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Adaptive Control for Marine Gas Turbine

Filip Niculescu, Adrian Savescu, Mirela Letitia Vasile
Automation Department
INCDT Comoti
Bucharest, Romania
filip.niculescu@comoti.ro

Abstract *— Gas turbines used in marine propulsion ensure increased efficiency and safety, with a very good power / weight ratio and with low maintenance and operation costs. The paper presents the control of the gas turbine so that it works in optimum operating conditions under any regime. The authors' contribution consisted in the elaboration of control equations starting from the general equations of the gas turbine. These equations have been implemented in a digital control system that metered the fuel depending on the speed deviation. Finding the control algorithm involved determining the adjustment parameters so that the engine behaves stable at any speed. After testing the configuration on the stand, the actual testing was carried out on board the ship.*

Keywords— turbines, adaptive control, control nonlinearities, digital control

I. INTRODUCTION

The propulsion of gas turbines is currently used on fast ships like ferryboats, cruise ships and large military ships (aircraft carriers, destroyers, frigates). The gas turbines have the advantage of generating great power, and their main disadvantage is the relatively high fuel consumption [1].

The use of gas turbines on board ships for specific advantages involved the development of automatic control and control systems optimized for this type of propulsion. A typical marine gas turbine propulsion system installation consists of separate controls for not only the gas turbine but also the ship systems, reduction gearbox and exhaust system. Advantages in reduction complexity, lower weight, ease of installation/ maintenance and reduced cost of ownership can be achieved by minimizing the quantity of individual subsystem controls [2].

The gas turbines, currently used for naval propulsion, are constructively similar to those used in aviation. Most naval gas propulsion systems with gas turbines used to propel commercial vessels are two-stage compression.

The ST40M is an aero derivative gas turbine, manufactured by Pratt & Whitney Canada, whose performance is correlated with the performance of the PW150A gas turbine. The power turbine (free turbine) consisting of two axial stages remained virtually unchanged except that the power shaft of the last two stages was lengthened to exceed the width of the new intake device. The combustion chamber is the same as inverted ring type, but with the modified geometry for the use of diesel instead of aviation fuel. Kerosene was replaced with standard naval diesel fuel for economic reasons [3].

The ST40M gas turbine has been modified to meet the marine standard, i.e. treated for resistance to salt mist corrosion.

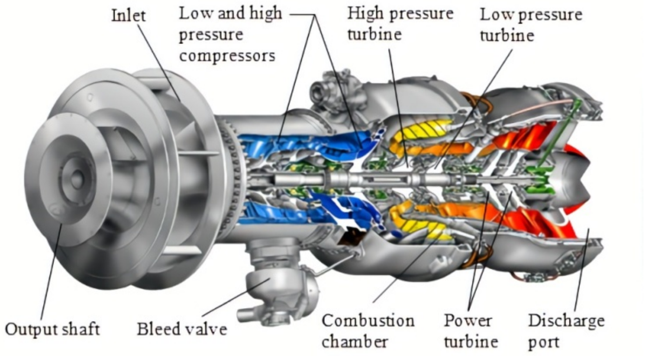

Fig. 1. Section through the model of ST40M gas turbine [4]

II. GENERAL GAS TURBINE EQUATIONS

In the gas turbines the regulated parameter is the compressor group speed n in the single-rotor engines or the high pressure compressor group NH speed, in the two-rotor engines, the regulating factor being the fuel flow Mc in the combustion chamber. As a starting point for the elaboration of the principle scheme of the regulators and the elements of the fuel system are the characteristics that give the variation of the different parameters depending on the regulated parameter.

The equations are linear if they are studied in the vicinity of a regime and solved for the parameters that interest us. When writing the nonlinear system of equations that describes the engine, the characteristics of the different elements of the gas turbine are usually used: the characteristic of the compressor, the characteristic of the combustion chamber and the characteristic of the turbine.

If the characteristics of the different elements of the gas turbine are used depending on its physical parameters, an infinite number of characteristics are obtained for the gas turbine. To overcome this difficulty when describing the characteristics of the gas turbine elements, combinations of the physical parameters of the engine with the parameters defining the input conditions, obtained based on the theory of similarity, are used. The similarity theory allows that, on the basis of similarity parameters, we can express, instead of a functioning

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regime, all the similar regimes between them, provided that the basic principle of similarity and the possible limits of extrapolation of the experimental or theoretical results are respected.

The similarity parameters according to which the characteristic of the compressor is expressed are [5]:

$$n_s = \frac{n}{\sqrt{T_1}} \tag{1}$$

$$M_{sa} = \frac{M_a \times \sqrt{T_1}}{\sqrt{P_1}} \tag{2}$$

Where:

n –Speed of engine compressor

Ma – Air flow through compressor

T1 – Air temperature at inlet of compressor

P1 – Air pressure at inlet of compressor

For the turbine characteristic, the similar parameters are used, but refer to the total pressure P3 and the total temperature T3 of the gas at the turbine inlet [5].

In the two rotors gas turbine, as is the case with the ST40M engine, the mechanical connection between the high and low pressure rotors is lacking. The connection between the two rotors is only gas-dynamic.

We obtain a system of 17 equations with 20 variables, where it results that these variables can be written as functions of 3 variables, taken as independent parameters [6]. As independent parameters, the similarity parameters of the speeds of the two rotors and the similarity parameter of the fuel flow are taken. Thus any parameter of the motor can be written as a function of the three parameters:

$$x_{i0} = f\,(n_{JP0}, N_{IP0}, M_{c0}) \tag{3}$$

Which shows that for the two-rotor gas turbine the dynamic characteristic is a figure in space (Fig. 2).

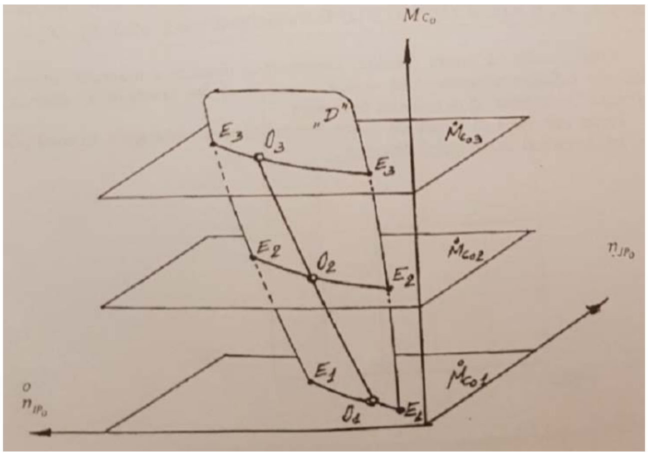

Fig. 2. O1-O2-O3 line of stationary regimes [5]

Along the line of stationary regimes there is the relationship between the reported low pressure rotor speed and the reported high pressure rotor speed:

$$n_{JP0st} = f\,(n_{IP0}) \tag{4}$$

Starting from this relationship, the control law can be established only between the fuel flow and the high pressure compressor speed [5].

$$M_{c0} = g\,(n_0) \tag{5}$$

The fuel flow determines the power output of a gas turbine. The fuel and air flow together determine the firing temperature, which is the gas temperature at exit of the combustion chamber [7].The stationary operating point is obtained by the intersection of this curve with that of the stationary operating modes of the engine:

$$M_{c0} = f\,(n_0) \tag{6}$$

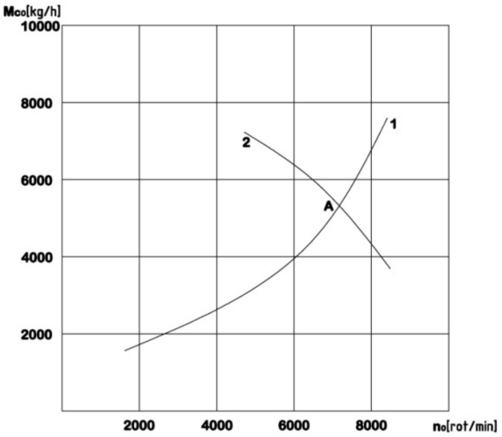

Fig. 3. The stationary operating point, 1-the line of stationary regimes, 2- the adjustment line

The system of these two equations having the solution:

$$n_0 = n_{0A} \tag{7}$$

The control laws can have different expressions, their main functions being to bring the engine as quickly as possible to the stationary point of operation, to avoid the surge areas in acceleration and deceleration and to protect the engine from exceeding constructive parameters such as the maximum temperature of the exhaust gases [8].

In adaptive control, the system repeatedly updates the controller parameters to reduce the error between the system's actual output and the output of an ideal target response model [9].

In the case of control laws, a particular interest is represented by the type functions produced by the parameters at real powers, an example being the one below [5]:

$$K = M_{c0} / (n_0 \times p_{20}) \tag{8}$$

Or:

$$M_{c0} = K \times n_0 \times p_{20} \tag{9}$$

III. ADAPTIVE CONTROL OF GAS TURBINE

The equations based on which the turbo engine control was developed have been coded as FADEC (Full Authority Digital Engine Control) and are the property of companies producing aircraft or industrial applications.

Although many system upgrades have been made since its conception, the lack of flexibility of the FADEC system for implementing logical functions or for adding additional inputs limits its use in marine installations [2].

The goal of the paper is to find some formulas based on which the engine can be controlled under optimal operating conditions.

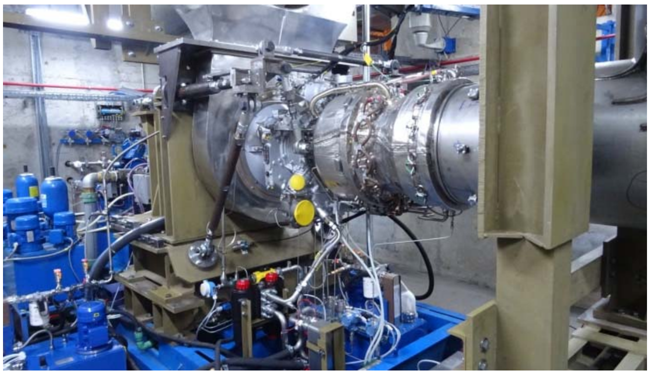

Fig. 4. The ST40M engine on the test bench

The chosen solution was the implementation of a proportional type regulator, but which has the proportionality factor variable with the deviation size.

Each $\Delta t = 0.2$ sec is calculated for NH – High pressure compressor speed:

$$\Delta NH = NHref - NH \text{ [rpm]} \quad (10)$$

It is calculated:

$$\Delta XDCC = KNH \times \Delta NH \text{ [\%]} \quad (11)$$

The proportionality factor KNH is variable and depends on the deviation from the NHref speed.

- If $\Delta NH < 30$ rpm, then:

$$KNH = 0.0002 \text{ [\%/rpm]} \quad (12)$$

- If $30 < \Delta NH < 70$ rpm, then

$$KNH = 0.0005 \text{ [\%/rpm]} \quad (13)$$

- If $[\Delta NH] > 70$ rpm, then

$$KNH = 0.0008 \text{ [\%/rpm]} \quad (14)$$

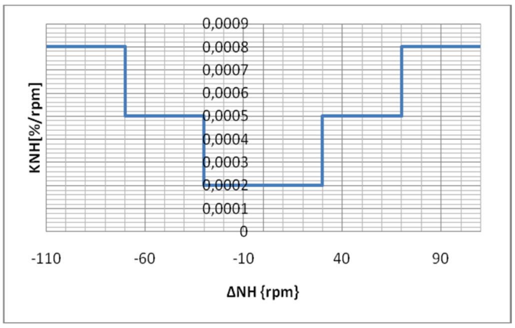

Fig. 5. The variation of proportionality factor with deviation from the NH ref speed

The software implementation in Proficy Machine Edition of the above formulas is shown in Fig. 6.

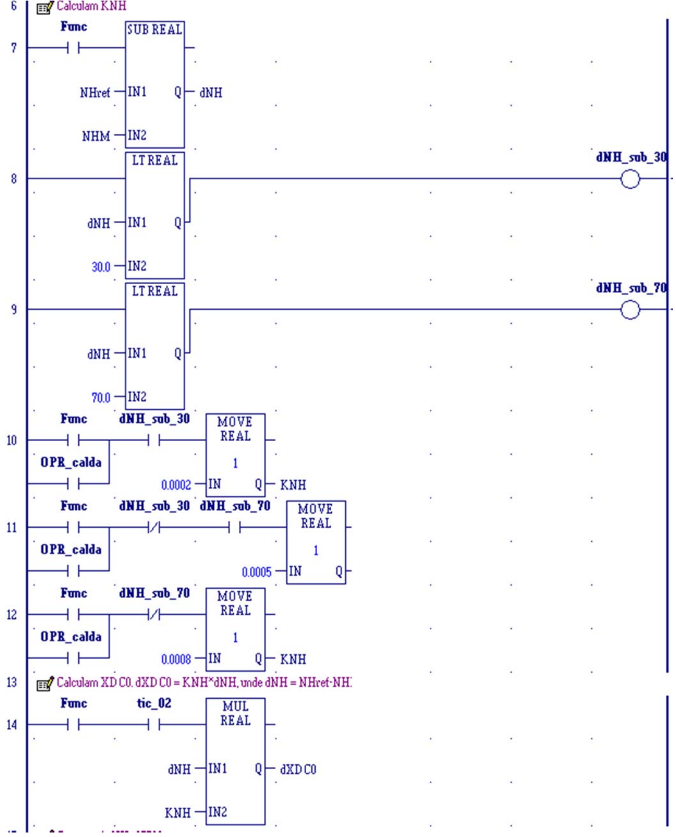

Fig. 6. Software module KNH calculation

To avoid the rapid acceleration of the gas turbine, which can lead to mechanical problems, it is limited the increase of the deviation of the fuel metering valve position ΔXDCC by fixing the maximum value.

- If NH<25 500 rpm, then

$$KN = 0.4 \quad (15)$$

- If NH> 25 500 rpm, then

$$KN = 0.2 \quad (16)$$

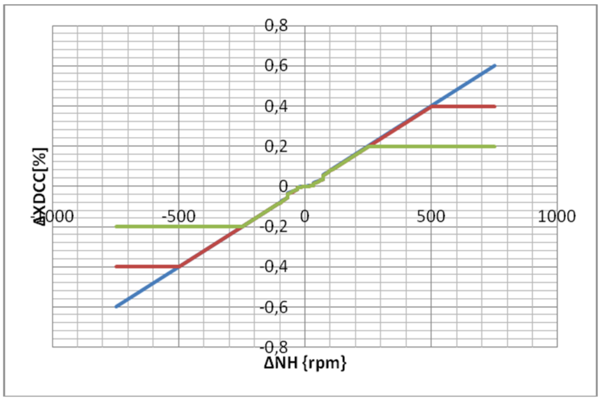

Fig. 6. The limitations of deviation XDCC

It is fixed:

- if $\Delta XDCC > KN$ [%], then

$$\Delta XDCC = KN \text{ [\%]} \qquad (17)$$

- if $\Delta XDCC < -KN$ [%], then

$$\Delta XDCC = -KN \text{ [\%]} \qquad (18)$$

It is calculated:

$$XDC0 = XDC_{n-1} + \Delta XDCC \text{ [\%]} \qquad (19)$$

Also we have software implementation in ladder of the limitation formulas is shown in Fig.8.

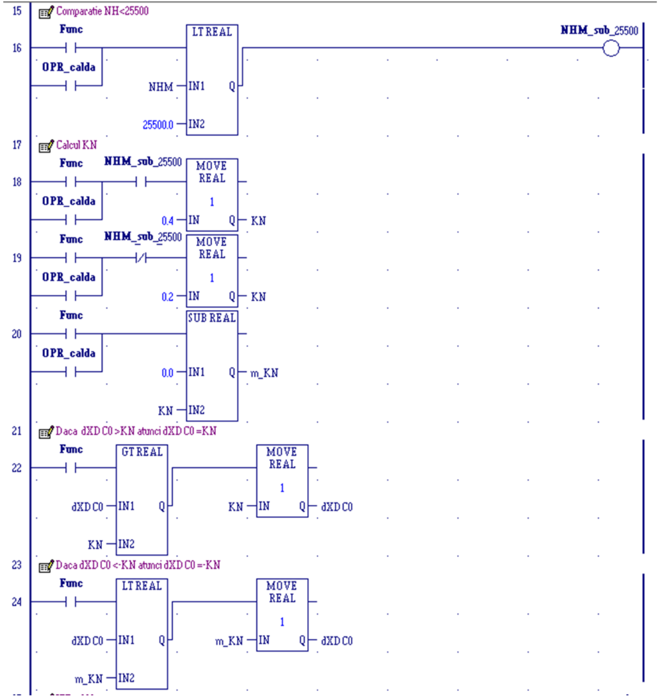

Fig.8 Limitation software implementation

At each step of the program, the XDC sequence is executed which modifies the current supplied to the fuel metering valve motor. This sequence links the position of the fuel metering valve to the fuel valve actuator [10].

The logic diagram of the fuel control in the stationary states of the engine is based on the formulas established for the control of the fuel flow depending on the speed of the NH high pressure compressor (Fig.9).

The results of tests made with the engine are showed in Fig. 10 and 11. It can be seen that the evolution of the NH speed and the reference speed NHref.

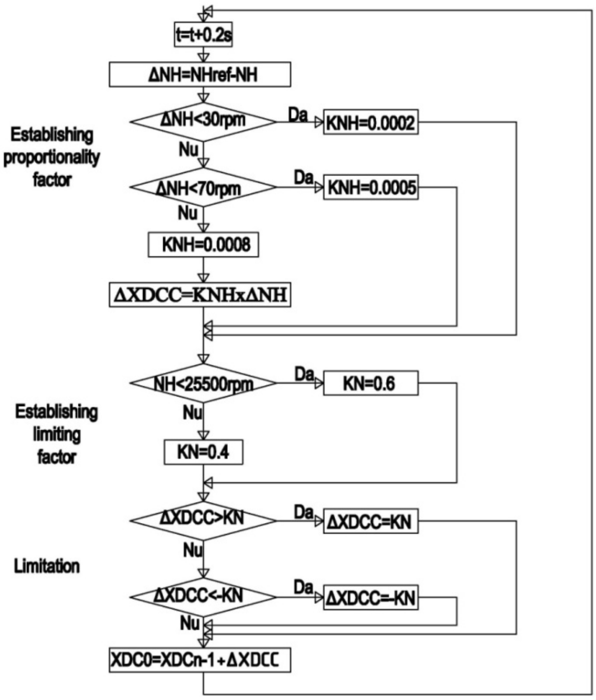

Fig.9 Logic diagram for regulating the position of the fuel valve with the speed of high pressure compressor

It is observed that the value of the NH speed follows the value imposed by the NHref speed, especially at high speeds.

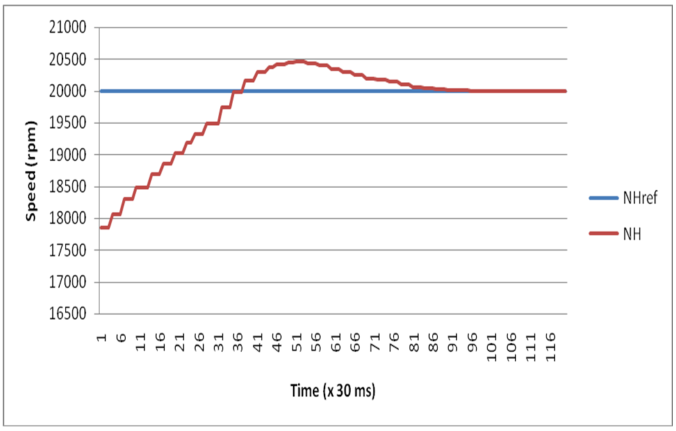

Fig.10 Override at startup

From the graph above we calculate the override factor as:

$$R_S = (Nv-Nr)/Nr \times 100 = 2.5 \text{ [\%]} \qquad (20)$$

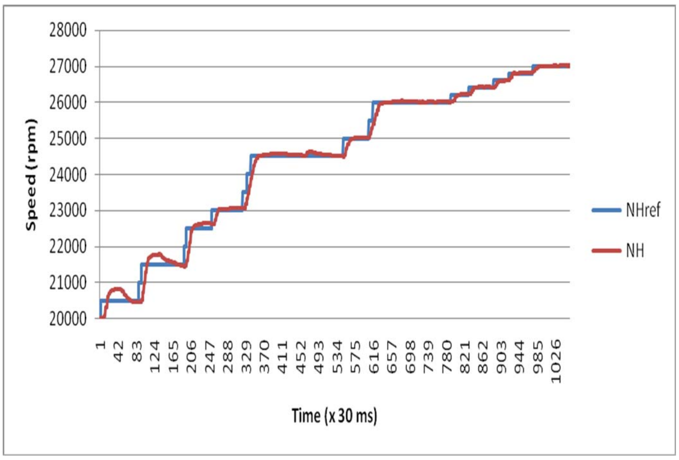

Fig.11 Evolution of high pressure compressor speed

In this graphic it is observed that the over-regulation decreases at high speeds which mean that the engine will quickly reach the required speed.

IV. CONCLUSIONS

Starting from bi rotor gas turbine general formulas, it has established and tested effective formulas for controlling a marine gas turbine. The authors have developed for the control of the engine a variant of proportional algorithm, in which the proportionality factor is variable depending on the deviation of the parameter to be controlled.

This mechanism was used in the setting of a gas engine for naval applications. The results obtained in the practical tests with the gas engine were very good.

ACRONYMS AND SYMBOLS

FADEC - Full Authority Digital Engine Control
NH – Speed of engine high pressure compressor
NL – Speed of engine low pressure compressor
FMU – Fuel Metering Unit
NHref – Speed reference of high pressure compressor
ΔNH – Deviation of high pressure compressor compared to the reference
KNH – Speed multiplying factor
KN – Increase / decrease speed limit
ΔXDCC – Position deviation of fuel metering valve corrected with NH speed
ΔXDC0 – Position deviation of fuel metering valve compared to the reference
XDCn-1 – Previous position of fuel metering valve
XDC – Actual position of fuel metering valve

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