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PECULIARITIES OF IDENTIFYING A POWER-GENERATING SINGLE-SHAFT GTE MATHEMATICAL MODEL

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The processes of designing and developing gas turbine engines (GTE) are based on using mathematical models (MM), reflecting the physical picture of engine operation processes. One of the ways of improving the MM validity is its identification on engine bench test results. Identifying MMs of modern energy GTEs is a very demanding task due to the necessity to identify the main controllable engine parameters determined in the course of experimental studies, depending on a large number of the parameters that are not controlled during the experiment. In this regard, the actual direction of reducing the complexity of the process of identifying MMs is using identification software systems. Developed by the A. N. Podgorny Institute of Mechanical Engineering Problems of NASU, the methodology and means of identifying the parameters and characteristics of power plants, using experimental data (Otpimum software package), allows one to conduct a directed search for an optimal solution based on modern mathematical methods. This, in turn, leads to a reduction in identification execution time, increases the MM adequacy and allows one to more reliably determine the characteristics of engine components. The article proposes an approach to identifying a non-linear unit MM, with a detailed calculation of a turbine flow path to the level of blade rows on the D045 engine bench test results. It describes the choice of variable and controllable parameters as well as the ranges of their changes. The results of solving the identification problem showed the possibility of using the Optimum software for optimizing and identifying parameters and characteristics of power plants when identifying D045 GTE MMs. The use of the developed methodology for identifying GTE MMs that is based on bench test results, allows one to take into account the maximum number of variable variables and significantly reduce the complexity and time of this process. The analysis of the results shows that with significant deviations of GTE characteristics from design values, a large amount of a priori information is needed to solve the identification problem. On the basis of the information, ranges of changes of variable and controllable parameters are assigned, as well as their values in the first approximation.

Keywords: *mathematical model, identification, gas turbine engine, variable parameters, controllable parameters, objective function.*

Introduction

To date, IT technologies have been introduced into all life cycle phases of gas turbine engines. One of the examples is GTE MMs, which accompany the engine from the moment of design to its modernization in future. Thus, one of the phases of a GTE life cycle is GTE engineering development. The engineering development phase is rather long and expensive. The use of MMs makes it possible to reduce the number of field tests by replacing them with theoretically-calculated experiments, but such calculations require that adequate MMs be used. One way to increase the MM validity is to identify it on the engine bench test results.

The identification of MMs of modern power-generating GTEs presents a very demanding task due to the necessity to identify the key controllable parameters determined in the process of experimental studies and dependent on a great number of parameters (30…50 values) that are not controlled during the experiment and whose values may vary in the process of identification. In view of this, the use of a bench test results-based identification software complex (SC), which enables to reduce the labor intensity of the above works, is a rather pressing task.

When SE SPGTCE "Zorya"-"Mashproekt" performed the engineering development works on D045 GTEs, the necessity arose to identify its MMs on the test results.

Throughout the world, there are widely used CAE-technologies for modeling GTE characteristics. These technologies can be divided into two main groups.

The first group includes MMs implemented in such programs as SIMULINK / MATLAB and EcosimPro, which are not software complexes but they make it possible to solve systems of nonlinear equations, including GTE MMs. The following ones can be mentioned among them: Dymola (based on the Modelica programming language) [1], Simulink (integrated into the MATLAB environment) [2], TRANSEO (based on the MATLAB environment) [3], PROOSIS (based on EcosimPro system) [4] etc. allowing a wide range of problems to be solved.

The second group includes the specialized modeling systems, or software packages (SP). In particular, in the process of GTE designing and engineering development, the GASTURB, GECAT, JCTS, GSP, GRAD, and ASTRA software packages are used [5–9]. These are characterized by great functionality and are ready to develop static and dynamic MMs for different GTE configurations investigate throttle, climatic and external characteristics, and identify MMs on bench test results.

In the second group, separately worth noting are the programs developed by branch design bureaus (BDB) and intended to be used within the objectives of the tasks of these enterprises. These include those developed and used in ZMBDB "'Progress", JSC "UEC-Saturn", JSC "UEC-Aviadvigatel", JSC "Kuznetsov", SE GTRPC "Zorya"-"Mashproekt". These programs are intended, in general, for calculating one fixed GTE configuration and take into account the operational peculiarities of the units included into the scheme under consideration as well as the methodological and experimental experience of the DBs in this sphere to the fullest extent possible.

In SE GTRPC "Zorya"-"Mashproekt" in the calculation of GTE static characteristics and during its engineering development, extensively used is a non-liner MM with a detailed turbine flow path calculation to the level of blade rows. [10]. This MM has proved to be effective in the process of designing and engineering development of the M70, M80, and M90 engines. This MM has been developed as a multipurpose program capable of modeling the GTE schemes each having up to 5 compressor spools and up to 11 turbine stages. Originally, the model was developed for calculating the characteristics of multi-shaft GTEs with free power turbines. In the process of the enterprise developing single-shaft power-generating GTEs, MM was adapted to be capable of calculating such engine parameters.

Additionally, the following were included in MM:

– hydraulic losses in the combustion chamber due to heat supply [11], which is particularly relevant for single-shaft GTEs, where, at a practically constant air flow, the degree of heating in the combustion chamber changes significantly from idle to nominal mode;

– consideration of the reduced clearance that allows to consider the deviation of the actual installation clearances from the design ones and their influence on turbo-machine efficiency.

– the value of the turbine gas outlet flow angle effect on the value of hydraulic losses in the GTE gas outlet duct, which is due to the substantial change of the gas outlet flow angle during the operation mode change from idle to nominal mode with the GTE rotor speed being constant, exerting a significant impact on the value of losses in the engine outlet duct.

A detailed model structure is given in paper [12].

A distinguishing feature of the above-mentioned specialized SPs is working with particular MMs implemented and functioning only as parts of the above SPs. This makes it impossible to identify MMs developed by third parties with the aid of other software based on the practical experience of a particular research engineer. With that in mind, a decision has been taken to identify GPP-60 MM, developed and used by SE GTRPC "Zorya"-"Mashproekt", with the aid of the "Optimum" multi-purpose and multi-level optimization model-software complex developed by the A. Podgorny Institute of Mechanical Engineering Problems of NASU[13].

Research Objective

The object of this research is the thermo-technical characteristics of the power-generating D045 GTE. The D045 GTE tests were carried when it was part of the GPP-60 gas power plant with electric power supplied to the power network.

The problem of identification on bench test results can be solved for a non-linear unit D045 GTE MM with a detailed turbine flow path calculation to the level of blade rows [10]. In order to solve the problem in MM, it is necessary to identify the variable and controllable engine parameters as well as determine objective functions.

The above controlled parameters are the most important engine design characteristics measured during the experiment. In this particular case they are the following parameters: electrical power, engine inlet airflow, fuel gas consumption, total inlet pressure losses, total compressor outlet pressure, total air compressor outlet temperature, total turbine exhaust gas pressure, and total turbine exhaust gas temperature (total 8 parameters). When solving the identification problem, non-symmetrical ranges of controllable parameters variation were specified based on the a-priori information within the measuring equipment accuracy limits (measurements error).

The above variable parameters are the following: compressor map modeling coefficients, throat dimensions of turbine nozzle assemblies and rotors, proportionality factors of total pressure losses in the air inlet and gas exhaust ducts as well as in the combustion chamber, relative quantity of cooling air in the turbine blade rings and blade rims, as well as energy loss factors in them. After the test problem had been solved, the variable parameters were supplemented by those of air temperature and pressure, which were measured during the testing process and affected the calculation results. Consequently, the number of variable parameters increased to 48. The variable parameters were assigned non-symmetrical measurement ranges depending on their type (geometrical and thermo-gas-dynamical) and the available a-priori information.

The objective functions (identification criteria) are represented by the values of the above-listed controllable parameters determined on MMs whose variation range is determined based on the results of the direct measurements of flow parameters along the engine flow path and received during bench tests.

The problem of identification, in this case, is that of minimizing a set of objective functions (identification criteria). In the process of solving it for each controllable parameter under study, the variation in the values received based on the engine test and MM calculation results in the specified variation range is minimized. This means, in fact, the problem of multi-criteria conditional optimization is solved.

Below is the description of the identification procedure.

The identification was performed in two stages. At first, the problem was solved for the maximum power mode with 8 controllable and 48 variable parameters.

Then, taking into account that in this MM the amount of the total inlet and outlet pressure losses, hydraulic losses in the combustion chamber as well as values of cooling air bleeding/return are the functions of the engine parameters (depend on the mode of its operation), after the parameters had been balanced in the maximum power mode, it was decided to "freeze" their modeling coefficients after solving the identification problem in lower modes. In addition, the following geometric parameters, which did not vary depending on the GTE operation mode, were "frozen": the throat dimensions of turbine nozzle assemblies and rotors (the area difference resulted from the thermal expansion of blade material was ignored). At that, number of variable parameters was reduced to 19.

In the maximum power mode (the first stage), the identification problem at the initial point was solved:
– with zero deviations of the variable parameters;
– with deviations of the variable parameters in the middle of the range;
– with maximum deviations of the variable parameters.

With a satisfactory solution having been chosen in the maximum reached mode, a set of problems was solved along the operating line with a number of the "frozen" variable parameters described above.

The decision on the identification results being satisfactory, in addition to that on the convergence of the problem with the required accuracy, was taken based on the comparison of the obtained results with MM manually identified by "Zorya"-"Mashproekt" specialists taking into account the additional data received in the testing process.

MM Identification Results

The paper presents MM identification results based on the data per one testing day.

The result of solving the identification problem for the maximum power mode is given in Table.

Identification problem solution result in the maximum power mode

Controllable parameter	Set deviation, %	Received deviation,%
Electrical power at the electric generator terminals	±1	-0.008
Actual air flow rate through the engine	-0.5..1 %	-0.336
Fuel gas consumption	±1.4	1.481
Total inlet pressure losses	-0.4..0 %	-0.064
Total compressor outlet air pressure	0..0.4	0.186
Total air compressor outlet temperature	-0.5..2 %	-0.008
Total turbine exhaust gas pressure	0..0.4	0.104
Total turbine exhaust gas temperature in the GTE diffuser	-1..+2 %	-1.008

Figures 1–3 show the identification results for some parameters in comparison with those of the bench tests in relative values.

It should be noted that the identification was performed for each experimental point, where the corresponding sets of modeling coefficients then determined. That resulted in a number of adequate MMs being obtained for particular points of the throttle curve. Consequently, the next step is the above MM correction with consideration of change in the modeling coefficients depending on the mode parameters that will allow obtaining an adequate mathematic model making it possible to receive the information over the entire range of engine operating modes.

Conclusions

The use of the developed method of the GTE MM identification based on the bench test results enables to take into account the maximum number of variable parameters and considerably save the labor intensity and time required for this process.

The result analysis shows that large amounts of a-priori information are required for solving the identification problem with the significant deviations of GTP characteristics from design values.

The next stage is to input the change dependences of the received modeling coefficients in the MM structure in order to receive an adequate model making it possible to determine installation parameters over the entire range of engine operating modes.
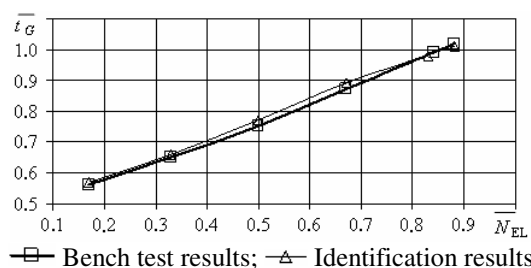

—▫— Bench test results; —△— Identification results

Fig. 1. GTE outlet gas temperature (t_G) dependence on power at the generator terminals (N_{EL})

—▫— Bench test results; —△— Identification results
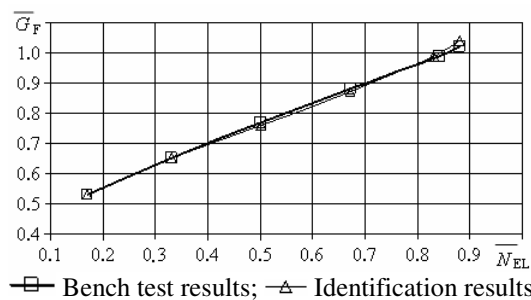
Fig. 2. Fuel consumption (G_F) dependence on power at the generator terminals (N_{EL})
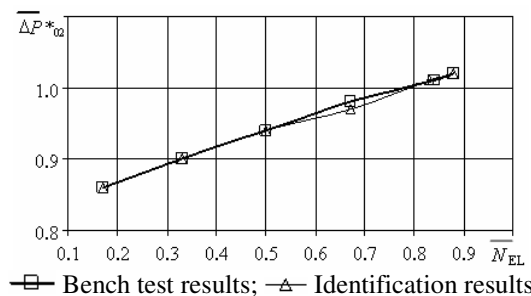

—▫— Bench test results; —△— Identification results

Fig. 3. Total air compressor outlet pressure (P^*_{02}) dependence on power at the generator terminals (N_{EL})

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Особливості ідентифікації математичної моделі одновального енергетичного газотурбінного двигуна

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Процеси проектування і доведення ГТД базуються на використанні математичних моделей (ММ), що відображають фізичну картину процесів функціонування двигуна. Одним із шляхів підвищення достовірності ММ є їхня ідентифікація за результатами стендових випробувань двигуна. Ідентифікація ММ сучасних енергетичних ГТД є дуже трудомісткою задачею. Це пов'язано з необхідністю ідентифікувати основні контрольовані параметри двигуна, що визначаються в ході експериментальних досліджень і залежать від великої кількості параметрів, неконтрольованих в ході експерименту. Через це актуальним напрямом зниження трудомісткості процесу ідентифікації ММ є застосування програмних комплексів ідентифікації. Розроблена Інститутом проблем машинобудування ім. А. М. Підгорного методологія та засоби ідентифікації параметрів і характеристик енергетичних установок за експе-

риментальними даними (програмний комплекс Optimum) дозволяє вести спрямований пошук оптимального розв'язку на основі сучасних математичних методів. Це, в свою чергу, приводить до скорочення часу виконання ідентифікації, підвищує адекватність ММ і дозволяє більш достовірно визначати характеристики вузлів двигуна. У статті запропоновано підхід до ідентифікації нелінійної повузлової ММ, з деталізацією розрахунку турбінного тракту до рівня лопаткового вінця, за результатами стендових випробувань двигуна Д045. Описується вибір варійованих і контрольованих параметрів, а також діапазони їх змін. Результати розв'язання задачі ідентифікації показали можливість застосування програмного комплексу оптимізації та ідентифікації параметрів і характеристик енергетичних установок Optimum під час ідентифікації ММ ГТД Д045. Застосування розробленої методології для ідентифікації ММ ГТД, що ґрунтується на результатах стендових випробувань, дозволяє враховувати максимальне число варійованих змінних і значно знизити трудомісткість і час цього процесу. Аналіз результатів показує, що за значних відхилень характеристик ГТД від проектних значень для розв'язання задачі ідентифікації необхідно мати великий обсяг апріорної інформації, на підставі якої призначаються діапазони зміни варійованих і контрольованих параметрів, а також їх значення в першому наближенні.

Ключові слова: математична модель, ідентифікація, ГТД, варійовані параметри, контрольовані параметри, функція мети.

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