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AUTOMATION SYSTEM OF AN EDUCATIONAL TEST BENCH FOR NAVAL PISTON DIESEL ENGINES

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Keywords: Automation control system; Supervisory control and data acquisition; Test bench; Marine propulsion; Diesel engine.

The paper focuses on the custom automation system of a test bench for diesel engines used on navy ships, namely on tugboats. The test bench, with its automation system, is developed for practical training at a naval academy. The test bench aims to meet the highest standards in the education of Navy students and personnel. It facilitates undertaking practical laboratory works regarding the main constructive elements, operation, monitoring, and maintenance of four-stroke internal combustion engines, of the gearbox, as well as of the propeller load simulated by a hydraulic brake. The custom-made automation control system includes a modular cabinet with drives and automation sections, featuring a local command console for engine control and a remote command console for the entire test bench, with a large display for parameter monitoring.

1. INTRODUCTION

Marine diesel engines [1–6] ensure the efficient operation of naval ships, serving as the primary movers in propulsion systems, and can also generate electrical energy through cogeneration [7] to power auxiliary installations. Therefore, ensuring a proper testing of these engines by replicating the on-board operation conditions on the test benches is of utmost importance.

Test benches that simulate propeller loads for marine applications [8–12] are crucial for the behaviour prediction [13], fault detection [14, 15], and assessing the performance and efficiency [16, 17] of the propulsion systems. The entire kinematic chain from the internal combustion engine to the driven ship propellers on board must be tested, including all the intermediary elements such as gearboxes and the afferent shaft couplings. Setups like these can replicate the resistive forces and loads encountered in marine environments, enabling engineers to measure important parameters such as thrust, torque, power, and efficiency in various scenarios with controlled conditions.

A test stand comprising a piston diesel engine [18, 19], a reduction gearbox, and a hydraulic brake simulating the propeller load [9, 20] ensures the practical relevance of a laboratory. Meeting and complying with the highest educational standards provided by naval universities to their students, preparing the cadets with practical skills for real on-board missions.

The test bench presented in this paper was designed to reproduce as closely as possible the operating conditions encountered on board tugboats, while addressing the competence requirements for cadets in marine academies. Its configuration respects the scope of work [21] and was defined in collaboration with the teaching staff and ship engineers. It has already been used during several laboratory sessions, where feedback from instructors and students has been used to refine the operating procedures and interface.

2. THE TEST BENCH FOR PISTON ENGINES

The test bench, presented in Fig. 1, integrates the following main components:

- A reciprocating diesel engine, Volvo Penta D16 MH 600 HP, with its cooling air fans.
- A reversing gearbox for reducing the engine's speed to ensure the speed compatibility with the propellers, also being able to reverse the rotational direction.
- Multiplier gearbox for increasing the speed to the driving speed of the brake. For low speeds, the brake would have been very large in dimensions and very expensive.
- A hydraulic brake with its water tank and pumps, used for simulating the propeller's resistive torque on navy ships.
- Automation system, comprising a drives cabinet, an automation cabinet with programmable logic controller (PLC) and its programmed software [22–24], two control consoles for local and remote control, as well as a large display replicating the screen displayed on the remote console's Panel PC.

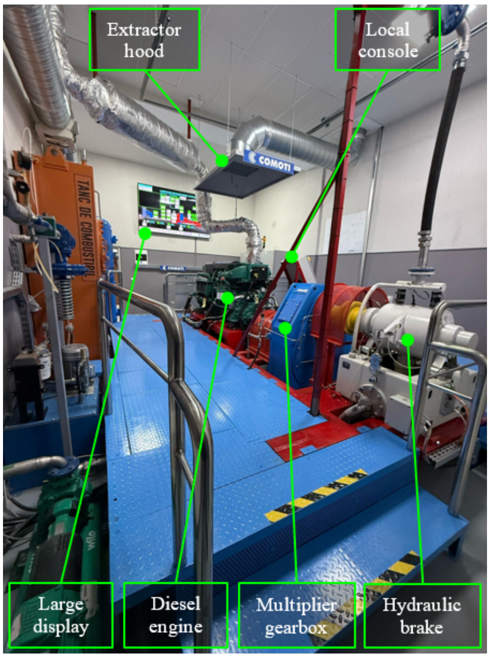

Fig. 1 – Test bench components.

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An isometric view of the computer-aided design (CAD) model of the test bench assembly is presented in Fig. 2.

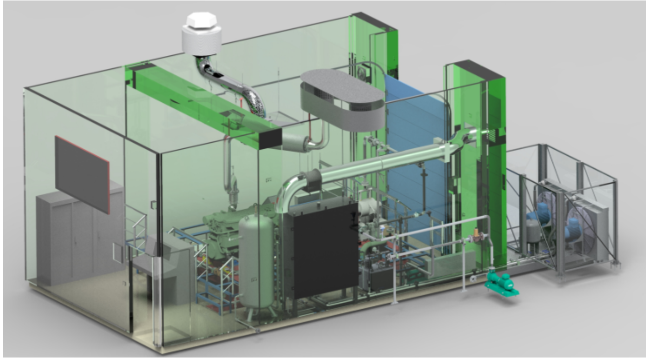

Fig. 2 – Isometric view of the 3D CAD model of the test bench.

3. AUTOMATION CONTROL SYSTEM

The automation control system is integrated into the test bench according to the schematic diagram in Fig. 3. The panel PC and the PLC communicate through Ethernet cables. The remote console communicates with the engine's electronic control unit (ECU) and engine local control point (LCP) via J1939 protocol built on top of the physical and data link layers of the controller area network (CAN). The analogue signals are transmitted in a 4-20 mA unified signal via signal adapters in the junction box (JB).

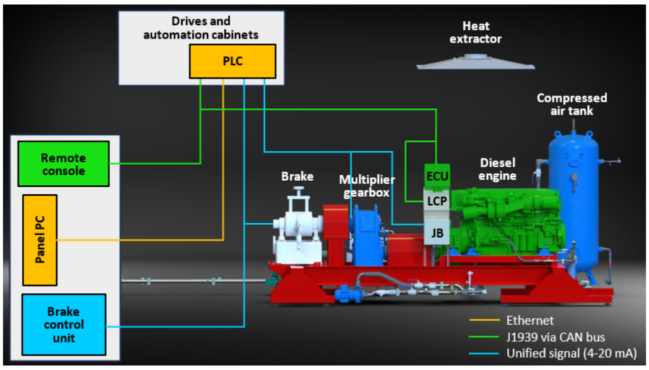

Fig. 3 – Schematic diagram of the test bench with integrated automation.

The automation control system comprises a drives cabinet with frequency inverters and an automation cabinet with PLC (Fig. 4). Two command consoles are provided, one for the local command of the engine and one for the remote control of the entire test bench. Additionally, a large 98" diagonal display is wall-mounted so trainees can follow the installation parameters.

Fig. 4 – Control cabinets.

The drives cabinet (Fig. 5), which has two doors, is equipped with:

- Three frequency inverters:
  - One that controls the variable-speed air fan for engine cooling. There are two air fans for engine cooling: one with a fixed speed and direct power supply, and another with variable speed, used when the fixed-speed fan cannot provide proper engine cooling.
  - One for the return pump for the brake's working fluid (water). The command of the pump's motor speed depends on the water level in the tank beneath the brake, from which the water exits and accumulates. The water enters from above from a reservoir and exits from below the brake into the tank.
  - One for the recirculation water pump for engine cooling.
- A switch for batteries, used when power outages occur.
- Three uninterruptible power supplies (UPS).
- Contactors.
- Motor protection.
- Fuses.
- Relays.
- Terminal blocks.
- Other auxiliary equipment, useful for the drives section.
- A thermostat for controlling the fans when the temperature in the room reaches 60 °C.

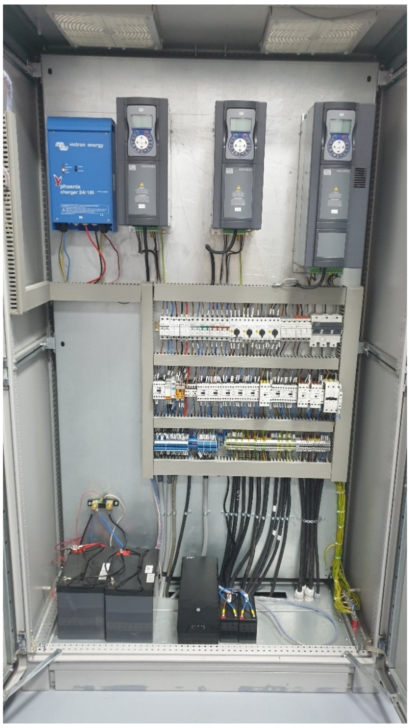

Fig. 5 – Drives cabinet.

The automation cabinet is equipped with an Emerson VersaMax PLC (Programmable Logic Controller), which includes a Central Processing Unit (CPU), and I/O (Input/Output) modules, as follows:

- 1 CPU type IC200CPUE05, which includes a slot with a DC power source IC200PWR102;
- 3 analogue input (AI) 15-channel (each) modules, type IC200ALG264;
- 1 analogue output (AO) 8-channel module, type IC200ALG326;
- 1 digital input (DI) 32-channel module, type

IC200MDL650;

- 1 digital output (DO) 32-channel module, type IC200MDL742;
- 6 module carriers IC200CHS022 for the I/O modules above.

The automation cabinet (Fig. 6) also includes all the necessary components, such as: DC source, contactors, relays, fuses, temperature adapters, pressure adapters, safety barriers for temperature and pressure signals from the fuel tank.

The Human-Machine Interface (HMI) and the visualization of the acquired data are realized from a touchscreen Panel PC installed on the remote console. The screens are replicated on a larger 98-inch TV display mounted on the rear wall behind the remote console.

Fig. 6 – Automation cabinet.

The local command and control console (Fig. 7) simulates the command console located in the engine room on board naval ships. It includes a lever for engine speed control, the engine start-up screen and buttons, as well as an emergency shutdown button. From the local console, only the engine can be controlled, this one being provided with a screen with a cover on which the essential parameters are displayed as clocks, according to how the display is realized on board ships.

Fig. 7 – Engine local control point console.

The remote command and control console (Fig. 8) simulates the command console located remotely on the deck, onboard naval ships. It is provided with a touchscreen Panel PC for controlling the entire test bench, including the lever and control screen for the engine, and also embedding computers for the hydraulic brake.

Fig. 8 – Remote control console of the test bench.

In Fig. 9 below, a part of the dedicated software program developed in Proficy Machine Edition 10.4 is presented, based on which the PLC commands the operation sequences of the test bench and monitors its parameters.

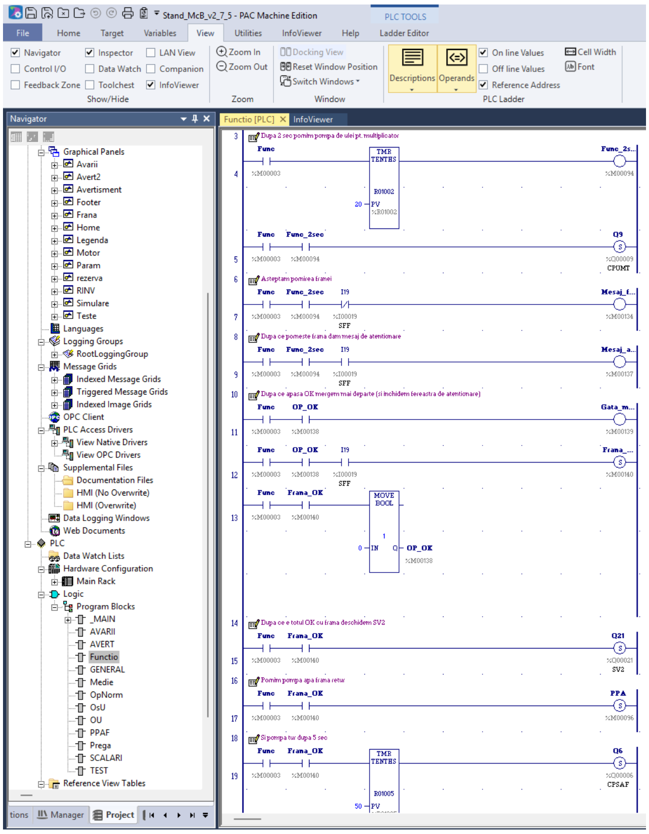

Fig. 9 – Sequences from the Prophet Machine Edition ladder diagram software.

4. **TEST BENCH OPERATION**

The stand that we developed and commissioned, along with its documentation (technical book, operation manual, wiring diagrams, *etc.*), replicates the propulsion system found on tugboats that were visited before designing the test bench. The academy staff's request was that the engine be operated separately, from its own console, to reproduce the real on-board operation. The propulsion system was driven between idle and rated speed during commissioning tests, eventually proving operation in good conditions. A speed-torque operation curve is implemented in the control unit of the brake, mimicking the propeller load found on tugboats.

The parameters monitored and observed on the main screen are listed in Table 1.

Table 1

Test bench parameters that are displayed on the main screen.

No.	Parameter name	Symbol	Unit
1.	Cooling water pressure	**Par_M**	bar
2.	Cooling water temperature	**Tar_M**	°C
3.	Ambient air temperature	**Taer_B**	°C
4.	Carbon dioxide detector	**CO2_B**	ppm
5.	Carbon monoxide detector	**CO_B**	ppm
6.	Fuel vapours detector	**Vap_B**	%LEL
7.	Fuel temperature	**Tcb**	°C
8.	Fuel level	**Ncb**	mm
9.	Fuel flow rate in	**Qcb_t**	l/h
10.	Fuel flow rate out	**Qcb_r**	l/h
11.	Fuel consumption rate of the engine	**Qcb**	l/h
12.	Brake water pressure, before regulator	**Par_iF**	bar
13.	Brake water pressure, after regulator	**Par_F**	bar
14.	Brake inlet water temperature	**Tar_iF**	°C
15.	Brake outlet water temperature	**Tar_dF**	°C
16.	Brake speed	**n_F**	rpm
17.	Brake resistive torque	**Nm_F**	Nm
18.	Brake water level	**Nar_F**	mm
19.	Brake power (horsepower)	**Wh_F**	hP
20.	Multiplier gearbox oil pressure	**Pu_Mt**	bar
21.	Multiplier gearbox oil temperature	**Tu_Mt**	°C
22.	Exhaust gas temperature	**Egt1**	°C
23.	Air pressure in the reservoir	**Paer_R**	bar
24.	Start-up air pressure	**Paer_M**	bar
25.	Engine water pump drive	**NVSD1**	rpm
26.	Retour water pump drive (from brake)	**NVSD2**	rpm
27.	Engine colling water fan drive	**NVSD3**	rpm

The operation is very simple, as needed by marine personnel on board ships. The manoeuvres that need to be performed only involve powering the automation cabinets and pressing the virtual buttons according to the operation sequences programmed in the software. These sequences are displayed on the panel PC serving as a human-machine interface (HMI).

The test bench is operated during guided laboratory sessions in which students follow the predefined sequences displayed on the HMI.

- The cycle begins with **INIT**, when the automation cabinet is powered. Using the remote console, the operator then advances through the stages.
- In the **TESTS** phase, students verify the proper functioning of pumps, fans, valves, and signalling devices. This familiarizes them with the test bench layout and with the link between the technological diagram and the physical components.
- During **PREPARATION**, the lubrication and cooling circuits are brought to operating conditions. The lube oil pump is started, the oil is preheated, the hydraulic brake is started up, and the manual air valves for the pneumatic starter are opened. Students check on the HMI that all monitored parameters (pressures, temperatures, levels, gas concentrations) are within normal ranges before proceeding.
- In **OPERATION**, the fuel valve is opened, and the engine is started from its local console, which replicates the onboard engine-room controls. Engine speed is set using the lever on the local console, while the hydraulic brake on the remote console is used to adjust load, enabling the study of various operating points and their impact on fuel consumption, exhaust temperature, and gearbox behaviour.
- **NORMAL SHUTDOWN** demonstrates a correct marine practice: fuel supply is cut, and the cooling system remains active for four minutes to ensure a controlled thermal cooldown. Once safe limits are reached, auxiliary systems stop automatically.
- **EMERGENCY SHUTDOWN** can be initiated manually via any mushroom push-button or automatically if the monitored parameters exceed alarm thresholds. In this case, both the engine and all auxiliary systems stop immediately, illustrating the safety logic and typical interlocks of marine propulsion automation.

The main screen projected on a large display (Fig. 10) makes the test bench and parameters easy to follow.

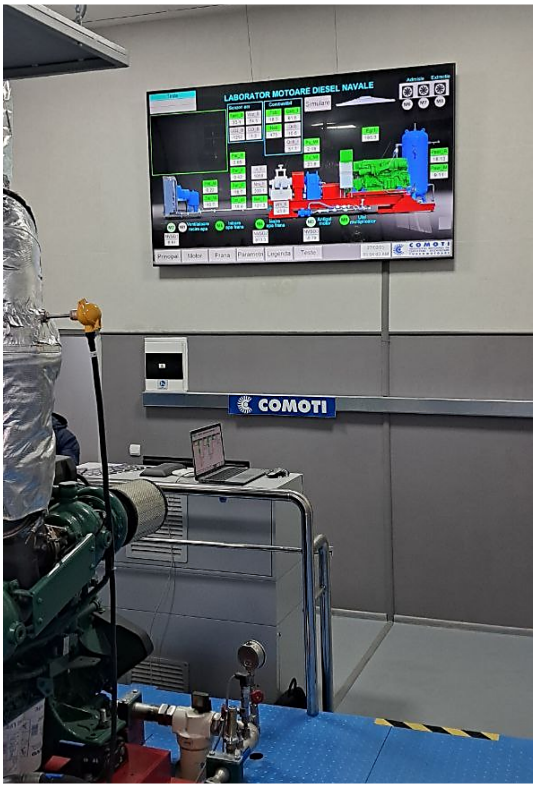

Fig. 10 – Wall display replicating the screen on the panel PC.

The main screen with the technological diagram of the test bench is presented in Fig. 11, in the *Preparation* phase. It can be noticed that the parameters have their boxes coloured in green, yellow, red, or grey. Figure 12 shows the main screen with the technological diagram of the test bench, in the *Operation* phase. All the parameters are within normal operation ranges, their boxes being coloured in green.

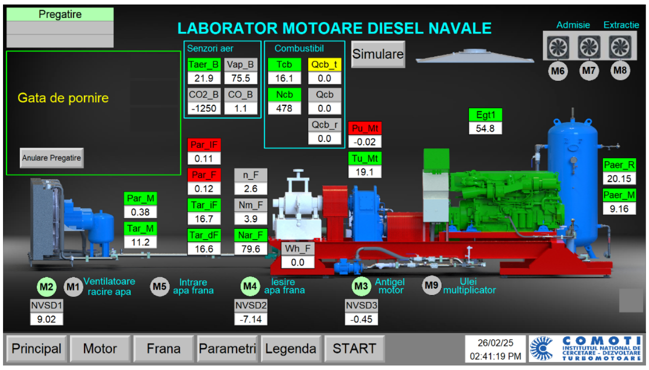

Fig. 11 – The technological diagram screen, in the *Preparation* phase.

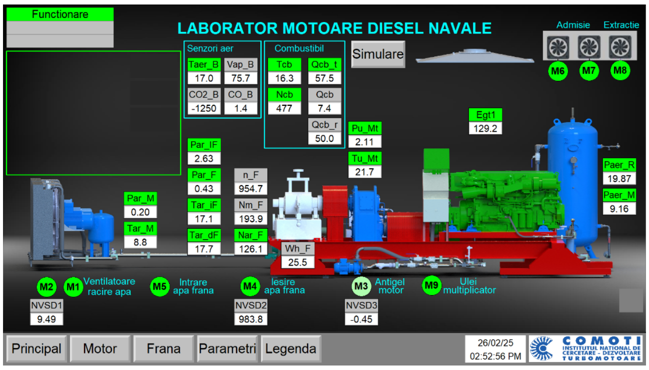

Fig. 12 – The technological diagram screen, in the *Operation* phase.

In the two figures above, the significance of the parameters text boxes' colours is as follows:

- Green – the parameter values are within normal range;
- Yellow – the values exceed the warning limits;
- Red – the values are (still) outside alarm thresholds;
- Grey – parameters without warning/alarm thresholds.

5. RESULTS AND DISCUSSION

The acquired data was processed to fully assess the proper operation of the test bench. Since only the brake's torque can be measured directly momentarily, some computations were needed to derive the engine power and torque.

The computational model relies on the measured brake torque and on the fact that the shaft power is constant all along the kinematic chain. From the engine to the hydraulic brake, the only power losses are recorded at the level of the two gearboxes, rendering the following relation:

$$P_{\text{engine}} = \frac{P_{\text{dyno}}}{\eta_{\text{red}} \cdot \eta_{\text{multi}}}, \tag{1}$$

where: P_{engine} [kW] – engine power; P_{dyno} [kW] – brake power; η_{red} [ND] – reduction gearbox efficiency; η_{multi} [ND] – multiplier gearbox efficiency.

The engine torque is calculated with relation (2), relying on the calculated engine power and the engine speed.

$$M_{\text{engine}} = \frac{P_{\text{engine}}}{\omega_{\text{engine}}} = \frac{P_{\text{engine}} \cdot \frac{60}{2\pi} \cdot 10^3}{n_{\text{engine}}}, \tag{2}$$

where: M_{engine} [Nm] – engine torque; ω_{engine} [rad/s] – engine angular velocity; n_{engine} [rpm] – engine speed.

The engine speed was calculated relying on the measured brake speed and the transmission ratios of the two gearboxes, using eq. (3).

$$n_{\text{engine}} = n_{\text{dyno}} \cdot \frac{i_{\text{red}}}{i_{\text{multi}}}, \tag{3}$$

where: n_{dyno} [rpm] – Brake speed; i_{red} [ND] – reduction gearbox transmission ratio; i_{multi} [ND] – multiplier gearbox transmission ratio.

Introducing eq. (2) and (3) in relation (1), we obtain relation (4) for engine torque, which is directly related to the measured brake torque.

$$M_{\text{engine}} = M_{\text{dyno}} \cdot \frac{i_{\text{multi}}}{i_{\text{red}}} \cdot \frac{1}{\eta_{\text{red}} \cdot \eta_{\text{multi}}}, \tag{4}$$

where: M_{dyno} [Nm] – Brake torque.

The calculated engine torque at 100% load, relying on the measured brake torque, follows a similar trend with the theoretical curve given in the datasheet, with very close values (Fig. 13). The maximum relative error is below 6%.

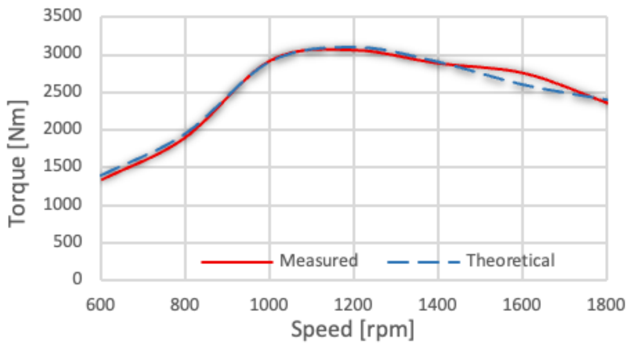

Fig. 13 – Calculated vs. theoretical engine torque.

The same torque values were used to calculate the resistive torque considering different partial loads (50%, 60%, 70%, 80%, 90%, 100%). Provided that the computation error is acceptable, the computation formulae allowed us to determine the engine torque at the partial loads exerted by the brake (Fig. 14).

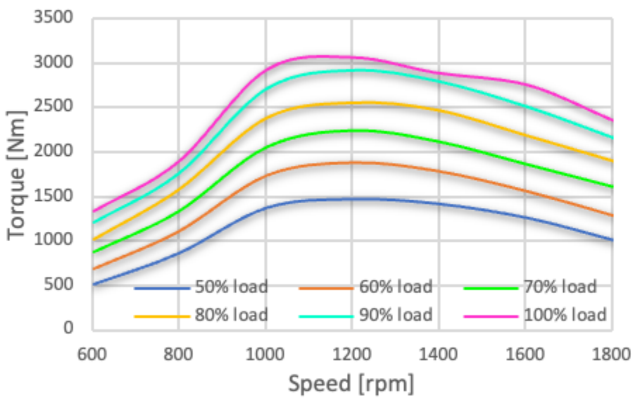

Fig. 14 – Engine torque at different simulated loads.

The results presented were obtained by the authors during the implementation and commissioning of the test bench.

The practical training and laboratory work that are performed at the Naval Academy include [25]:

- Construction of 4-stroke internal combustion engines;
- Identification of propulsion system components;
- Monitoring of marine diesel engine operating parameters;
- Monitoring the reduction gearbox operating parameters;
- Monitoring the hydraulic brake operating parameters;
- Successive loadings of the marine diesel engine and

interpreting its behaviour;
- Practical determination of the average indicated pressure and combustion pressure of a diesel engine;
- Lever control and ignition of internal combustion engines.

6. CONCLUSIONS

The paper presents an educational test bench, designed and developed for naval diesel engines, that provides all the necessary elements for delivering a practical study object for complete practical laboratory work. The test bench proved a good and reliable operation, proving its usefulness for the practical laboratory works required in a marine academy.

The automation control system proved reliable and robust. The acquired data, based on which the presented torque curves were plotted, have normal values and trends, as expected from an internal combustion engine operating normally within the entire kinematic chain comprising a multiplier and a reduction gearbox.

The multiplier gearbox elevates the speed to match the required value for the engine, which allowed us to choose a more compact and less expensive brake.

Future work will consider the integration of a communication module in the automation system, enabling the reading of the engine parameters from the remote console. This would upgrade the solution and make it much closer to the real on-board experience on tag boats driven by piston engines.

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CREDIT AUTHORSHIP CONTRIBUTION

C. Săvescu:	conceptualization, writing (draft, review and editing), visualisation.
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V. Năvrăpescu:	validation, supervision.
D. Lale:	investigation, methodology, hardware.
R. Conțiu:	formal analysis, investigation, computations, data curation.
F. Niculescu:	resources, supervision.

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