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Using the technique of planning experiment for appointing characteristics of the naval gas turbine

In the process of the routine exploitation naval gas turbine the most important for exploiter is cooperation characteristic engine and his power receiver, in particular if a controllable pitch propeller is it. Because of the fact that ship's documentation does not often contain the that kind of characteristic, they undertook the attempt for her to appoint. Taking preliminary character of examinations into account they decided to carry them out on the laboratory stand with the gas turbine engine GTD–350. Appointing the mathematical model of above characteristics is an issue folded, requiring applying the theory of planning experience. In the article a manner of preliminary implementations of studies and their results were presented. Next results of statistical and content-related analysis of received findings and conclusions expressed on their base.

Key words: *naval gas turbine, experiment design, characteristics of the naval gas turbine*

Wykorzystanie techniki planowania eksperymentu do wyznaczania charakterystyk okrętowego turbinowego silnika spalinowego

W procesie eksploatacji okrętowych turbinowych silników spalinowych, spośród charakterystyk eksploatacyjnych, najistotniejszą dla eksploatatora jest charakterystyka jego współpracy z odbiornikiem energii. W szczególności jeżeli jest nim śruba o skoku nastawnym. Z uwagi na to, że dokumentacja okrętowa często nie zawiera tego rodzaju charakterystyki, podjęto się próby jej wyznaczenia. Mając na uwadze wstępny charakter badań, postanowiono je wykonać na stanowisku laboratoryjnym z turbinowym silnikiem spalinowym GTD–350. Wyznaczenie modelu matematycznego powyższej charakterystyki jest zagadnieniem złożonym, wymagającym zastosowania teorii planowania doświadczeń. W artykule przedstawiono sposób realizacji badań wstępnych oraz ich wyniki. Następnie wyniki analizy statystycznej i merytorycznej otrzymanych wyników badań oraz sformułowane na ich podstawie wnioski.

Słowa kluczowe: *okrętowy turbinowy silnik spalinowy, plan eksperymentu, charakterystyki okrętowych turbinowych silników spalinowych*

1. Introduction

During the exploitation multiengine power transmission systems very much from endurance considerations a regularity of straining driving engines is an important issue. It is particularly important in the event that a work is appearing two or more engines to one line shafts. Many means of implementation of the evenness of loads against working engines exist. However controlling their work according to the torque is the best solution. In such cases drive characteristics of power transmission systems are very important, in it also of driving engines. They let for determining their applications, analysis performance and cost-effectivenesses of the work, in the process let their exploitation for setting the strategy and costs. Then the exploiter is controlling load engines according to included characteristics in the instruction of exploitation or in case of automatic systems of steering, he is not participating directly in steering, for him an arrangement of automatic steering is doing it. An arrangement of automatic steering loading the ship's turbine engine with LM 2500 can be an example here. This arrangement is carrying out the program of keeping the constant speed of the ship selecting the pitch propeller and the stream of fuel. The realization is spending evennesses of loads based on the appointed torque not on the basis of the measurement, and on the basis of thermodynamic parameters. A so-called computer of the torque is carrying it out, which he line a torque of the power turbine appoints beloveds of physics quantities describing the work of an engine on the basis of the measurement. Not having at one's disposal the mathematical model, according to which he is appointed, a problem appeared in periodic of his verification e.g.: during diagnostic tests.

It became above with inspiration to undertake preliminary examinations, of which an inspection was a purpose whether a possibility of drawing up the credible mathematical model letting the energy appoint characteristics for different conditions for cooperation of the ship's gas turbine engine with the receiver in the form of the screw about the controllable pitch propeller. For appointing the mathematical model of above characteristics a theory of planning experiment which simultaneously lets for rational and effective conducting examinations was

used. Because of preliminary character of examinations they decided to conduct them on the laboratory stand with the gas turbine engine GTD – 350.

2. Preliminary examinations

Aspiring for appointing characteristics of the cooperation of the ship's gas turbine engine with the controllable pitch propeller, one should consider not one propeller characteristics, but their family. The family of these characteristics forms the field of the interaction of the power turbine of the engine with the controllable pitch propeller. From a point of view of the exploiter and the specificity of the use of ship's gas turbine engines, characteristics should present the relation of the useful energy led to the receiver of energy expressed through the useful torque, depending from:

- of the parameter being characteristic of an energy state of the gas generator of the engine:
  - rotation speed of the gas generator n_{GG};
  - temperature of the exhaust gas behind a combustion chamber T_3 or behind gas generator T_{04};
  - pressure of the air behind compressor p_2.

  The rotation speed of the gas generator n_{GG} is the most often use parameter.
- of parameter being characteristic of a cooperation of the power turbine with the propeller, at the pitch determined for her. It is most often the rotation speed of the power turbine n_{PT}.

They effected appointing the mathematical model of above characteristics according to the theory of planning experience. The theory of planning experiment has character general, independent of the scientific, combining the theory of experience and the theory of measurements. An entirety constitutes activities of examinations being aimed at appointing functional dependencies between sizes being characteristic of a object of examinations. It is embracing with oneself mathematical modeling, planning experience (of experiments) and statistical and content-related analysis of results of measurements [1,5,6]. Modeling constitutes the entirety of activities associated with determining the principle of functioning of the object of examinations. A device or a team of devices, as well as a set of events associated with functioning of the team of devices called the process can be an object of experimental examinations [5]. Getting the credible mathematical model is an aim of modeling (with covered with the degree of the simplification), enabling visualising of real functioning and behaving the object of examinations in different conditions of his work [1,5].

In examinations of machines and technical devices it is possible to distinguish the following purposes of creating of models [5]:

- for the purposes of the design, where the model is used for an optimization of the structure and parameters of the constructed object and is a tool of the quality assessment of structure, of elimination of weak points etc.;
- for the purposes of diagnostics, where the model is a ground for establishing the algorithm of diagnosing which he is leading for determining the current state (diagnoses) and of future object (prognosis);
- for the purposes of the use and steering, using the model for the decision making connected with functioning of the object (exploitation decisions).

The mathematical model of the object of examinations is determined with the physics quantities typical of him, between which they are occurring relations about character causally consecutive. These relations are reflecting the currently had knowledge about the object of examinations, from here models are also liable to a process of constant improving. They at construction of the mathematical model first are using basic rights and axioms of physics, expressing the balance of power, of moments, energy balances etc. They enable theoretical analysis of the object of examinations which can be independent of experimental examinations. For if theoretical bases are unknown or phenomena appearing in the object of examinations peculiarly are folded, it is possible to act differently. One should then create the quality model, next to draw the plan of experience up, and after carrying experience out and the analysis of the results to aspire with the help of function of the object of examinations, being only an approximating function, for creating the model of the mathematical building of examinations. Aspiring for creating the mathematical model one should take into account the fact that the model is a perfect, abstract notion which is formed on the basis of assumptions certain, established from above simplifying the object of examinations. So the model is always „real" as the mathematical notion, however his adequacy is open to criticism to the real object of examinations. It is possible so to state that the object of examinations is only one, however of mathematical models can be a lot. One should so choose the most appropriate mathematical model of the building of examinations, considering adopted criteria of the adequacy to the real object of examination [1,5].

It is possible to appoint the function of the object of examinations as the relation approximating results of measurements. In the general perspective, issues concern the approximation of the function of the object of examinations:

- of choice of the function being supposed to constitute the function of the object of examinations;
- of choice of the method of the approximation of results of measurements of the function with the help chosen.

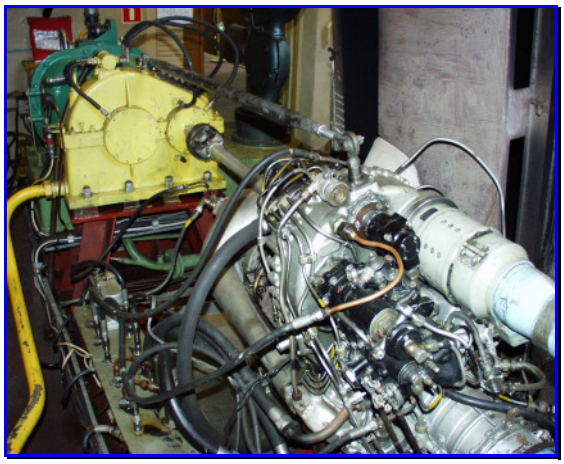
Planning experience is a consecutive research stage (of experiment) consisting measurements on accepting the appropriate programme of experience,

according to which they will be made. This program is often called the plan of experience (with program of measurements). Measurements should be made with preserving the required measurement uncertainty, with the calibration previously carried out of measuring paths. Choice of the relevant program of experience constitutes one of important decisions, which undertakes experimental examinations at the very beginning with. To this decision they have three essential premises [1,5]:

- information about the object of examinations, and especially about the type of the object and his properties;
- the usefulness of examinations, but especially an expression or examinations have cognitive or utilitarian character
- determining the quality mathematical model (of function) of object of examinations, connected directly with the state of the acquaintances typical of this model of theoretical bases

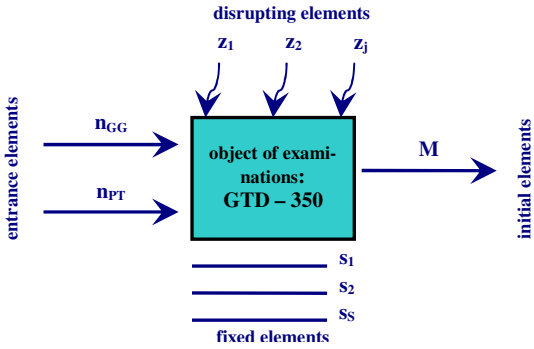
Many classifications of programs of experience exist depending on adopted criteria. Universally their division is accepted to static and dynamic. Static programs are applied for static objects of examinations, they are marked by establishing systems of the value of examined x_i factors before commencing experiment, and results of individual measurements are not affecting his program. However dynamic programs are applied to dynamic objects of examinations, they are characterized by the fact that next measuring points result from previous e.g. by applying iterative methods of the selection of arrangements of points. In examinations universally static programs which are being divided [1,5].

In connection with the above first they effected characterizing and determining principles of functioning of the object of examinations. Were decided to conduct examinations on the laboratory stand with the gas turbine engine GTD–350. The stand is presenting with oneself miniaturised ship's propellant systems with the gas turbine engine. Main elements constitute positions: two-rotor gas turbine engine GTD–350, one-step reducing transmission gear H-564 and the receiver of the energy in the form of the water-powered brake Froude'a of HWZ–3 type. Because of his rule of operation this brake is loading the engine similarly to a controllable pitch propeller about the adjustable jump [3,4]. The view of the stand is showing picture. 1.



Pic. 1. The laboratory stand with the gas turbine engine GTD–350

Next they effected determining the set of elements being characteristic of a object of examinations. They are entrance elements: the rotation speed of the gas generator n_{GG} and the rotation speed of the power turbine n_{PT}. A useful torque M is an initial element. For the harvest of the element of constants which values are not changing oneself in the process of examinations, to rank it is possible e.g.: parameters of the structure of the considered object of examinations. Fixed elements are often omitted from the consideration to founded and their unchanging influence on initial elements in the process of examinations. However disrupting elements these are other parameters, of which values they can change in the process of experience and they can influence the initial element e.g. a temperature, a pressure and a relative humidity of surroundings or a technical condition of individual elements of the engine are being ranked among these parameters. Therefore hereinafter of examinations results of measurements will be brought about to normal weather conditions.



Pic. 2. Elements being characteristic of a considered object of examinations

Too normal weather conditions is entertaining one another: barometric pressure $p_{0WZ} = 101325 Pa$, absolute temperature $T_{0WZ} = 288{,}15 K$ and absolute

humidity $\varphi = 0$. Picture 2 is showing elements being characteristic of a considered object of examinations.

On the basis of the harvest of elements being characteristic of a object of examinations his quality mathematical model was determined:

$$M(n_{GG}, n_{PT}) = 0 \tag{1}$$

as well as an approximation function was accepted into figures of the polynomial, as well as the method of the approximation. To most often applied approximation polynomials are applied [2,5]:

- linear polynomials;
- linear polynomials with interactions (cooperations taking into account);
- square polynomials;
- square polynomials with interactions of the first order.

During further research decided they made simultaneous analysis of a few approximation polynomials with a view to choosing the most fitted to results of measurements. A method of the least squares was used for the approximation [6]. Considering above they decided to accept functions of the object of examinations in the figure of the following polynomials:

- linear function without interaction, expressed with formula:

$$M = b_0 + b_1 \cdot n_{PT} + b_2 \cdot n_{GG} \tag{2}$$

- linear function with interaction, expressed with formula:

$$M = b_0 + b_1 \cdot n_{PT} + b_2 \cdot n_{GG} + b_{12} \cdot n_{PT} \cdot n_{GG} \tag{3}$$

- square function without interaction, expressed with formula:

$$M = b_0 + b_1 \cdot n_{PT} + b_2 \cdot n_{GG} + b_{11} \cdot n_{PT}^2 + b_{22} \cdot n_{GG}^2 \tag{4}$$

- square function with interaction of the first order, expressed with formula:

$$M = b_0 + b_1 \cdot n_{PT} + b_2 \cdot n_{GG} + b_{11} \cdot n_{PT}^2 + b_{22} \cdot n_{GG}^2 + b_{12} \cdot n_{PT} \cdot n_{GG} \tag{5}$$

Accepting the appropriate programme of experience, according to which they will be was a consecutive, very important research stage performed measurements and enabling to appoint accepted approximation polynomials. After all, for further research a static determined, polyselection, rotation program was chosen. This program allows for appointing the linear and square function of the object of examinations, apart from that enables the appointment approximate values of the volume of the initial area with the same accuracy in all directions appointed of the reply [1,5]. The implementation of studies on the basis of the polyselection program requires the substantially justified compromise between informative-ness and with effectiveness. An also recalled already tractable-ness of the program is essential [5]. This condition in case of the considered object of examinations comes down to testing available associations of the n_{GG} value and n_{PT} in individual measuring points. So that the error of the approximation is possibly smallest individual values of entrance elements should be equivalent to roots of Czebyszewa polynomials. These roots are set from the relation [1,5]:

$$\hat{x}(T) = -\cos\frac{\pi \cdot (2 \cdot u - 1)}{2 \cdot n} \tag{6}$$

where:

u – next agreement (measuring point) of program;

n – number of arrangements of the program.

In the rotation program entrance elements assume five, meant symbolically values: $-\alpha$, -1, 0, 1, $+\alpha$. Measuring points consisting of the ± combination 1 they are being called the nucleus of the program, ± α points are so-called star points, and zero points constitute the centre of the program. Using the rotation program increasing is recommending to the number of measurements the program in the centre particularly in case of the objective impossibility of achievement of the programme in sure about him point [1,5]. They took advantage of such a possibility and they accepted not one, but five measurements in the centre of program.

Intrinsic values of individual standardized entrance sizes are being calculated from the pattern:

$$x = \bar{x} + \hat{x} \cdot \Delta x \tag{7}$$

where:

$$\Delta x = \frac{x_{\max} - x_{\min}}{2 \cdot \alpha} \tag{8}$$

$$\bar{x} = \frac{x_{\max} - x_{\min}}{2} \tag{9}$$

$\hat{x}$ - standardized value ($-\alpha$, -1, 0, 1, $+\alpha$)

The standardized α value is being called the element of the star shoulder and he is tabulated. In planned experience for two entrance elements the star shoulder is taking out α = 1,414 [5]. Program of rotation, two-factor, experiment without repeating they presented in table 1. Ranges of values of entrance elements are taking out for: of the rotation speed of the gas generator $n_{GG} \in \langle 57;80 \rangle$ and for the rotation speed of the power turbine $n_{PT} \in \langle 60;100 \rangle$.

Table 1. Program of measurements according to the rotation program for $n_{GG} \in \langle 57;80 \rangle$ and $n_{PT} \in \langle 60;100 \rangle$

No. of the measuring point u	Place of the measurement	Standardized value input elements		Input values real as the function of the elements standardized	
		$\hat{n}_{PT}$	$\hat{n}_{GG}$	n_{PT} [%]	n_{GG} [%]
1	nucleus of the measurement	-1	-1	65,86	60,37
2		-1	1	65,86	76,63
3		1	-1	94,14	60,37
4		1	1	94,14	76,63
5	star points	1,414	0	100	68,5
6		-1,414	0	60	68,5
7		0	1,414	80	80
8		0	-1,414	80	57
9	centre of the program	0	0	80	68,5
10		0	0	80	68,5
11		0	0	80	68,5
12		0	0	70	73,5
13		0	0	70	73,5

On the basis of the above program they made measurements for established conditions of the work of an engine on every load. They made measurements with the help of the measuring-registering system [3]. On individual established burdens they made the measurement of physics quantities during 10 sec., with the sampling rate of 10 Hz, and then they averaged. Later results of measurements were brought about to the arrangement of SI units or their multiples, a pressure of surrounding at appointing ruthless pressures was taken into account, and next results of measurements were brought about up to normals of weather conditions. On the basis of results of measurements they did calculations: of the power, the torque and the individual fuel consumption for each of recorded loads. The rotation speeds of the gas generator n_{GG} and the power turbine n_{PT} were described in [%] because of the fact of appearing of this individual on control and measurement devices, according to which they were controlling straining the engine. Taking measurements was preceded with carrying out the calibration of individual measuring paths with determining their measuring uncertainties.

3. Statistical analysis and content-related of findings

A statistical analysis was conducted on the basis of preliminary findings. For her aim the approximating relation was a purpose useful torque of the power turbine from parameters being characteristic of an energy state of the gas generator, around possibly with the best accuracy. For appointing the approximation relation accepted polynomials served (2), (3), (4), (5). Above approximation polynomials they surrendered to the statistical estimation, using measures of the accuracy of the approximation among which he ranks [1,5,6]:

- average mistake of the respect of the rate of the regression, S_{bi}
- quotient of the value of rates of the regression and the average mistake of the respect of rates of the regression $t = \frac{b_i}{S_{bi}}$, which apart from using for the evaluation the accuracy of the estimation, is a test of the gravity of parameters simultaneously in the process of the statistical verification of the model;
- sum of rests MS;
- rate of the determination R^2;

With best fitted approximation polynomial under the statistical account the one, for which the sum of rests MS is smallest and the rate are closest to the determination unities. Additionally one should pay attention to the value of the average mistake of the respect [1,5]. In table 2 values of characteristic elements and measures of the evaluation of fitting the approximation function were put together of considered object of examinations.

Taking into account above and given included in table 2 they stated that a square polynomial with interactions and of the first order was the best function of the object of examinations, on account of the smallest sum of rests and the rate closest to the unity of the determination. Apart from that this polynomial is characterized by cheapnesses of the average mistake of the respect, what values of the quotient are also providing the t about. Approximation relation after all sought they accepted in the form:

$$\begin{aligned} M = {} & 3109{,}007 + 3{,}009 \cdot n_{PT} - \\ & - 109{,}507 \cdot n_{GG} - 0{,}012 \cdot n_{PT}^2 + \\ & + 1{,}169 \cdot n_{GG}^2 - 0{,}152 \cdot n_{PT} \cdot n_{GG} \end{aligned} \qquad (10)$$

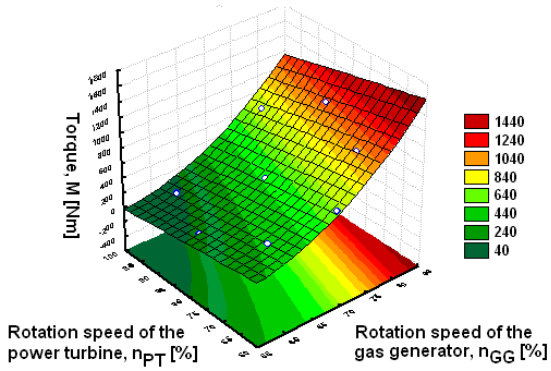
The received approximational polynomial lets the relation of the useful torque the deletion for the any rotation speeds of the gas generator n_{GG} (being characteristic for her of an energy state) and any speed rotational of power turbine n_{PT} (being characteristic of for her loading at the cooperation with the controllable pitch propeller about the given pitch). Relations of the useful torque in the function of the rotation speed of the gas generator and the power turbine they presented in picture 3.

Accuracy of estimating the received approximational function they carried determining the standard deviation [6]:

$$\sigma[M(n_{PT}, n_{GG})] = 3{,}5 \text{ N·m} \qquad (11)$$

as well as on the basis of the relative average square error [6]:

$$\sigma_{M(n_{PT}, n_{GG})} = 0{,}32\ \% \qquad (12)$$

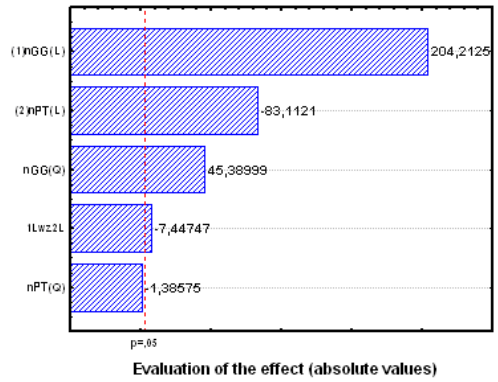


Pic. 3. Relation of the useful torque M in the function of the rotation speed of the power turbine n_{PT} and the gas generator n_{GG} for the scope of the scheme of experience

Table 2. Putting together characteristic elements and measures of the evaluation of fitting the approximation function of object of examinations

No.	Element		Analysed function of the object, M = *f*(n_{PT}, n_{GG})			
			Linear (without interaction)	Linear (with interaction of the first order)	Square (without interaction)	Square (with interaction of the first order)
1	Rates of the regression b_i	Const.	-1565	-1905	3873	3109
		n_{GG} (L)	41	46	-119	-110
		n_{GG} (Q)	-	-	1,15	1,17
		n_{PT} (L)	-9,4	-5,24	-7,44	3,01
		n_{PT} (Q)	-	-	-0,01	-0,012
		$n_{GG} \cdot n_{PT}$ (L)	-	-0,06	-	-0,15
2	Average mistake of the respect S_{bi}	Const.	243	1790	400	176
		n_{GG} (L)	2,9	26	10	4
		n_{GG} (Q)	-	-	0,07	0,03
		n_{PT} (L)	1,7	22	3,83	1,96
		n_{PT} (Q)	-	-	0,02	0,008
		$n_{GG} \cdot n_{PT}$ (L)	-	0,31	-	0,02
3	Quotient $t=b_i/S_{bi}$	Const.	-6,4	-1,06	10	18
		n_{GG} (L)	14	1,78	-12	-29
		n_{GG} (Q)	-	-	16	45
		n_{PT} (L)	-5,6	-0,24	-1,94	1,53
		n_{PT} (Q)	-	-	-0,53	-1,39
		$n_{GG} \cdot n_{PT}$ (L)	-	-0,19	-	-7,4
4	Sum of rests	MS	4603	5094	166	21
5	rate of the determination	R^2	0,957	0,957	0,998	0,999

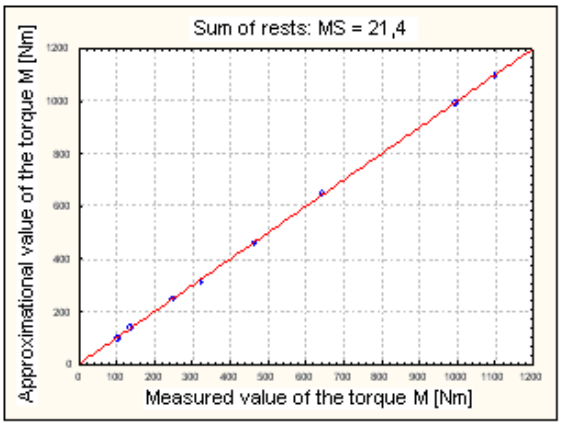
Next a graph of the evaluation of effects of fitting both the influence of individual entrance elements and their interaction to the torque was carried out, accepting the confidence level $\alpha = 0{,}05$ what was presented on the picture 4.



Pic. 4. Graph of effects standardized for the useful torque M

From the above picture it is possible in the simple way to read out, which effects of entrance elements are enjoying considerable influence to the determined initial element. Individual rates are put in order according to their absolute value what additionally is depicted in the bar form. They on the basis of the value of described rates in picture 4 state that both the rotation speed of the gas generator and the rotation speed of the power turbine are enjoying considerable influence to the useful torque. Taking into consideration the accepted function of the object of examinations (10) linear effects are most essential, and a square effect of the rotation speed of the power turbine is a least essential rate.

Later a picture of the relation of measured values was also carried out and approximate of useful torque what was shown on the picture below. Additionally a sum of rests which by the curve is gaining was put on it MS = 21,4 N·m.



Pic. 5. Relation of measured values and approximate of useful torque M

The above graph can serve the accepted adequacy for the preliminary examination of function of the object of examinations, since comparing the measured value of the torque during measurements with enumerated values is presenting with received approximate polynomial. The accepted function of the object of examinations well is reflecting the real object of examinations, since next points are negotiating in length for the straight, and the sum of rests is little.

Content-related analysis of findings constituted the final research stage, consisting in conducting the logical evaluation of received relations with real occurrences occurring in the inspected object. Examining the received adequacy is one of the most frequent forms of content-related analysis approximate relations. Examining the adequacy consisted in comparing characteristics of the interaction of the power turbine with the controllable pitch propeller, for chosen set pitch propeller H and the rotation speeds of the gas generator n_{GG}, received on the basis of measurements and calculations. Picture 6 is showing graphical interpretation of findings of the adequacy.

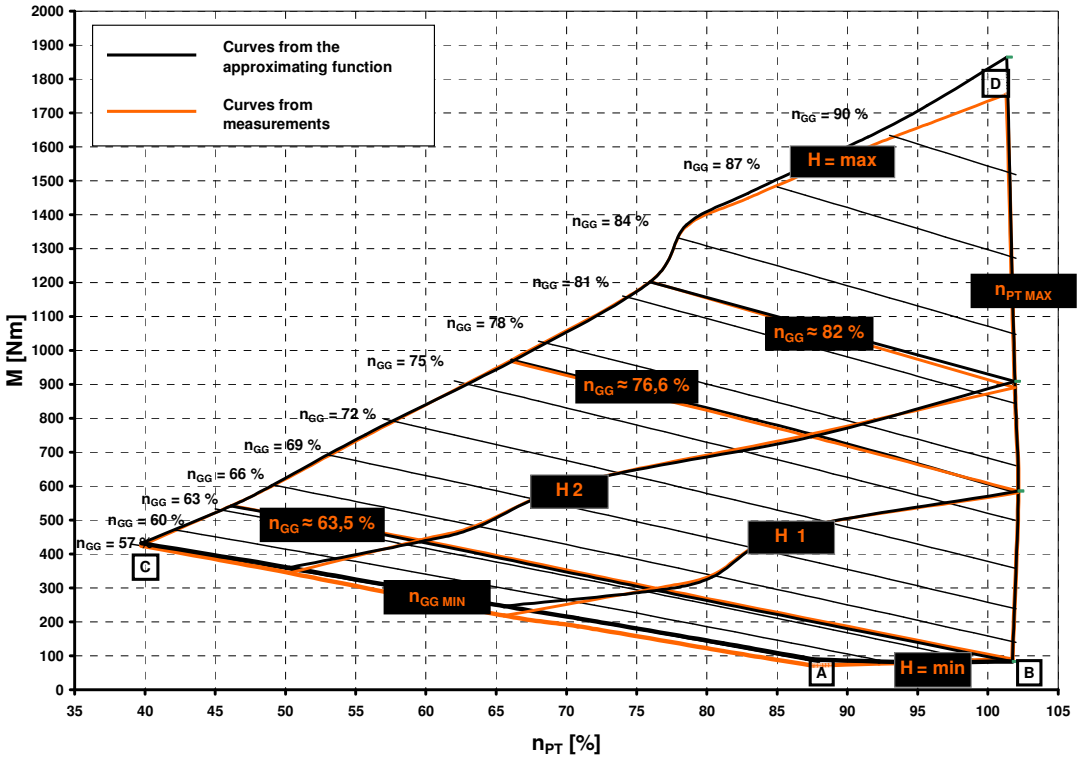
On the basis of the above picture and the results of calculations included in table 2 it is possible to state that the received approximational polynomial lets the cooperation with the great accuracy outline field of GTD–350 engine with the controllable pitch propeller. Lower accuracies are appearing only in areas which were not embraced with plan of experience. It concerns area, including the rotation speeds close to the gas generator in particular nominal. With plan in area grasped of experience mistakes are not crossing the approximation 0,5 %.

4. Conclusions

On the basis of findings of conducted preliminary examinations the following conclusions were expressed:

1. There is a possibility of drawing up the credible mathematical model letting the energy appoint characteristics for different conditions for cooperation of the naval gas turbine engine with the receiver in the form of the controllable pitch propeller.

2. The approximational relation drawn up lets in the indirect way appoint the useful torque of the power turbine from parameters being characteristic of an energy state of the gas generator of the considered gas turbine engine, for any parameters of the state surroundings.



Pic. 6. Graphical interpretation of findings of the adequacy

3. The relation drawn up lets for appointing the useful torque in the way moved closer, but with the accuracy sufficing in engineering applications.
4. Get abilities and computational experience can be used in the process of the use of naval gas turbine engines, in particular for construction of steering systems with straining the engine according to the torque and a security system of the engine before overloading.

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