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RESEARCH ARTICLE

Integrated System and Experimental Study of a Compact Electro-Hydraulic Actuator for Marine Applications

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ABSTRACT

To address issues such as loose structure, low integration, and reliance on imports in existing marine electro-hydraulic actuators, this paper presents an integrated compact electro-hydraulic actuation device. The device integrates the drive unit, connection block, hydraulic actuation unit, and feedback signal box into one assembly. Through the integrated design of a built-in radial piston pump and valve block, a micro hydraulic power unit with no external pipelines is achieved. This paper elaborates on the structural composition, working principle, and key module design of the device, and analyzes the implementation of its triple redundancy operation modes: "electric - manual hydraulic - manual mechanical". Six-probability (reliability, maintainability, etc.) design and risk analysis were conducted, a reliability model was established, and the predicted Mean Time To Repair (MTTR) meets the shipboard requirement of $\leq$2h. Performance test results show that the device achieves a maximum working pressure of PN16, power $\leq$300 W, and an adjustable rotation angle of 90° $\pm$ 3°, realizing high integration and compact layout. The device was designed and manufactured in collaboration with a domestic marine valve actuator manufacturer.

Keywords: Electro-hydraulic actuator, Integrated design, Radial piston pump, Reliability, Marine application

1. Introduction

With advances in microelectronics and intelligent control, ship automation has been improving steadily. Valve remote control systems now demand more from actuators. Electro-hydraulic actuators are widely used in marine piping systems because they deliver high driving force, precise regulation, and fast switching 1]. Beyond ships, they are also found in aerospace flight controls, industrial robots, heavy construction machinery, and subsea blowout preventers—anywhere that needs high power density and fail-safe operation. Domestic shipping companies have long depended on imported electro-hydraulic actuators, which keeps manufacturing costs high. Many existing products lack an integrated design for the actuator, pump, and control valves [2]. As a result, their structures are loose, integration is low, they take up a lot of space, and external piping increases leakage risk and maintenance difficulty [3].

Pneumatic and electric actuators each have limitations in intelligent applications. Therefore, developing high-performance domestically produced electro-hydraulic actuators is urgent. Recen[t studies have focused on the integration of hydraulic components to achieve compact actuation systems. This paper proposes a compact electro-hydraulic actuation device integrating a drive unit, connection block, hydraulic actuation unit, and feedback signal box. Key technology analysis and experimental verification demonstrate that the device achieves miniaturization, high efficiency, and high-precision control.

2. Materials and methods

2.1. Overall structure of the actuator

The electro-hydraulic integrated actuation device is primarily used for the opening and closing control of rotary valves and can feed back position signals to

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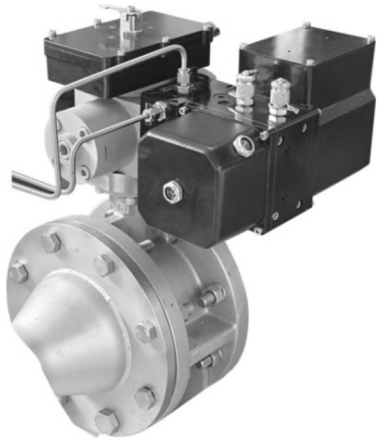


Fig. 1. Physical diagram of electro-hydraulic integrated actuator.

external systems. The device integrates the electro-hydraulic power component, hydraulic actuator, and hydraulic connection block. Its physical diagram and outline structure are shown in Figures Figs. 1 and 2.

The drive unit includes a motor, a valve block, and an oil tank. The valve block sits between the motor and the tank and houses a micro-hydraulic pump along with control valves. An interface for an emergency hand pump is located between the valve block and the hydraulic actuator. The hydraulic actuation unit consists of a cylinder body, end caps, pistons, and a rack. A feedback signal box holds micro-switches or sensors to monitor valve position in real time.

Inside the electro-hydraulic power unit, the valve block contains an oil suction hole, a valve shaft, and an eccentric bearing. A piston cylinder sits on the valve shaft and can rotate. Oil inlet and outlet grooves run along the front and rear of the shaft. The piston cylinder has radial bores, each holding a piston. A motor turns the piston cylinder through a transmission sleeve. Oil is distributed by the interaction between the valve shaft and piston cylinder. The layout is compact, and power transfer is efficient.

2.2. Working principle

The electro-hydraulic actuation device features three operation modes: electric control, manual hydraulic, and manual mechanical. Its control principle is shown in Fig. 3.

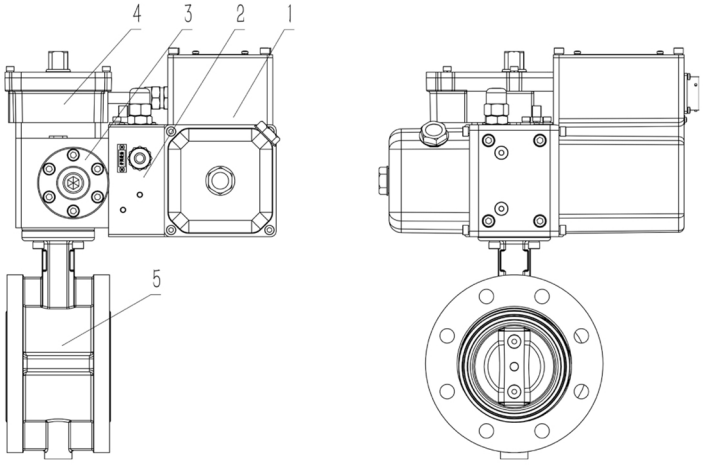
In electric mode, the motor drives the piston pump, sending pressurized oil through the hydraulic block into the cylinder. The piston moves, the rack turns the gear shaft, and the valve opens or closes [4]. Reversing the motor changes the direction of oil flow, which determines whether the valve opens or closes [5].

Manual Hydraulic Mode: When the motor fails, connect the emergency hand pump to the oil inlet and outlet ports of the connection block. Manually operating the pump generates pressurized oil to drive the hydraulic cylinder action.

Manual Mechanical Mode: When the hydraulic system fails, open the bypass valve and directly drive the square tenon on top of the feedback signal box using a handle for emergency operation.

2.3. Main performance parameters

The design followed marine operating requirements and relevant standards, including GB/T 24923-2010, GB/T 13852-2009, and ISO 5211:2023. The core performance parameters of the device were determined as follows:



1-Drive unit; 2-Connection block; 3-Hydraulic actuation unit; 4-Feedback signal box; 5-Butterfly valve

Fig. 2. Outline structure diagram of electro-hydraulic actuator.

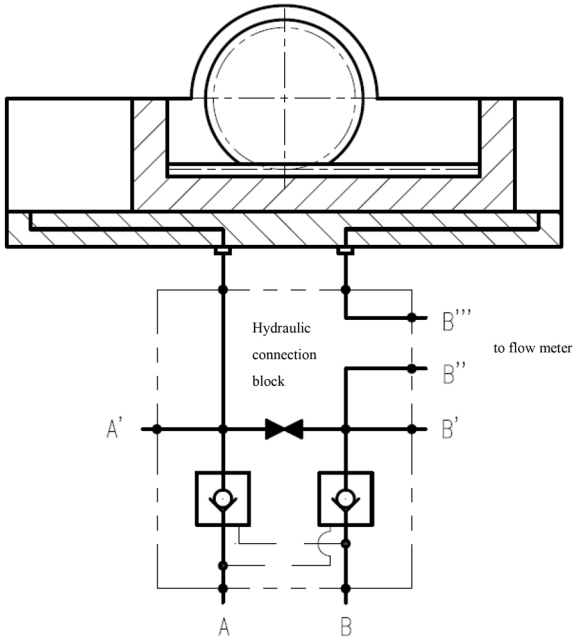


Fig. 3. Control principle diagram of electro-hydraulic actuator.

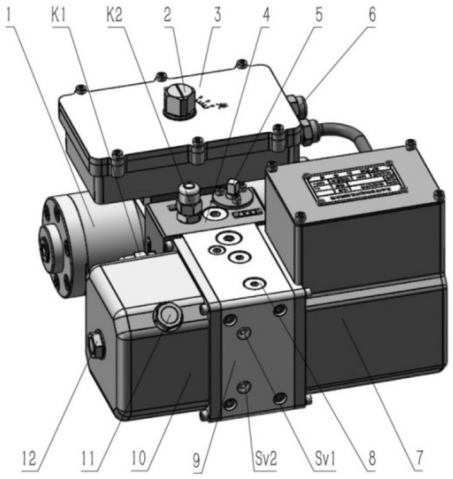


Fig. 4. Schematic diagram of the electro-hydraulic integrated actuation device. 1-Hydraulic cylinder; 2-Rack (90° rotatable); 3-Signal box (with terminal block); 4-Hydraulic connection block; 5-Bypass plug; 6-Stuffing box or aviation plug, explosion-proof cable gland; 7-Motor assembly; 8-Pressure display interface/filler plug; 9-Power module; 10-Oil tank assembly; 11-Oil filling window; 12-Inspection window; Sv1-Opening pressure valve; Sv2-Closing pressure valve; K1, K2-Quick-release couplings

a) Maximum working pressure: PN16;
b) Power supply: AC220V 50Hz, Power ≤300 W;
c) Motor duty cycle: S3-10%, equipped with overheat protection;
d) Oil tank capacity: V = 0.4–1.45 L (adaptable);
e) Feedback signals: Passive switching signal; Active opening signal;
f) Action type: Double-acting;
g) Rotation angle: 90° ± 3° adjustable (hydraulic actuation unit).

2.4. Integrated hydraulic power unit design

The power unit highly integrates the motor, pump, valve, and oil tank into one assembly. The valve block simultaneously serves as the pump body, valve body, and connector [6]. Its structure is shown in Fig. 4.

The valve block has precision blind holes that connect hydraulic components. The oil replenishment valve core, hydraulic lock, and relief valve are cartridge-mounted on the block and linked through internal passages [7, 8]. A gravity oil suction ball and support spring sit at the end of the suction pipe, so oil intake stays reliable no matter the orientation[9]. Radial piston pumps have been widely studied for improving power density in compact hydraulic systems.

2.5. Hydraulic actuation unit design

The actuation unit uses a double-acting rack and pinion design. It is compact, symmetric, and runs with steady torque and good efficiency [10]. A machined rack on the piston meshes with the output gear shaft. Pressurized oil pushes the piston; the rack moves, and the shaft turns. Two pistons sit opposite each other to keep the assembly narrow. Piston seals are combined rings—low friction, minimal leakage, and a service life over ten years. Rotation can be set to 90° ± 3° by adjusting the plugs. Rack and pinion mechanisms have been proven effective in marine valve actuators for delivering high torque.

The actuator was sized for a DN150 (6-in) marine butterfly valve at PN16, which needs about 250N·m of output torque. With a gear pitch radius of 0.025m, the required tangential force comes to 250/0.025=10,000N. Two pistons share this, so each supplies 5,000N. Operating pressure is 16MPa. The needed piston area is $10{,}000/(2 \times 16 \times 10^6)=3.125 \times 10^{-4}m^2$, which gives a diameter of about 20mm. Motor power was estimated as (0.7L/min × 16MPa)/0.85≈220W. A 250W motor was selected to leave a safety margin.

2.6. Feedback signal module design

The feedback box holds either micro-switches for switching signals or an angle sensor for analog signals, depending on what is needed. Electrical hookups use WY28K8Z series aviation plugs—waterproof and built to handle vibration, which suits marine use.

2.7. Reliability design and maintainability prediction

According to relevant standards such as GJB 450B-2021 (Reliability program for equipment

Table 1. Maintainability prediction of electro-hydraulic actuator.

No.	Item Name			Time element (h)						
	Name	Failure Rate $\lambda_i \times 10^{-5}$	Quantity Q_i	$\lambda_i Q_i \times 10^{-5}$	T_P	T_{FI}	T_D	T_I	T_R	T_A	T_C
1	Electro-hydraulic power module	2.3	1	2.3	0.1	0.1	0.8	0.2	0.8	0.1	0.1
2	Hydraulic connection block	0.4959	1	0.4959	0.1	0.1	0.8	0.2	0.8	0.1	0.1
3	Hydraulic actuator	0.4959	1	0.4959	0.1	0.1	0.2	0.2	0.2	0	0.1
4	Signal box	0.4959	1	0.4959	0.1	0.1	0.4	0.1	0.4	0.2	0.25
5	Seals	2.0125	1	2.0125	0.1	0.1	0.4	0.1	0.4	0.2	0.25
6	Total	5.8002	5	5.8002							

Table 2. Main risks and control measures.

Risk Event	Risk Level	Control Measures
Insufficient valve body pressure capacity	Medium	Precise calculation, optimal material selection, rigorous testing
Hydraulic lock sealing failure	Medium	Optimal material selection, strict assembly process
Power module overheating	Medium	Optimize heat dissipation design, motor selection validation
Oil tank cover water ingress failure	Medium	Optimize sealing structure, selection validation
Piston pump function failure	Low	Strict manufacturing and assembly, enhanced process control

development and production) and GJB/Z 1391-2006 (Failure mode, effects and criticality analysis program), the equipment must meet: Reliability life ≥10,000 cycles; Mean Time to Repair (MTTR) for mechanical parts ≤2 h; MTTR for electrical parts ≤0.5 h.

Maintainability is predicted by the time accumulation method. Maintenance work splits into seven time elements: preparation TP, fault isolation TFI, disassembly TD, replacement TI, reinstallation TR, adjustment TA, and inspection TC. Mean Time to Repair is then:

$$\mathrm{MTTR} = \frac{\sum_{i=1}^{n} \lambda_i Q_i T_i}{\sum_{i=1}^{n} \lambda_i Q_i}$$

Maintainability prediction data are shown in Table 1.

$$\mathrm{MTTR} = \frac{\sum_{i=1}^{n} \lambda_i Q_i T_i}{\sum_{i=1}^{n} \lambda_i Q_i} = \frac{2.3\times2.2+0.4959\times(2.2+0.9+1.55)+2.0125\times1.55}{5.8002} = 1.8h \le 2h$$

The calculated Mean Time To Repair came in at 1.8h, which meets the system requirement of ≤2h. Reliability modeling here drew on several sources. Rausand and Høyland (2004) developed system reliability theory for hydraulic systems with redundant configurations [11]. GJB450B-2021 provides standard procedures for military electro-hydraulic equipment [12]. He et al. (2014) introduced an uncertainty modeling and reliability calculation method for an electro-hydrostatic actuator [13]. Hou et al. (2025) used fault tree-Monte Carlo simulation to analyze actuator reliability [14]. Li et al. (2016) presented a Bayesian network-based assessment for an electro-hydraulic servo actuator [15]. These approaches guided the construction of the reliability model in this study.

2.8. Safety design

The safety design complies with GB/T 7932-2017 and ISO 4413:2010. Main features are a built-in hydraulic lock to block unintended operation, a relief valve that limits maximum pressure, motor overheat protection, a manual backup, and electrical connections that resist water and vibration. The device is not rated for explosive atmospheres unless it also meets ATEX or IECEx requirements. No assumptions here contradict any relevant safety standards.

2.9. Risk Analysis and Control Measures

Risks were identified and assessed during design, manufacturing, and testing. Supporting references include ISO 12100:2010 and IEC 60812:2018. Table 2 lists the key risks and the controls put in place.

3. Results and discussion

3.1. Test plan

Performance tests—strength, sealing, pressure regulation, and operation—were carried out on the prototype following standards GB/T 15622-2008 and JB/T 10365-2014. Table 3 shows the results. The

Table 3. Main test results.

Test Item	Test Condition	Test Result	Acceptance Criteria	Conclusion
Strength Test	Inlet pressure 24 MPa (1.5 times rated), hold for 10min	No leakage, no visible deformation	No sweating, leakage, or permanent deformation	Qualified
Static Seal Test	Inlet pressure 16 MPa, hold for 5min	No pressure drop, no leakage at sealing surfaces	Zero pressure drop, no visible leakage	Qualified
Dynamic Seal Test	Rated pressure 16 MPa, reciprocating cycle 100 times	Normal opening/closing, external leakage = 0	No external leakage, smooth operation	Qualified
Pressure Regulation Test	Inlet pressure 12~16 MPa, regulate outlet pressure 0.5~4.5 MPa	Sensitive regulation, outlet pressure fluctuation ≤ ±0.05 MPa	No jamming, abnormal vibration, stable pressure	Qualified
Operational Test	Continuous opening/closing 50 times under no-load and full-load	Smooth operation, no jamming, accurate position feedback signal	Flexible operation, normal signal	Qualified
Pressure Withstand Test	Inlet pressure 24 MPa, hold for 3min	No abnormal sound, no leakage	No rupture, no leakage	Qualified

test setup followed standard procedures for hydraulic actuator testing.

The test rig consisted of a hydraulic power supply (25MPa max), a pressure sensor (±0.5% accuracy), a flow meter (0–2L/min, ±1%), a torque sensor (0–500N·m, ±0.5%), an angular displacement sensor (±0.1°), an NI DAQ system, and the prototype actuator. The actuator was connected using quick-release couplings. (A photograph cannot be included under a confidentiality agreement with the manufacturer, but the schematic and component specifications are fully provided.)

At the rated pressure of 16MPa and a motor speed of 2800rpm, the measured output flow was 0.68L/min, close to the design target of 0.7L/min. Suction flow stayed steady at 0.72L/min with almost no cavitation. Output torque changed nearly linearly with pressure, reaching 248N·m at 16MPa, which meets the requirement for a DN150 butterfly valve. When speed went up from 500rpm to 3000rpm, torque fell by about 8% because of internal leakage, still within acceptable limits.

3.2. Result analysis

At 1.5 times rated pressure, the device showed no deformation or leakage. Static seals held pressure without any drop. Dynamic seals remained leak-free after 100 cycles. Pressure regulation stayed within ±0.05MPa, which meets high-precision requirements. Position feedback signals came through accurately during operation. All indicators were within design specifications, and the device ran reliably.

The radial piston pump design cut the overall footprint significantly while keeping power output similar to that of larger systems. The triple-redundancy operating modes described in Section 2.2 give the device a fail-safe capability that is essential for marine use.

Unlike traditional electro-hydraulic actuators, this design needs no external piping and is 30% smaller overall, yet it still delivers PN16 working pressure and draws under 300W. Mean time to repair is 1.8h, which meets naval requirements for quick field maintenance.

4. Conclusion

The designed integrated compact electro-hydraulic actuation device, through the integrated assembly of the drive unit, connection block, actuation unit, and feedback signal box, eliminates external pipelines, solving the problems of loose structure and low integration found in traditional products.

The device features triple redundancy operation modes: electric, manual hydraulic, and manual mechanical, significantly improving system reliability and safety.

Reliability model analysis shows MTTR = 1.8 h, meeting the shipboard requirement of ≤2 h; whole-process risk control ensures product quality.

Performance test results indicate that the device achieves a maximum working pressure of PN16, power ≤300 W, and an adjustable rotation angle of 90° ± 3°. All performance indicators meet design requirements, indicating good application prospects.

Conflict of interest

The authors declare no conflict of interest.

Author contribution statement

The author confirms sole responsibility for the following: study conception and design, data collection, analysis and interpretation of results, and manuscript

preparation. The author reviewed the results and approved the final version of the manuscript.

Data availability

The author confirm that the data supporting the findings of this study are available within the article[and/or] its supplementary materials.

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