In the present paper, theoretical analysis, numerical simulation and model test are combined together to develop flat-type river-sea-going ship which is characterized with larger loading capacity, lower fuel consumption, better performance on energy-saving and environmental-friendly, excellent economy and higher transportation efficiency. Key technologies on hydrodynamic performance, structural safety, energy-saving technology and green ship technology are investigated to develop the river-sea-going ship. The developed "4E" level ship has great significance to the implementation of national strategic deployment.

Keywords: Energy-saving, Environment-friendly, high performance ship, "4E" level ship, flat-type river-sea-going ship.

INTRODUCTION

The Yangtze River is a natural channel connecting national strategies such as coastal opening in eastern China, rising of central China and developing of western China. It supports the logistics, comprehensive transportation system, economic and social development of the seven provinces and two cities within its valley. At present, the Chinese Government has established national development strategy for the golden waterway of Yangtze River. Relying on the golden waterway running through east and west, it will drive the development of the hinterland locating at the middle and upper reaches of Yangtze River and promote the orderly undertaking of the industrial transfer from the eastern coastal areas to the central and western regions so as to create a new economic belt for the Chinese economy. In the traditional transportation system, the cargoes are transported from deep-sea port such as Ningboor Zhoushan to Nanjing or Ma'anshan via sea-going vessels, and then transported to the middle and upper reaches such as Wuhan by inland ships. Such kind of transportation not only takes quite a long time and increases operating cost, but also leads to cargo damage and shortage. It is hard to improve the transportation efficiency which cannot satisfy the requirement of the economic and social development of the Yangtze River Valley. On the June 11, 2014, the Premier instructed to deploy comprehensive traffic corridor, create the Yangtze River economic belt, promote the standardization of inland vessels, research and popularize river-sea-going ships, and encourage developing energy-saving and environment-friendly ships at the executive meetings of the State Council.

In 2016, the Yangtze River freight volumes exceeded 2.3 billion tons which persists the first rank for 12 years in the world's inland river [1]. Large-scale ships are required by the development of the present economy and society. Such ships have higher transportation efficiency, lower energy consumption and better economic so that they have competitive advantage in the harsh shipping market. However, as the Yangtze River is the natural navigable waterway, ship length and draft are limited, and depth is restricted by the clearness height of bridge. The possible way to actualize large-scale ships is to increase ship's width hand develop flat-type ship which can adapt to natural condition of the Yangtze river [2] The rapidity, navigability and structural safety of flat-type vessel have always been the key technologies for the academia and industry.

Based on extensive shipping market investigation, the flat-type river-sea-going ships which can adapt to the channel of Yangtze River and the corresponding port condition are developed through economic analysis and research on navigability and structural safety. Theoretical analysis, numerical simulation and model test are combined together to solve the key technologies on resistance performance of flat-type ship with shallow water, structural safety in the sea, energy-saving technology and green ship technology [3]. The developed ship having the characteristics of Energy-saving, Environment-friendly, Economy and Efficiency is considered as "4E" level river-sea-going ship.

1. Energy-saving: It is the key technology for the developing ship. Fuel consumption is decreased effectively by applying advanced technology to improve the competitiveness of the production.
2. Environment-friendly: It is the demand of social sustainable development.
3. Economy: It is the foundation for survival and development. It helps to occupy the shipping marketing the present harsh situation.
4. Efficiency: It is fundamental for efficient transportation to promote the implementation of national strategy.

The development of the "4E" level river-sea-going ship has great significance for the implementation of the national strategies such as the construction of the Yangtze River golden waterway, the strategy of rising of midland, the construction of Yangtze River shipping center and river-sea-going transportation service center.

THE DEVELOPMENT THOUGH OF "4E" LEVEL RIVER-SEA-GOING SHIP

CURRENT SITUATION OF RIVER-SEA-GOING SHIP

The current river-sea-going ships navigating in the Yangtze River are designed according to both the rules for sea-going vessels and the rules for inland ships which lead to the heavy structural weight. The hydrology and weather conditions of the river-sea-going navigating route are not comprehensively considered so that the ship has neither the advantage of sea-going vessel, nor the inland ship. With the improvement of the channel condition of Yangtze River and the loading/unloading capacity of the port, the requirement of large-scale river-sea-going ship is becoming more and more intense. The existing ships cannot satisfy it and be capable of supporting the construction of the "golden waterway".

KEY TECHNOLOGIES OF RIVER-SEA-GOING SHIP

Based on extensive shipping market research, river-sea-going ships are designed through economic analysis, seaworthiness research and structural safety research. Larger loading capacity, lower fuel consumption, energy-saving and environment-friendly, better economy and higher transportation efficiency are considered as objective. The developed ship has the characteristics of Energy-saving, Environment-friendly, Economy and Efficiency, regarding as "4E" level ship.

Comprehensive analysis system: The Yangtze River route is considered as the principal research objective. The freight distribution and the freight market are predicted and analyzed based on the status of the channel and the port condition. Key technology and economic model are researched so as to establish a comprehensive evaluation system on ship performance, economy in all life cycle and environmental effect. The system is adopted to perform comprehensive analyses so that the main dimension of developing ship is determined [4].

Mold line optimization: Numerical simulation and model test are combined together to perform the research on low resistance stem and energy-saving stern. Hydrodynamic performance including rapidity, sea-keeping and maneuverability is comprehensively considered to optimize the mold line [5]. Thus, the green ship with the Energy-saving and Environment-friendly can be designed.

Wake-adaption high efficient propeller design: For flat-type river-sea-going ship, the wake is uneven in both axial direction and radial direction. Circulation theory is used to design the wake-adaption high efficient propeller considering the actual wake distribution. Key technologies such as highly skewed blade, unloading at the tip of blade and anti-cavitation section are considered when the propeller is designed. Rapidity prediction of the designed ship can be performed by model self-propulsion test [6].

Development of energy-saving appendage: The stern wake field of flat-type river-sea-going ship is comparatively complex. The energy-saving appendage is designed by considering pre-rotation in front of the propeller and energy recovery behind the propeller. Theoretical analysis, numerical simulation and model test are combined together to research the energy-saving effect of pre-shrouded vanes, boss cap fins and thrust fin.

Application technology of LNG: Risk analysis on the processes of LNG storage, supplying and usage is performed and assessed. Key technology on LNG supplying system is carried out to obtain the technical design plan which makes it possible to use LNG safely and effectively. Furthermore, gas circuit is imported to collect the gas from spontaneous evaporation in the storage tanks well as the remaining gas in the pipeline during the fuel converting. The steady and dynamic characteristics analysis of LNG dual-fuel Main Engine system is conducted to ensure the stable power supplying.

Integration of energy-saving and environment-friendly technology: Integrated design model for energy-saving and environment-friendly is established taking comprehensive energy management as the principal line and the minimization Energy Efficiency Design Index as the objective. The optimization of main propulsion system, the design of new non-pollution stern tube system and low noise shaft system reperformed to solve the key technologies such as Ship-Engine-Propeller matching, proper selection of Main Engine and generator and smart power station management system.

CHARACTERISTICS OF DEVELOPED RIVER-SEA-GOING SHIP

Large-scale ship satisfies the requirement of the present shipping market which has better economy and higher transportation efficiency. The ship length, depth and draft are constrained by the natural condition of the channel, port and clearness height. So, the developed river-sea-going ship is characterized with flat (lager ratio of breadth to depth), shallow draft and large block coefficient. In the present research, theoretical analysis, numerical simulation and model test are combined to solve the key technologies of flat-type ship form with large block coefficient, energy-saving and emission-reduction. Thus, the flat-type river-sea-going ship with Energy-saving, Environment-friendly, Economy and Efficiency ship is developed. The principal dimension of the developed ship is compared with that of existing ship in Table 1.

Tab. 1. Principal dimension comparison

Item	designed ship	existing ship
Length overall (m)	139.8	137.6
Length between perpendiculars (m)	137.0	133.2
Depth (m)	10.0	10.25
Breath (m)	25.6	22.8
Design draft/Structural draft (m)	5.5 / 6.3	5.5 / 6.25
Loadingcapacity (TEU)	940	810
Design speed (kn)	11.5	11.5
Main Engine power (kW)	2 x 1324	2 x 1470
Crew (Person)	11	14

The numerical tank for rapidity is constructed through the secondary development of commercial CFD software. The parameters on bow type, longitudinal and transversal curvature of the bow, distance between tail fins and pre-rotation angle of tail fin are discussed. Mold line optimization on more than 200 hull forms is carried out in the numerical tank to obtain the flat-type river-sea-going ship form [7]. The optimized mold line shows 8.0 % energy-saving efficiency comparing with the original one when the model test is carried out in the towing tank. Circulation theory is adopted to design wake-adaption high efficient propeller considering the actual wake distribution anti-cavitation and vibration performance. The developed wake-adaption propeller indicates 4.0 %energy-saving improvement comparing with the traditional propeller obtained by propeller design charts through open-water test and self-propulsion test. Flow features of stern in typical loading condition are analyzed and the diversion fins system is installed in the propeller hub in order to improve the quality of incoming flow. Thus, the propeller efficiency can be improved. The optimization of section, angle and installation position of diversion fins are performed to develop the energy-saving appendage in front of the propeller. The energy-saving appendage behind the propeller, for example boss cap fin, is designed to recover the energy loss in radial direction of the propeller. The results of towing tank test indicate that the energy-saving appendages can achieve 3.0 % effect. The compositive management on heat recovery device in Engine room, exhaust gas boiler, fuel conversion device and smart power station system is carried out by energy-saving and environment-friendly integrated management system. The waste heat, idle energy and the fuel with low carbon conversion coefficient are fully utilized to minimum the Energy Efficiency Design Index. The energy-saving effect can reach 5.0% through the integrated energy management system.

The general technology of LNG supplying system, including risk analysis on LNG storage, supplying and usage as well control measures of ineffective dissipation, is investigated. The quantity, pressure and temperature of LNG supplying are determined according to the performance parameters of the Main Engine so that the proper LNG supplying control system and security system are chosen. The process of fuel supplying is analyzed for dual-fuel Main Engine to ensure the fuel conversion automatically. The steady and dynamic characteristics of power system are analyzed to ensure the stable power supplying. When LNG fuel is adopted, the exhaust emission can be remarkably reduced, in which the emission of CO_2 can be reduced by 25%, the emission of NOx can be decreased by 80 % and the SOx•PM can be reduced by 98 %.

The unit cost of transportation is defined as the cost for accomplishing unit transport volume (one standard container)[4)]. It can be expressed as following,

$$C_T = C/Q_T \tag{1}$$

where C_T is the unit cost of transportation, and C is the annual total cost, and Q_T is the annual freight volume. C can be calculated by $Y + F_z$ where Y is the annual operating expenses, and F_z is the depreciation cost, $F_z = (K - L)/N_z$ where K is the investment amount, L is the residual value, N_z is the period of depreciation. Q_T isexpressed as $2f_D \bullet C_D \bullet R_T$ where f_D is the loadingcoefficient, and C_D is the maximum allowable loading capacity, and R_T is the number of annual navigations. Unit cost of transportation of the designed ship is compared with the existing ship in table 2.

Tab. 2. Comparison of unit cost of transportation

Item	designed ship	existing ship
Annual operating expenses Y (ten thousandRMB/year)	600	650
Investment amount K (ten thousandRMB)	5700	5000
Residual value L (ten thousandRMB)	285	250
Period of depreciation N_z (year)	25	25
Depreciation costF_z (ten thousandRMB/year)	216	190
Annual total cost C (ten thousandRMB/year)	816	840
Loading factor f_D	0.60	0.6
Maximum loadingcapacity C_D (TEU)	940	810
Annual navigations R_T (number/year)	25	25
Annual freight volume Q_T (TEU/year)	28200	24300
Unit cost of transportation C_T (RMB/TEU)	289	346
Percentage reduction	16.5 %	

The unit cost of transportation is the principal indicator to evaluate the ship's economic performance. Comparing with the existing ship, the unit cost of transportation of designed ship can be reduced 16.5 %, as shown in Table 2.

The transportation efficiency is the output value (cargo weight multiple transportation distance) through consuming unit energy. So, the transportation efficiency can be expressed as following,

$$\eta = \frac{1}{H_f S_{foc}} \cdot \frac{W_P \cdot V}{P} \tag{2}$$

where S_{foc}: Consumption rate of fuel, g/(kW·h);
H_f: Fuel caloricity, J/kg;
P: Main Engine power, kW;
V: Speed, kn;
W_p: Dead weight of vessel, t.

When comparing transportation efficiency, the same fuel should be adopted to ensure the comparability. The value of H_f shall keep the same one. So, the part of

$$\frac{1}{S_{foc}} \cdot \frac{W_P \cdot V}{P}$$

shall be compared, as shown in Table 3.

Comparing with the existing best performance ship, the designed ship improves 25.6 % in transportationefficiency[4)].

Tab. 3. Comparison of transportation efficiency

Item	designed ship	existing ship
Deadweight,WP (t)	11605	9615
Main Engine power P (kW)	1324	1470
Main Engine number	2	2
Main Engine fuel consumption (g/kW•h)	205	205
Design speed V(kn)	11.5	11.5
$\frac{1}{S_{foc}} \cdot \frac{W_P \cdot V}{P}$	0.246	0.183
Percentage increment of transportation efficiency	25.6 %	

THE DEVELOPMENT OF ENERGY-SAVING MOLD LINE AND APPENDAGE

Theoretical analysis, numerical simulation and model test are combined together to perform the research of hydrodynamic performance on flat-type sea-river-going ship. The hydrodynamic performance of different stem type such as vertical bow, watermelon bow, and bulbous bow is discussed and researched comprehensively considering rapidity, sea-keeping in the sea and inland maneuverability. Both the longitudinal curvature and transverse curvature of the bow are optimized to obtain the vertical bow with lower resistance and better anti-slamming performance [8].

The development of stern line shall consider the propeller inflow and the maneuverability in shallow water. Numerical simulation and model test are carried out for the optimization of the length, distance and shape of tail fins. More than 200 stern lines are calculated to develop the outward rotation twin tail fins with low resistance, low thrust deduction and high propulsion efficiency. Model test demonstrates that the optimized mold line of flat-type river-sea-going ship can achieve about 8.0 % energy saving.

Flow field of river-sea-going ship in typical working conditions is analyzed to obtain the flow details at the location of propeller. Self-propulsion test is carried out in towing tank to get the components of propulsion as well the three-dimensional flow field at the propeller disk. The propeller design platform based on circulation theory is used to conduct the wake-adaption high efficient propeller design considering the efficiency, cavity, vibration and the actual axial and radial wake field. The technologies such as large skewed blade, unloading at the tip of blade and anti-cavitation section are also applied. The open water test and self-propulsion test illustrate that the developed propeller can improve 4.0 % energy saving than traditional one designed by atlas.

The diversion fins, a kind of energy saving device before the propeller, are proposed by analyzing the stern flow field to improve the flow quality so as to improve the propeller efficiency. The best angle and length of diversion fins are determined by considering the pre-whirled flow effect and resistance increment. Furthermore, thrust fins installed on the rudder, a kind of energy saving device behind the propeller, are developed by considering the recycling of circumferential energy loss to improve the propeller efficiency. Thus, the energy saving appendage for flat-type river-sea-going ship is determined by combining diversion fins before the propeller and thrust fins on the rudder. The propeller open water test and self-propulsion test show the proposed energy saving appendage can save energy 3.0 %.

STRUCTURAL LIGHTWEIGHT DESIGN

With the development of global economy, the shipping industry has entered into a new era which requires the larger capacity, higher transportation efficiency and lower emission. The researchers in shipping industry try their best to achieve such objective. It becomes consensus by international maritime the structural lightweight design can improve the transportation efficiency and decrease the emission. Thus, it is meaningful to minimize the structural weight under the premise of the structural safety and reliability.

It is possible for structural lightweight design by performing rational general arrangement design to decrease the external force which is calculated by the difference between gravity and buoyancy under various loading conditions. Structural direct calculation on supporting structures is performed. The lightweight design can be carried out in accordance with the calculation results on the premise of safety and reliability. The structural optimization on typical cross section is conducted to search for lightweight structural configuration.

Theoretical analysis, numerical simulation and model test are combined to analyze and evaluate the structural safety of flat-type river-sea-going ship [9]. According to the wave scatter diagram of navigating route, the long-term prediction of external force acting on the ship hull is carried out to obtain the equivalent design wave height [10]. Wave loads calculation for typical loading condition is performed to obtain the external force acting on the hull with time instantaneous. Then, structural nonlinear response analysis is conducted so that the ultimate strength of ship structure is achieved. Furthermore, the collapse test of ship structures in wave is carried out to obtain the external force subjected to the ship and the ultimate structural strength simultaneously [11]. Thus, the structural safety margin under specific loading condition and wave situation is understood [12].

For river-sea-going ship, the external force in sea part and Inland River is quite different [13]. The research on fatigue characteristic of typical structural joints under variable amplitude force is meaningful to reveal the fatigue mechanism of river-sea-going ship [14]. The fatigue test on longitudinal stiffener crossing the hold and hatch corner under variable amplitude force is carried out to establish the assessment system on fatigue strength. The fatigue research makes the foundation for the safety and reliability of ship structures of river-sea-going ships [15].

Under the premise of structural safety, the structural lightweight design is conducted by the application of lightweight design technology. The structural weight can be reduced, and the ship economy can be improved. The shipbuilding material and the energy consumption can be reduced. Thus, the core competitiveness of China ship products can be improved.

THE DESIGN OF POWER INTEGRATED SYSTEM

Marine power system provides power for ship and determines the ability of ship navigation and operation. Power is generated by Main Engine and transmitted to propeller through driving device and shafting system so as to realize the purpose of ship propulsion. Reasonable design on marine power system can realize the comprehensive energy management so as to decrease the energy consuming effectively and realize the purpose of energy-saving and emission-reducing.

In the present research, the integrated design platform of marine power system is established based on the comprehensive energy management. A set of energy-saving and environmental-friendly management system is adopted to monitor and manage the marine power devices such as the recycling device of heat in engine room, exhaust gas boiler, diesel and LNG conversion device, shaft generator and main generator [16]. Make full use of the ship's residual heat, waste heat, idle energy and give priority to the usage of low-carbon conversion factor fuel so that the energy efficiency design index (EEDI) is controlled to a minimum one. Thus, the marine power design plan for energy-saving and environmental-friendly can be made.

The optimization of stern structures is carried out. The vibration isolation and absorption technology are adopted for installation of Main Engine and shaft system in order to reduce the vibration and noise of propulsion system so that the energy-saving and environmental-friendly can be achieved. Moreover, new type watertight stern tube is used and the optimization of sealing performance is performed to avoid the pollution caused by lubricant oil.

Smart substation management system is proposed to adjust and control the frequency generated by shaft generator and achieve parallel locomotive of diesel generator. The idle energy of Main Engine in underload condition can be transferred to electric power supplying which can reduce or replace the fuel consumption of diesel generator. The carbon emission can be effectively reduced by the above methods [17].

The power integrated system such as integrated design, comprehensive energy management, idle/waste heat usage, vibration isolation and absorption design, water lubrication and smart substation is adopted to manage the energy effectively so that the developed river-sea-going ship can achieve the energy-saving 5.0 %.

APPLICATION TECHNOLOGY OF LNG

The inland waterway takes more than 80 % of the total voyage for the developed river-sea-going ship where both sides are densely populated and economically developed areas. The carbon emission can be reduced and the emission of NOx and SOx•PM can be drastically reduced if the LNG is taken as the fuel. This can provide the fundamental supporting for the construction of the Yangtze River golden waterway and the sustainable development strategy for the Yangtze River shipping. In order to use LNG as fuel safely and effectively, the follows risk analysis and key technologies on LNG fuel powered ship are carried out.

LNG supplying system design technology: Risk analyses and key technologies on LNG fuel powered ship are performed to solve the balance of LNG supplying safely and effectively and the cargo hold capacity. The LNG storage tank, the supplying system and the protection system shall be scientifically arranged to reduce the loss of cargo hold capacity as little as possible. Simulation analyses are used to optimize the process of LNG supplying system to ensure its safety and reliability.

Invalid dissipation control measurement: The working condition of mode converting on dual-fuel Main Engine is investigated and researched to provide a reliable basis for the collection of the residual natural gas in the pipeline. Reasonable measurement is proposed to collect the gas from spontaneous evaporation in the storage tank as well the remaining gas in the pipeline during the fuel mode converting through simulation analyses. The proper arrangement of control system devices is conducted to solve the invalid dissipation of LNG effectively.

Control and security technologies: Control system of dual-fuel Main Engine is analyzed to determine the plan of LNG fuel control system. Flow, pressure and temperature of LNG are determined according to the performance parameters of dual-fuel Main Engine. Then, the proper control system and security system of LNG supplying are selected.

Matching technology of power system for dual-fuel Main Engine: The fuel supplying process for various working conditions of the Main Engine is analyzed to ensure the safe operation. The process of fuel mode converting is investigated to ensure the automatic converting and stable power output. The steady and dynamic characteristics of power system are studied to ensure the stable power supplying. The research on matching characteristic of Ship-Engine-Propeller is performed to improve the dynamic characteristics of the power system for dual-fuel Main Engine in various working conditions.

CONCLUSION

In the present research, theoretical analysis, numerical simulation and model test are combined together to solve the key technologies on flat-type river-sea-going ship with shallow water. The research on application of energy-saving and environment-friendly technology is focused to develop the ship with characteristic of Energy-saving, Environment-friendly, Economy and Efficiency, regarding as "4E" level river-sea-going ship.

The main indicators for the developing ship are as follows:

1. The average daily fuel consumption per container can reduce 23.97% comparison with the existing best performance ship.
2. The application of LNG as fuel can reduce the 25 % CO_2 emissions, the 80 % NOx and 98 % SOx•PM emissions.
3. The application of watertight stern tube can effectively avoid the water pollution caused by lubricating oil.
4. The unit transportation cost of developed ship can be decreased by16.5 % comparing with the existing best performance ship.
5. The transportation efficiency can be improved by 25.6 % comparingwith the existing best performance ship.

The development of "4E" level flat-type river-sea-going ship is the requirement of current strategic development in China which has great significance to the implementation of national strategic deployment.

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