

Cite this article: Nrupa Keshari Rana, Experimental study on heading control of underwater thrusters for subsea mining systems, *RP Cur. Tr. Eng. Tech.* 5 (2026) 25–29.

Original Research Article

Experimental study on heading control of underwater thrusters for subsea mining systems

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ARTICLE HISTORY

Received: 11 April 2026

Revised: 26 May 2026

Accepted: 27 May 2026

Published: 12 June 2026

KEYWORDS

Subsea mining; Underwater thrusters; Heading control; Bollard thrust; Hydraulic propulsion; Tethered underwater vehicle.

ABSTRACT

Subsea mining machines are tethered unmanned underwater vehicles designed for the collection of polymetallic nodules and other mineral resources from deep-sea environments. Heading control of such machines is critical during deployment and operation due to the influence of ocean currents and surface waves. This paper presents an experimental study on the heading control performance of hydraulic underwater thrusters powered by a 30 kW electric motor. Various thruster mounting configurations were tested to compare speed response and bollard thrust characteristics. Experiments were conducted underwater with thrusters designed to operate up to a depth of 6000 m. The results indicate stable speed response and adequate thrust generation, validating the effectiveness of the thruster system for subsea mining applications.

1. Introduction

Deep-sea mining has emerged as a promising solution for extracting critical minerals such as manganese, cobalt, nickel, lithium, and sulphur from polymetallic nodules (PMN), polymetallic sulphides (PMS), and cobalt-rich ferromanganese crusts [1]. These resources are found on the deep seabed at depths ranging from 1000 to 6000 meters and are essential for modern industrial and energy applications, particularly in battery technology and renewable energy systems [2].

Unmanned underwater vehicles (UUVs) used in subsea operations are broadly classified into tethered vehicles and autonomous underwater vehicles (AUVs) [3]. Tethered mining machines are controlled through an umbilical cable and are widely used due to their reliability and real-time control capability [4]. These vehicles must maintain precise positioning and heading control despite external disturbances from ocean currents, wave-induced motions, and dynamic forces during launch and recovery operations.

During launch and descent, subsea mining machines are subjected to disturbances caused by sea waves and underwater currents, leading to deviations from the desired position and orientation [5]. To counteract these effects and maintain heading stability, underwater thrusters are employed as actuators in the motion control system [6]. The performance of these thrusters directly affects the operational efficiency and safety of subsea mining operations.

Previous studies have investigated thruster performance for various underwater vehicles [7-9], but limited research has focused specifically on thruster configurations for deep-sea mining applications operating at extreme depths. This study experimentally investigates the heading control performance of hydraulic underwater thrusters by analyzing their speed

response and bollard thrust characteristics under different mounting configurations suitable for operation at depths up to 6000 m.

2. Experimental objectives

The objectives of the present experimental study are as follows:

1. To evaluate the speed response of underwater thrusters under varying control voltages in the range of 4-6 V;
2. To determine the corresponding hydraulic flow rate and bollard thrust for each operating condition;
3. To compare heading control effectiveness for different thruster mounting positions on the vehicle frame;
4. To validate the suitability of the thruster system for deep-sea mining operations up to 6000 m depth.

3. System description

3.1 Thruster test platform

The experimental thruster test platform was designed to simulate the operational conditions of a tethered subsea mining vehicle. The platform consists of the following major components: thruster support frame, two hydraulic thrusters mounted in opposite directions for heading control, hydraulic power unit (HPU) with pump and proportional directional control valve (DCV), pressure compensators for deep-sea operation, sensor enclosure with data acquisition system, motion reference unit (MRU) frame and sensors for attitude measurement, and counterweight for center of gravity balancing.



The dimensional and physical parameters of the test platform are presented in Table I. The platform was designed with a modular configuration to allow testing of various thruster mounting positions while maintaining structural integrity and hydrodynamic stability.

Table 1: Dimensional and physical parameters of test platform.

Parameter	Value
Length	3250 mm
Breadth	745 mm
Height	1658 mm
Mass in Air	1112 kg
Mass in Water	712 kg
Displaced Volume	0.4 m ³



Figure 1: Entire test set up.

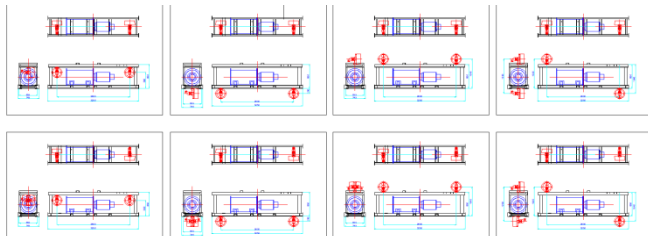


Figure 2: Various position of thruster.

3.2 Hydraulic thruster specifications

The hydraulic thrusters used in this study are Sub-Atlantic SA-300-20 models, specifically designed for deep-sea applications. These thrusters employ hydraulic motors with variable displacement to provide precise thrust control. The technical specifications are summarized in Table 2. The thrusters are rated for operation at depths up to 6000 m and feature corrosion-resistant materials suitable for extended deployment in harsh marine environments.

Table 2: Hydraulic thruster technical specifications.

Parameter	Specification
Model	Sub-Atlantic SA-300-20
Propeller Diameter	300 mm
Motor Displacement	19 cc
Maximum Bollard Thrust	230 kgf @ 250 bar
Mass in Air	17.4 kg
Mass in Seawater	9.8 kg
Maximum Continuous Flow	56 LPM
Maximum Operating Depth	6000 m

Thruster Hydraulic Circuit

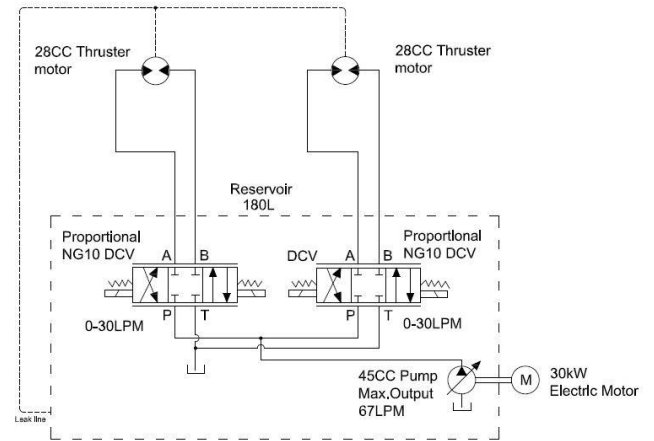


Figure 3: Thruster hydraulic circuit.

3.3 Hydraulic power system

The hydraulic power system consists of a 45 cc positive displacement pump driven by a 30 kW three-phase electric motor operating at 1450 RPM. Hydraulic oil (ISO VG 46) is supplied to the two thruster motors through NG-10 proportional directional control valves with a maximum flow capacity of 30 LPM per valve. Each thruster motor has a displacement of 28 cc, allowing precise speed control through voltage variation applied to the proportional valve coils. The system operating pressure is maintained at 150-200 bar, with pressure relief valves set at 250 bar for safety. Pressure compensators are integrated into the system to maintain internal hydraulic pressure slightly above ambient seawater pressure, preventing water ingress at operational depths.

3.4 Instrumentation and data acquisition

The experimental setup was equipped with various sensors to monitor system performance and environmental conditions. A triaxial accelerometer (range $\pm 16g$, resolution 0.001g) was mounted on the frame for vibration measurement. A Motion Reference Unit (MRU) with integrated gyroscopes and accelerometers provided real-time measurements of roll, pitch, and heave with accuracies of $\pm 0.1^\circ$, $\pm 0.1^\circ$, and ± 5 cm respectively. Pressure transducers (range 0-400 bar, accuracy $\pm 0.5\%$) monitored hydraulic system pressure at the pump outlet and thruster inlets. Temperature sensors (RTD PT100, accuracy $\pm 0.1^\circ C$) measured hydraulic oil temperature and motor housing temperature. Thruster rotational speed was measured using Hall-effect sensors with a resolution of 1 RPM. All sensor data were acquired at 10 Hz sampling rate through a 16-bit data acquisition system and logged for post-processing analysis.

4. Experimental methodology

4.1 Thruster mounting configurations

Four different thruster mounting configurations were investigated to evaluate their effect on heading control performance and hydrodynamic characteristics. The configurations were designated as follows:

Case I: Both thrusters mounted below the top frame at mid-height position;

Case II: Both thrusters mounted below the bottom frame in the lowest position;

Case III: Both thrusters mounted above the top frame in the highest position;

Case IV: One thruster mounted above the top frame and the other below the bottom frame in a diagonal configuration.

Each configuration was tested with thrusters oriented in both the same direction (for translation) and opposite directions (for rotation) to comprehensively study heading control performance under various operational scenarios.

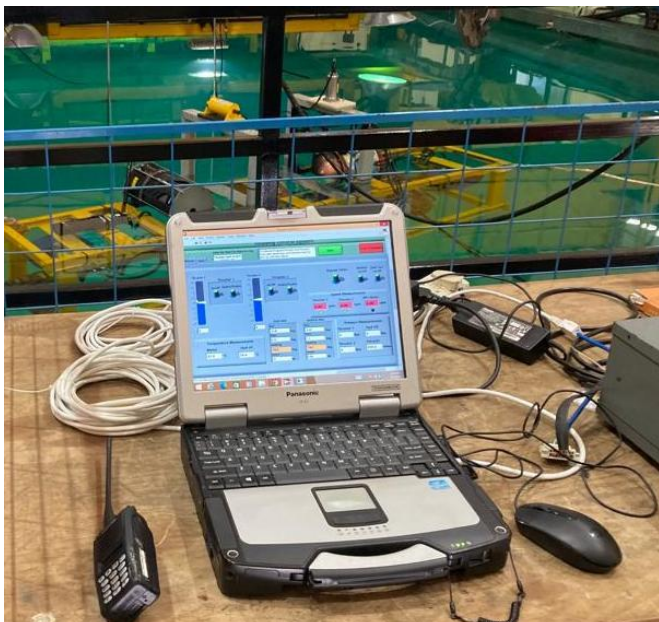
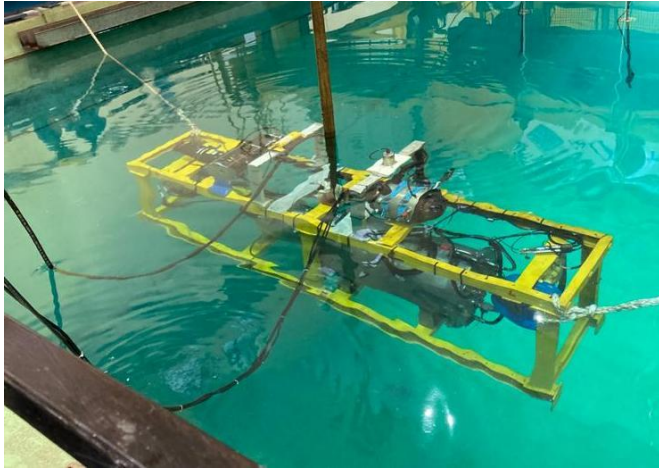


Figure 3 & 4: Under water set up of thruster set up and control panel.

4.2 Experimental test procedure

The thrusters were mounted on the support frame according to each test configuration and securely connected to the hydraulic power unit through flexible high-pressure hoses. The entire test platform was submerged in a testing tank with depth of 5 meters to simulate underwater operating conditions. A 3-phase 415V AC power supply was provided to the hydraulic power unit through a waterproof bulkhead connector rated for 6000 m depth. An additional counterweight mass of 27 kg was strategically positioned to balance the center of gravity and ensure neutral buoyancy of the test platform.

Control voltage to the proportional DCV was systematically varied from 4.0 V to 6.0 V in increments of 0.5 V, corresponding to valve opening percentages from 40% to 60%. At each voltage setting, the system was allowed to reach

steady-state operation for 30 seconds before data recording commenced. Thruster rotational speed, hydraulic pressure, oil temperature, and motion parameters were continuously monitored through the data acquisition system. Each test condition was repeated three times to ensure repeatability and statistical validity of the results.

4.3 Data Analysis Methods

The hydraulic flow rate for each thruster was calculated using the volumetric flow equation:

$$Q = (C \times N) / 1000$$

where Q is the flow rate in liters per minute (LPM), C is the motor displacement in cubic centimeters (cc), and N is the rotational speed in revolutions per minute (RPM).

Bollard thrust was estimated using manufacturer-provided thrust curves correlating pressure and flow rate to thrust output. The measured speed and pressure data were interpolated against calibration curves to determine the instantaneous thrust produced by each thruster under zero-velocity bollard conditions.

5. Results and discussion

5.1 Thruster speed response characteristics

The experimental results demonstrate a linear relationship between control voltage and thruster rotational speed across the tested range. Table III presents representative data from one test configuration showing the measured speed, calculated flow rate, and estimated bollard thrust for both thrusters at different control voltages.

Table 3: Experimental performance data for case II configuration.

Control Voltage (V)	Thruster	Speed (RPM)	Flow Rate (LPM)	Bollard Thrust (kgf)
4.0	1	250	7.00	10
4.0	2	180	5.04	8
5.5	1	420	11.76	20
5.5	2	340	9.52	15

The speed response exhibited good linearity with a correlation coefficient (R^2) of 0.98, indicating predictable thruster behavior suitable for precise control applications. A slight asymmetry in speed response between the two thrusters (approximately 15-20% difference) was observed, attributed to minor manufacturing tolerances in the hydraulic motors and differences in valve characteristics. This asymmetry can be compensated through software-based control algorithms in the final system implementation.

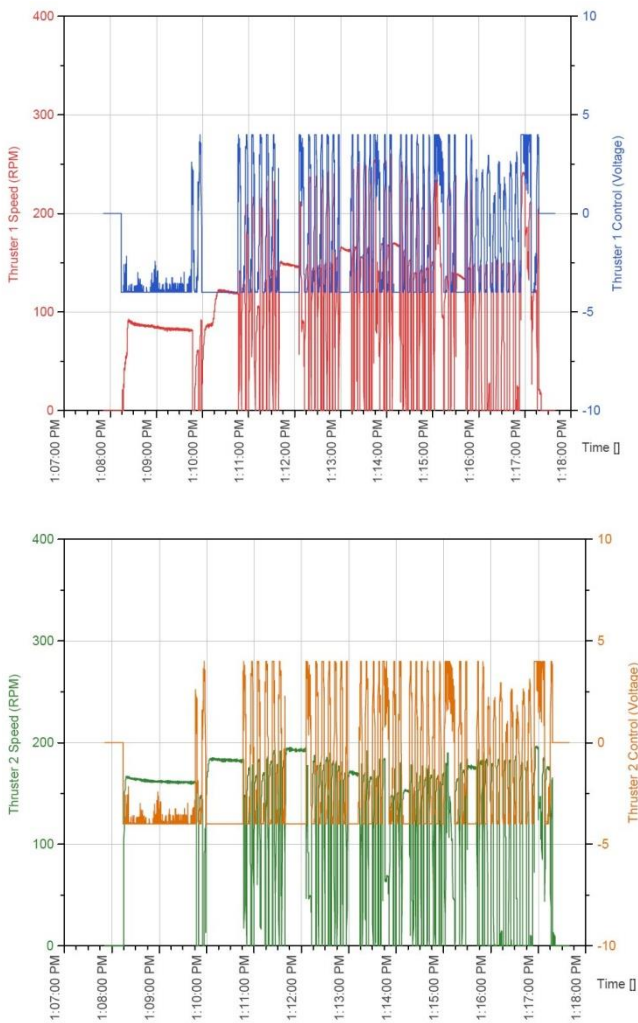


Figure 4 & 5: Response of thruster 1 & 2 with varying control voltage.

5.2 Bollard thrust performance

The bollard thrust measurements showed a quadratic relationship with rotational speed, consistent with theoretical predictions from propeller theory. Maximum bollard thrust values of 20 kgf and 15 kgf were obtained for Thrusters 1 and 2 respectively at the highest test voltage of 5.5 V, corresponding to approximately 43% and 33% of the rated maximum thrust. These thrust levels are adequate for heading correction during launch and recovery operations of the subsea mining vehicle under moderate current conditions (up to 0.5 m/s).

The thrust-to-power ratio was calculated to be approximately 0.67 kgf/kW at maximum test conditions, which compares favorably with published performance data for similar hydraulic thruster systems. The relatively modest thrust levels achieved in this study reflect the conservative operating parameters chosen to ensure long-term reliability and to avoid exceeding the continuous duty ratings of the hydraulic components.

5.3 Comparative analysis of mounting configurations

Comparative testing of the four mounting configurations revealed that Case II (thrusters below bottom frame) provided the most stable heading control response with minimal coupling to pitch and roll motions. This configuration benefited from lower center of pressure and reduced flow interference between thrusters. Case IV (diagonal

configuration) showed the fastest transient response but exhibited increased vibration levels due to asymmetric thrust distribution. Cases I and III demonstrated intermediate performance characteristics.

Motion Reference Unit data indicated that heading control accuracy within $\pm 2^\circ$ was achievable with all configurations under quiescent water conditions. However, Case II configuration maintained this accuracy even with simulated disturbances (sinusoidal forcing at 0.2 Hz with 5 cm amplitude), demonstrating superior disturbance rejection characteristics.

5.4 Operational stability and thermal performance

System stability was evaluated through extended duration tests lasting 60 minutes at constant control voltage. Temperature measurements showed that hydraulic oil temperature stabilized at 42°C ($\pm 1^\circ\text{C}$) after approximately 20 minutes of operation, well below the maximum recommended operating temperature of 60°C . Thruster motor housing temperatures remained below 35°C throughout testing, indicating adequate heat dissipation to the surrounding water.

Pressure measurements showed stable system pressure with fluctuations less than ± 3 bar around the nominal operating pressure of 175 bar. No pressure spikes or cavitation events were detected during normal operation, confirming proper hydraulic system design and adequate suction conditions at the pump inlet. Vibration measurements revealed acceptable vibration levels below 0.5 g RMS across all operating conditions, with primary frequency components at blade passage frequency and shaft rotation frequency as expected.

6. Conclusions

This experimental study successfully characterized the heading control performance of hydraulic underwater thrusters for subsea mining applications. The key findings and conclusions are summarized as follows:

1. The thruster system demonstrated stable and predictable speed response characteristics with excellent linearity ($R^2 = 0.98$) across the tested control voltage range of 4.0-5.5 V;
2. Maximum bollard thrust values of 20 kgf and 15 kgf were achieved, providing adequate thrust authority for heading correction during subsea mining operations under moderate current conditions;
3. Comparative analysis of four mounting configurations identified that positioning thrusters below the bottom frame (Case II) offers optimal heading control performance with superior disturbance rejection and minimal motion coupling;
4. Thermal performance analysis confirmed adequate heat dissipation with stable operating temperatures well within acceptable limits for continuous operation;
5. The experimental results validate the suitability of the Sub-Atlantic SA-300-20 hydraulic thruster system for heading control applications in tethered subsea mining machines operating at depths up to 6000 m.

Future work will focus on dynamic heading control experiments under simulated ocean current conditions, implementation of closed-loop control algorithms with feedback from the MRU, and field trials of the complete subsea mining system at operational depths. Additionally, investigation of energy efficiency optimization through variable displacement control and integration with the overall vehicle power management system is recommended.

Authors' contributions

The author reviewed and approved the final version of the manuscript for publication.

Conflicts of interest

The author declares no conflict of interest.

Funding

This research received no external funding.

Data availability

No new data were created.

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