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AUTOMATION CONTROL FOR REVAMPING THE PROPULSION SYSTEM OF A NAVY FRIGATE

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The paper presents the replacement of the current propulsion system of a T22 Romanian defence frigate with a Pratt & Whitney turboprop engine. Due to becoming out-of-date and reaching the maximum operation hours and expected lifetime, turbine engines need to be replaced. A ST40M engine of 4 MW power was tested in-house and installed on the frigate, replacing one of the Rolls Royce Tyne engines and proving its reliability. After the revamp, the defence ship will be equipped with two ST40M engines for cruise speed, and two Rolls Royce Olympus gas turbines for sprint speed. For the control, monitoring and warning functions, a modern automation and electronic control system was designed and implemented, customised for the ship. The local control panel displays the real time parameters and virtual engine controls. A mathematical model was developed for estimating the maximum power that can be achieved. Bench tests with the engine were performed to assess its behaviour and implement the automation control program, prior to onboard commissioning tests.

Keywords: automatic control system, PLC electronic control, gas turbine, turboprop engine, marine equipment

1. Introduction

A marine propulsion system's purpose is to convert a primary form of energy into mechanical power, and to convey this one to the propulsion system, in order to ensure the necessary torque for driving the propeller. Gas turbine engines experience degradations over time that cause great concern regarding engine reliability, availability, and operating costs [1, 2, 3]. Therefore, after becoming out-of-date and beginning to be unreliable for the precision required in marine ships, these engines need to be replaced.

The paper presents the replacement of an out-of-date marine gas turbine engine with a newer propulsion system, on a T22 frigate. The new Pratt & Whitney

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ST40M is derived from the PW150A aviation turboprop engine [4]. Its power is the same as the one of the old engine, Rolls Royce Tyne [5], namely 4 MW. However, after the last capital revision of the Tyne engine, the maximum power obtained decreased to less than 3 MW.

Fig. 1. T22 frigate to be revamped [6]

ST40M is currently being used only on the series of Norwegian small superfast, stealth missile corvettes Skjold, powered by a Combined Gas-and-Gas (CoGaG) propulsion system consisting of four Pratt & Whitney gas turbine engines: two ST18M with output power of 2,000 kW gas turbines for cruise speed, and two larger ST40M turbines of 4,000 kW for sprint speed [7]. These gas turbines have been tailored for marine applications and offer high efficiency and low weight [8].

Pratt & Whitney ST18 engines have been used for cogeneration purposes, at Suplacu de Barcău power plant, installed and commissioned by the Romanian Research and Development Institute for Gas Turbines COMOTI. The power plant was built with the aim of studying the efficiency in growing oil production with lower costs for the electrical and thermal energy used in oil field. Each line consists of an electrical generator powered by one aero derivative ST18 turbine engine, a heat recovery steam generator with afterburner, and linked installations. The ST18M proved its efficiency and reliability, with 32,000 hours between overhauls. Operating over 55,000 hours from 2004 to 2008, the two lines of the cogeneration plant provided an efficiency of 85% [9]. These gas turbines are tailored for marine applications, with high efficiency and low weight.

2. Mathematical model regarding engine operation

From energetic point of view, a marine propulsion system consists of the power source (main propulsion engine) and the energy consumer (thruster). Among currently used marine thrusters, propellers best cater for current naval technology, most frequently used, and generally most efficient type of marine propulsion [10].

Pratt & Whitney delivers ST40M power prop engine (Figure 2), without the control electronics. For functioning as cruise engine, this one has to be adapted to the specific type of ship.

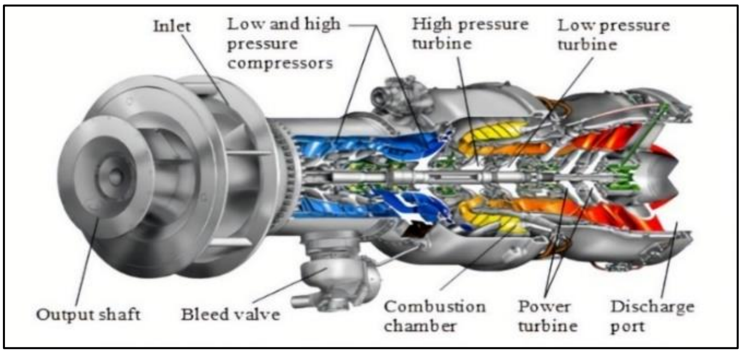


Fig. 2. Section through the 3D CAD model of ST40M gas turbine engine

The characteristic curve of ST40M gas turbine, given in the specifications [11] for natural gas fuel operation, shows the relation between the output power at shaft and the exhaust fuel gas flow. Relying on specified characteristic for power in relation with the fuel gas discharge flow, we extracted the data in Table 1, using the exhaust gas flow (G_{gT}), calculated with the relation:

$$G_{gT} = G_c \cdot (\alpha \cdot L_0 + 1) \tag{1}$$

where: G_c – fuel flow in kg/s; α – air excess; L_0 – stoichiometric coefficient iterated determining the excess air α used to calculate the power (3728 kW) from Table 1, using natural gas fuel, for which the stoichiometric coefficient L_0 is 17.16.

Table 1

Power at turbine shaft vs. exhaust gases

Shaft power SHP	Shaft power [kW]	Exhaust gas flow (lb/s)	Exhaust gas flow (kg/s)
1000	745.7	18	8.164
2000	1491.4	21	9.525
3000	2237.1	25	11.339
4000	2982.8	28	12.700
5000	**3728.6**	**30**	**13.607**
6000	4474.3	32	14.514
7000	5219.9	34	15.422

In Table 2 we determined Q_{cn} (exhaust gas flow injected in the combustion chamber of the turboprop engine) and the maximum shaft power in relation to the experimental fuel flow.

Table 2

Exhaust gas flow and maximum shaft power depending on fuel flow Q_{cn}

Q_{cn} [l/min]	Q_{cn} [kg/s]	Exhaust gas flow [kg/s]	Shaft power [kW]
2	0.0274	1.432	90.9
5.7	0.0780	4.081	156.4
10.4	0.1423	7.446	617.3
14.8	0.2025	10.59	1842.7
17.5	0.2394	12.53	2974.8
19.0	**0.2599**	**13.60**	**3728.7**
24.1	0.3297	17.26	6959.3

At a fuel flow Q_{cn} of 19 l/min, a maximum exhaust gas flow of 13.6 kg/s at a power of 3728.7 kW was calculated iteratively using relation (1). For this shaft power, we also determined the acceleration percentage and the fuel flow. Table 3 shows experimental data acquired, the bolded values being used for computations.

Table 3

Parameters of naval propulsion with ST40M gas turbine

Parameter	1	2	3	4	5
PCL [div]	24	40	50	54	56
Throttle [%]	6	42	64	76	**81.8**
P1 [bara]	1.008	1,000	0.997	0.993	0.990
T1 [°C]	19.0	19.0	19.0	19.0	19.3
NH [rpm]	23800	26140	27800	28600	29100
NL [rpm]	17700	21000	22900	23910	**24650**
NTP [rpm]	4920	6775	8580	9260	9900
ITT [°C]	471	611	719	772	**813**
T6M [°C]	414	488	540	563	**583**
Qcn [l/min]	5.7	10.4	14.8	17.5	**19.0**

Depending on the propulsion turbine speed NTL, the parabolic variation curves for acceleration (Throttle [%]), and fuel flow Q_{cn}) were determined, which allowed to calculate the acceleration percentage at 9900 rpm, namely 81.8%. The values of the free turbine speed and fuel flow required for acceleration of 81.8% and 100% respectively were determined using the universal characteristic of the turbine given by relation (2) hereinafter.

$$\overline{\boldsymbol{W}}_{\boldsymbol{TP}} = \boldsymbol{f}(\boldsymbol{G}_{\boldsymbol{gT}}, \boldsymbol{N}_{\boldsymbol{TP}}) \tag{2}$$

where: G_{gT} is the exhaust gas flow and N_{TP} is the propulsion turbine speed.

The variation curves and their polynomial approximation equations for propulsion turbine speed and fuel flow in relation with throttle opening percentage are represented on the graphs below.

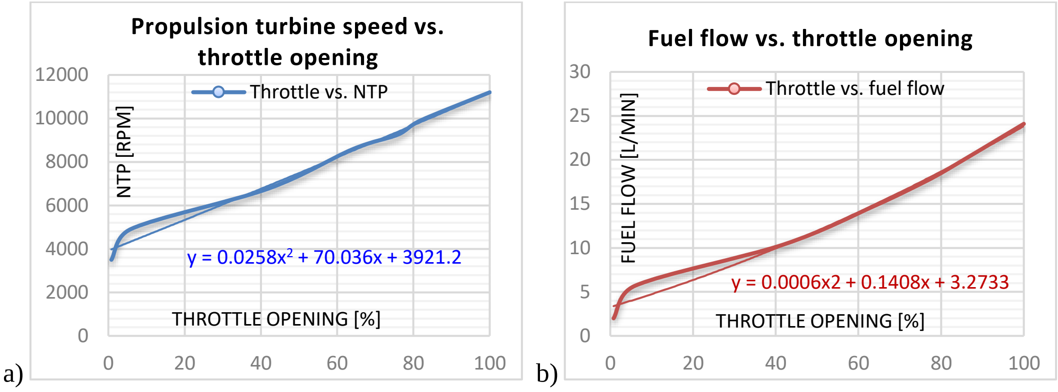


Fig. 3. a) Propulsion turbine speed and b) Fuel flow, depending on throttle opening percentage

Having the temperatures before and after the propulsion turbine, using the actual diesel fuel flow Q_{cn} in (kg/s), we can obtain the free turbine power W_{TP}:

$$\boldsymbol{W_{TP} = G_{gT} \cdot (H_{ITT} - H_6) \cdot \eta_T} \qquad (3)$$

where: H_{ITT} and H_6 are the exhaust gas enthalpies before and after turbine, depending on exhaust gas temperatures and excess air α, considered constant.

G_{gt} was determined, considering the stoichiometric coefficient of diesel fuel, L_0 = 14.7. The enthalpies were calculated according to the thermodynamic tables for exhaust gases using the excess air coefficient α = 2.991 **[**12**]**. Considering turbine efficiency η_T = 0.86, we obtain the real shaft power, $W_{TP\text{-}cor}$ in Table 4, along with the enthalpies for ITT and T_{6M}, with respect to the temperatures from Table 3. The shaft power is also given according to these parameters.

Table 4

Estimation of the shaft power depending on enthalpies

ITT (K)	**T_{6M} (K)**	**H_{ITT} kJ/kg**	**H_{T6M} kJ/kg**	**W_{TP} (kW)**	**$W_{TP\text{-}corrected}$ (kW)**	**$Q_{exhaust\_gas}$ (kg/s)**	**Throttle (%)**
471	414	482.3	421.2	258.6	222.4	3.51	6
611	488	633.9	501.8	1020.1	877.3	6.40	42
719	540	751.1	556	2144.1	1843.9	9.12	64
772	563	809.7	582	2958.9	2544.6	10.78	76
813	583	854.1	602	3556.7	**3058.8**	**11.70**	**81.8**
Theoretical maximum from P&W ST40M datasheet [11]					**4040**	**13.88**	**100**

The subsequent graphs show the power variation with throttle opening and with exhaust gas flow respectively, in the experimental data domain.

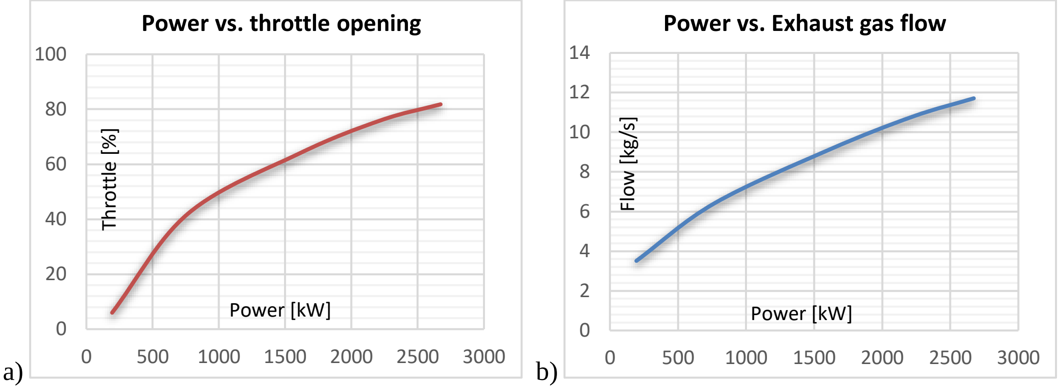


Fig. 4. Shaft power variation with: a) throttle opening and b) exhaust gas flow

From the ST40M data [11], the maximum power is 4040 kW, for fuel flow at 100% operation, at a gas flow of 13.88 kg/s (30.6 lb/s). Thus, at an acceleration of 81.8% we would have a theoretical axis power of 3304.72 kW. The difference between the two power values is:

$$\boldsymbol{\delta_{calculation}} = \frac{(\boldsymbol{P_{theoretical@81.8\%}} - \boldsymbol{W_{TP-corrected}})}{\boldsymbol{P_{theoretical@81.8\%}}} \cdot \mathbf{100} \; = \mathbf{19.1\%} \tag{4}$$

It has been demonstrated that changing the fuel from natural gas to diesel can modify the parameters with 2-4%, at the same shaft power [13]. Therefore, since the ship uses diesel, the total maximum difference from the theoretical power would be about 21-22%.

The propulsion turbine rotation speed NTP at maximum power would be below 12000 rpm (Figure 3), while the theoretical rotation speed is ~14000 rpm [11]. To sum up, because the lifetime of Tyne turboprop engine has shortened, both the acquired data and computations show that we would have a decrease in the maximum theoretical power with ~20%, down to 3100-3200 kW.

3. Automation and electronic control system design

Choosing a propulsion system for maritime applications supposes the integration of a large number of elements into a limited functional space, choosing its components (propulsion engine, gear transmission and thruster), and adjusting them according to the imposed constraints and available space, as well as arranging the components in such a configuration so as to comply with the required performance [10, 14]. The advantages of electronic control in terms of accuracy and adaptability to various differing requirements are renowned for a long time. Among the available control systems [15], electronic control currently offers the highest reliability and adaptability, and can easily and rapidly be custom tailored for any arising situation or parameter change [16]. An automated electronic control system with programmable logic controller (PLC) was designed, built, installed and tested together with the ST40 engine for the replacement of the old propulsion system.

The gas turbine control is performed from the engines room of the ship, situated on the deck above the hull, where the four propulsion engines of the frigate are installed. The gas turbines control is realized from the Panel PC on the local control cabinet (LCP) interfacing the PLC. This one receives the operator’s command, analyses the cruise mode of the ship, the regimes of the other propulsion systems, and conveys the electronic command to the PLC, which triggers the actuation elements for driving the engines. The PLC also monitors and acquires the parameters for operation in optimum conditions, setting thresholds for a safe and secure operation. The Panel PC offers all the functionalities of a computer, enabling the software program modification on-site, with all sequences and parameter limits.

The PLC assembly located in the local control cabinet is connected to the current adapters located in the junction boxes (temperatures – TJB, pressures – PJB, speeds and vibrations– VJB), in close proximity of the engine. The PLC’s central processing unit (CPU) communicates over Ethernet with the Panel PC on the local control cabinet in engines room, and with the control panel and tests computer in the engines control room. Bench tests (Figure 5a) of the engine with the automation system were conducted according to the ones recommended by manufacturer, after which this one was installed in the place of a Tyne on the frigate (Figure 5b).

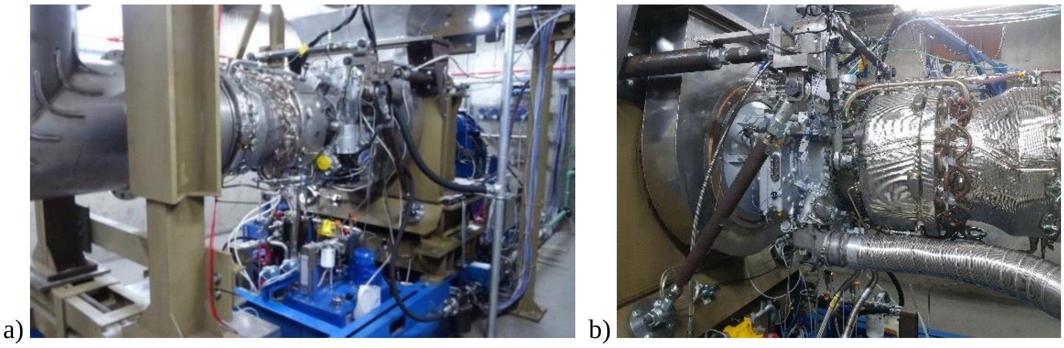
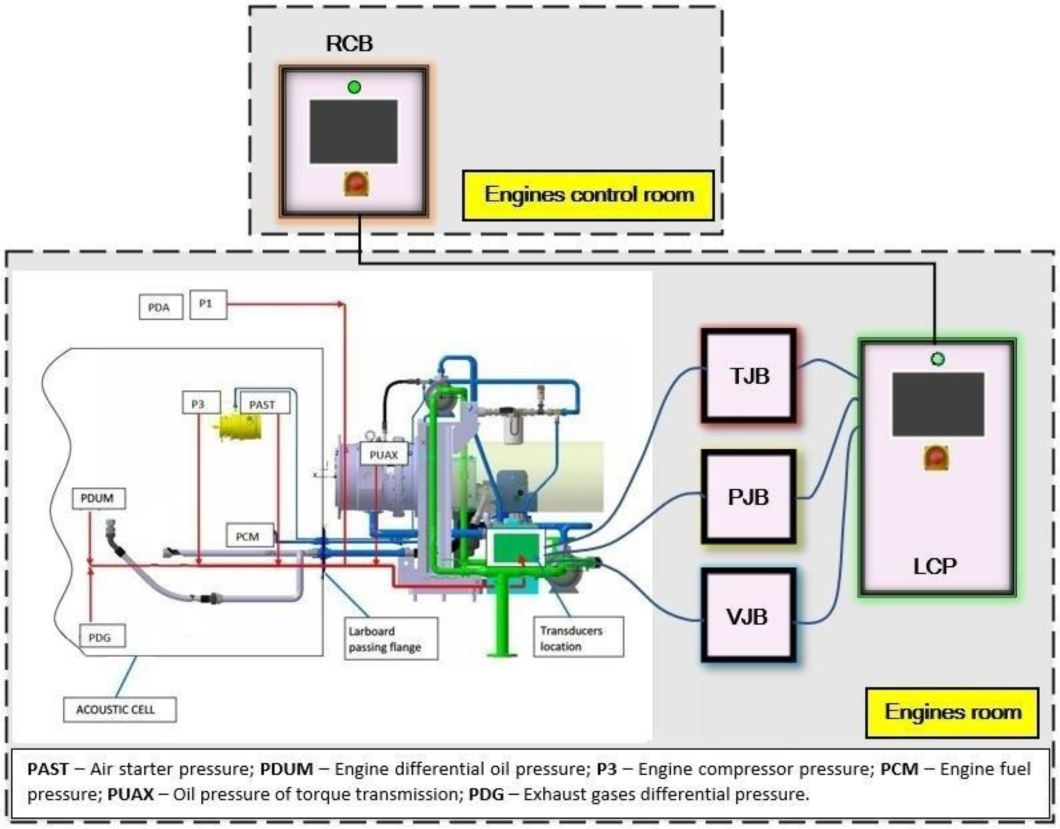


Fig. 5. ST40M gas turbine: a) on test bench, and b) installed on the ship

The block diagram of the automation system hardware physical components is presented in Figure 6 hereinafter. Placing the transducers configuration considered the distance from measured parameter, ease of debugging, and minimizing the environmental influences on the devices (such as a potential salt water penetration inside the ship, humidity, ambient temperature and pressure, etc.).



PAST – Air starter pressure; **PDUM** – Engine differential oil pressure; **P3** – Engine compressor pressure; **PCM** – Engine fuel pressure; **PUAX** – Oil pressure of torque transmission; **PDG** – Exhaust gases differential pressure.

Fig. 6. Block diagram of the automation control system

The designed automation system enables an integrated engine control and monitoring with programmable logic controller. The programmed sequences implemented in Proficy Machine Edition, the software for VersaMax PLCs, are presented hereinafter.

- **START-UP.** The conditions that must be met for the start-up sequence to begin are: Cool engine (inter turbine temperature ITT<150°C); Fuel pressure >0.8 bar; Engine speed <1000 rpm; Deactivated stop valves (stop valves bypass the fuel tray so that it does not get into the engine); An override button is provided, allowing engine start-up overseeing the above two temperature and pressure conditions. There are three start-up possibilities, presented hereinafter.

a) Cold start-up – is performed without fuel ignition, only by gradually opening the air inlet valve and, depending on the pressure attained, it is tried to maintain the engine at a speed of 6000 rpm. During in house tests, we obtained an 8 bar pressure, rendering a speed of ~5000 rpm.

b) Deco start-up – when it was just taken out of the warehouse (the fuel valve is opened at 15% and the fuel is cleaned of impurities).

In cold and deco start-up modes, the engine functions for 45 s and then stops.

c) Hot start-up – begins with opening the air inlet valve. When the engine reaches 3200 rpm, the speed is maintained constant by controlling the air valve. When reaching this speed, the spark plugs are ignited. The fuel valve is opened progressively. If 15 seconds after it has reached 3200 rpm, the inter-turbine temperature ITT does not increase over 150°C, the engine is automatically shut down, since not reaching this temperature means that the spark plugs did not ignite.

If ITT > 150°C, the opening of the fuel valve is continued and, at 1600 rpm, the spark plugs are turned off and the air valve is closed. The opening of the air valve is being carried on. If within 50 seconds after reaching 3200 rpm, from the moment fuel supply has started, the speed has not reached 19000 rpm, the engine is emergency shut down and the bypass valves are opened. The threshold speed between start-up and normal regime operation is 19700 rpm.

- **NORMAL REGIME OPERATION.** Hereinafter, if the hot start-up sequence finished successfully and all conditions are met, after reaching 20000 rpm, no action is taken for the next 3 minutes, as it is an interval reserved for thermal stabilization. In emergency situations that can arise during frigate operation on sea, this condition can be overridden. After these 3 minutes, the speed can be modified both from the power control lever (PCL) situated in engines control room, as well as by pressing the virtual arrows on the touchscreen panel. The only difference is that propeller angle cannot modified from the operator panel. Initially, the angle is 0°, the blades being in the same plane, perpendicular on the engine shaft. From the lever, the angle can be modified, for allowing ship advancing.

The command of ST40M gas turbine engine can thus be performed from the local control panel or from the engine control room. The so-called remote control from engines room is realised by means of the power control lever situated on the ship control board. ST40M also has two surge valves after the second compressor stage, namely valve 2.2 and valve 2.7. Valve 2.2 is gradually closed from the fully opened position at 20900 rpm, to completely closed at 23200 rpm. Valve 2.7 is closed at 21500 rpm, being an all or nothing flow control valve.

In the speed domain from 20000 rpm to 29500 rpm, the ship is in normal operation, being able to be controlled according to captain’s orders.

- **SHUTDOWN**

a) Normal shutdown – can be activated either automatically by exceeding the set limits of less important parameters (such as fuel pressure, oil pressure, oil temperature, vibrations etc.), or manually by pushing the shutdown button (usually for the sprint engines to enter regime or for accosting. The engine is decelerated until reaching 20000 rpm, maintaining it at this idle speed for 5 minutes. During this time, while the engine cools down, in case it was shutdown due to exceeding a parameter limit, there is another override button that cancels the shutdown sequence (for unexpected situations during frigate operations on sea). If the engine shutdown has not been cancelled during these 5 minutes, the stop valve is opened and the fuel valve is closed, the engine stopping completely in about 1 minute (speed 0).

b) Emergency shutdown – occurs when one of the important parameters (such as turbines speeds or ITT exceed the prescribed limits. The fuel is cut, the air valves and surge valves are opened, the air valve is closed, and the spark plugs are closed. It is realised by pushing either of the two emergency shutdown (ESD) buttons – one placed on the local control panel near the engine, and one on the remote control box upstairs in engine control room. In this room where the engines control is performed, there is a switch for controls commutation on deck to the ship's captain.

The tests performed on the ship involved a minimal intervention in the automatic control of engines and propellers. The throttle controlling the power of the old engine was used for the new engine so that this signal is acquired, and depending on it, the engine provides the necessary power to the ship (up to around 3.5 MW). The high-pressure compressor signal (throttle position) is converted into a unified 4-20mA signal by the pressure transducer. Its value is converted, by the implemented software program of the PLC, into the corresponding speed of the high-pressure compressor required for the ST40M gas turbine. Relying on this signal, the position or opening of the fuel valve is regulated automatically, for setting the desired speed of the ship. The main screen with ST40M diagram and real time parameter values displayed on the LCP is presented in Figure 7.

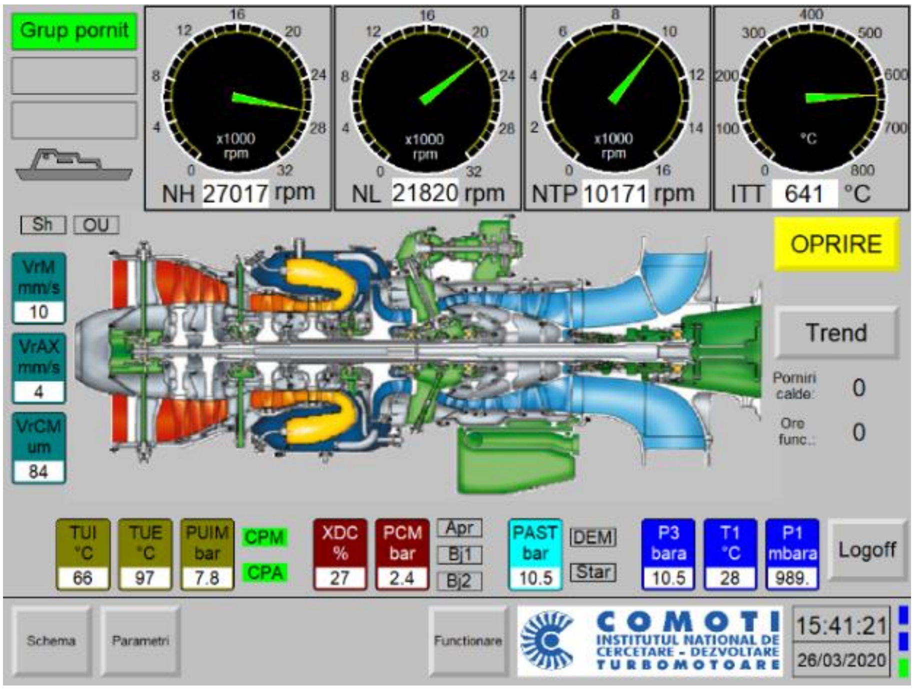


Fig. 7. Main screen with gas turbine and important parameters during operation

The graph in Figure 8, represented with acquired parameters, shows that during tests the engine reached a speed between ~22,000÷28,800 rpm. By using solely this engine, the ship was driven up to a cruise speed of 8 knots (~22 km/h).

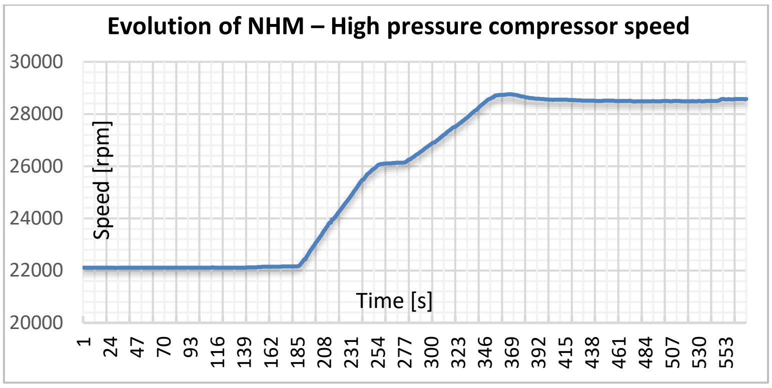


Fig. 8. Evolution of the acquired values for the speed of the high-pressure compressor

The inter turbine temperature is considered to be at least 800°C by fuel flow decrease condition ($ITT_{lim} = 800°C$). At every time increment $\Delta t = 0.4$ s, this condition is verified.

4. Conclusions

The evolution of the essential parameters recorded and acquired for ST40M gas turbine engine shows the stability of the engine in every functioning regime (idle and loaded). The implemented automated electronic control system has proved reliable, accomplishing the optimum control of the gas turbine, with the functions of monitoring, displaying and acquiring of the values of operation parameters. The operation was performed in good conditions and a safe and smooth engine characteristic was achieved by setting the temperature limiting protection. The touch screen control panels interfacing the PLC provide an easily and safely controlled operation, facilitating the revamp of the frigates by replacing the out-of-date Rolls Royce Tyne engine with Pratt & Whitney ST40M marine gas turbine engine, together with developing and implementing the afferent electronics tailored for this specific application. The chosen configuration of the system has proved its compatibility with the given naval requirements, also being easily adaptable.

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