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AUTOMATION CONTROL SYSTEM OF TECHNICAL CONDITION OF GAS TURBINE ENGINE COMPRESSOR

The article is devoted to one of the approaches to the construction of an automated system for solving the problems of diagnostics and monitoring of the flow duct of aircraft gas turbine engines and gas turbine plants. Timely detection of faults and subsequent monitoring of their development in operation are possible thanks to automated systems for assessing the technical condition of engines. This is particularly relevant in operating conditions as the knowledge of the technical condition of the engine is necessary in any engine maintenance system allows to choose the content and timing of maintenance, repair of the flow duct of gas turbine engines and gas turbine plants, as well as commissioning.

The engineering technique, which can be applied at performance of maintenance and at stages of tests and debugging of aircraft engines, is considered. The automated system implements a method of measuring the air flow through the compressor and a technique for assessing the technical condition of the compressor by the relative change in air flow.

To determine the air flow rate through the gas turbine engine, it is sufficient to measure only static pressure values in the flow part. The static pressure receivers are not located in the flow part and do not obscure it, and thus do not affect the compressor gas dynamic stability margin. The inspection area is selected for measuring in the flow duct of the air intake. Static pressure in the maximum and minimum cross sections of the chosen area is measured; the maximum cross-section area of the flow duct, the total temperature of the air flow is measured outside the air intake. To determine the air flow rate, the functional dependence of the air flow rate on the static pressure is used.

The algorithm for monitoring and diagnosing the operating condition of the engine is based on a comparison of the actual values of air flow rate with the air flow rate determined during the control tests or when using a mathematical model adapted for this gas turbine engine.

The positive effect of the using of the proposed automated control system of technical condition is that the air flow rate measured under operating conditions will significantly increase the objectivity of the control of the operation and technical condition of the gas turbine engine.

Keywords: *automated system; primary converters; metrological characteristics; air consumption; compressor; gas turbine engine; evaluation of technical condition; algorithm; metrological characteristics; functional scheme; approbation.*

Introduction

The control system of any engine is designed to estimate the technical condition of the engine as a whole and as for its individual units and systems.

The estimation of the operating conditions of the gas turbine engine (GTE), gas turbine power plant (GTU) refers to the control of their technical condition, both in accordance with the values of its main parameters with the requirements of the technical (operational) documentation, and according to the proposed criterion – the deviation of the air flow rate through the compressor. This allows us to determine not only the technical condition of the GTE, GTU, as a technical object, but also to estimate the efficiency of maintenance, the current repair of the flow duct of GTE, GTU, debugging (engine sink, elimination of cracks, regulation of compressor mechanization, etc.).

Correct and timely estimation of the operational condition allows maintaining the reliability of controlled equipment at a given operational level.

Controlled objects represent a complex multilevel technical system. Analysis of the failures and troubles of individual systems and units [1, 2], allows to identify the most frequently damaged parts in the operation. One of these parts is the flow duct of the GTE, which interacts directly with the working fluid (air, gas). Timely detection of faults, their estimation, as well as the subsequent control over their development in operation are possible due to automatic systems of estimation the technical condition of the GTE. The presence of efficient automatic systems based on modern methods (techniques) for estimation the technical state of the GTD are necessary in any system of their maintenance. Particularly relevant this factor is in operation conditions.

The basis of determination of airflow rate through the compressor is the following relationship [3]:

$$G = m\frac{P_B}{\sqrt{T_H^*}}F_B\left(\frac{k+1}{2}\right)^{\frac{1}{k-1}}\frac{\left(\frac{P_n}{P_B}\sigma_B\right)^{\frac{k+1}{k}}-A_B}{\left(\frac{P_n}{P_B}\sigma_B\right)^{\frac{2}{k}}-A_B}\times$$

$$\times\sqrt{\frac{k+1}{k-1}\left[1-\frac{\left(\frac{P_n}{P_B}\sigma_B\right)^{\frac{2}{k}}-A_B}{\left(\frac{P_n}{P_B}\sigma_B\right)^{\frac{k+1}{k}}-A_B}\right]}. \qquad (1)$$

where G – air flow rate. determined according the parameters of the air intake (Fig. 1);

m – coefficient taking into account the thermal physic properties of air;

P_B – static pressure in the minimum section of the measuring area;

T_H^* – total temperature of ambient air;

F_B - area of the minimum section of the measuring area;

k – adiabatic index;

P_n – static pressure in the maximum section of the measuring area;

σ_B – total pressure loss coefficient in the measuring part;

A_B – coefficient of the flow duct cross section area change in the measuring part.

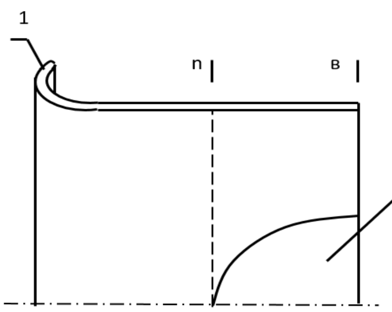

Fig. 1. The scheme of the flow part of the lemniscate air intake [4, 5]: 1 – air intake; 2 – engine air inlet nose cone; "n" – the maximum and "в" – minimum cross sections

The value of m is determined as follows:

$$m=\sqrt{\frac{k}{R}\left(\frac{2}{k+1}\right)^{\frac{k+1}{k-1}}},$$

where R – gas constant, is a constant value and for air it is 287 J /kg K.

In all engineering calculations adiabatic index k is accepted as a constant, the value of which for air is equal to 1.4.

The area of F_B is constant magnitude and is measured only one time.

The total pressure loss coefficient is a function of the Mach number M and in our conditions is taken to be a constant and equal to 1.0 [2, 3, 5].

The coefficient of the flow duct cross section area change in the inspection part

$$A_B=\left(\frac{F_B}{F_n}\sigma_B\right)^2,$$

where F_n is the maximum area cross section of the inspection part, is a constant as F_B and is measured only for one time. So A_B is constant too.

Thus, to determine the air flow rate through the flow duct of the compressor, which is equipped with an axial air intake (Fig. 1), the next is needed:

– pre-determine the constants k, F_B, F_n, σ_B, т, A_B;

– measure the temperature of the ambient air T_H^*;

– measure static pressure in the maximum area cross section of the measuring section P_n;

– measure static pressure in the minimum area cross section of the measuring section P_B;

– determine the air flow rate by dependence (1);

– reduce the airflow rate to the Standard Atmosphere.

The basis of this method is the invention [3]. According to this method the air flow rate measurement is performed in the air intake of GTE on the section of the flow duct between the maximal and minimal cross sections.

When the constants are substituted into the above-mentioned dependence, it simplifies and takes the form of the function G = f(P_B,P_n, T_H^*), where the external air temperature is measured by the regular receiver, and the static pressure values is measured by the using pilot-static tube, made in the form of opeings with a diameter of 1 mm [3 - 5] in the sections "n" and "в", which do not obscure the flow duct of the air itake and do not affect the main parameters of the GTE and gas dynamic stability of the compressor.

Reducing of the air flow rate value to the Standard Atmosphere is carried out by the formula (2) [2 - 5]:

$$G_{red}=G_{cur}\frac{760}{P_H}\sqrt{\frac{T_H}{288}}, \qquad (2)$$

where G_{red} – the reduced value of air flow rate, G_{cur} – current value of air flow rate, P_H, T_H – pressure and temperature of air in front of the engine.

Thus, in order to determine the air flow rate passing through the GTE in the flow duct, it is sufficient to measure only the static pressure values, the receivers of which do not settle in the flow duct and do not obscure it and not affect the compressor gas-dynamic stability.

It is proposed to use a criterion changing of the air flow rate through the compressor to estimate the effectiveness of maintenance activities, in parallel with the estimation of the technical condition of the GTU. This criterion is compared with the permissible value for it and, a conclusion about the state of the GTU is made on the basis of this comparison. That is, this technique is based on a comparison of the actual values of air flow rate with the basic (initial), which are determined by the factory corresponding characteristic (acceptance test, throttle performance), or using a mathematical model adapted for this GTU.

1. Crux of problem

Minimizing the measurement of air flow through the compressor of the gas turbine engine, processing and filing the results without operator intervention.

1.1. Construction of the basic flow characteristics

To construct, for example, the basic flow characteristics of the GTU D-336, the throttle performance of the gas turbine unit D-336 was used, the air flow of which is given in table. 1 in the form of functional relation $G_{b.red} = f(n_{hp.red})$.

Table 1

The functional relation $G_{b.red} = f(n_{hp.red})$

$n_{hp.red}$, rev/ min	12785	12920	13050	13170	13300	13425	13560	13700	13850
$G_{b.red}$, kg/s	27,7	28,6	29,7	30,7	31,7	32,7	33,6	34,6	35,4

According to table 3 the approximation of the basic characteristics was carried out and it was got in the graphic (Fig. 2) and analytical form:

$$G_{b.red} = -258,0720310738 + \\ + 0,0361099896 n_{hp.red} - 0,0000010768 n_{hp.red}^2 .$$

This representation makes it possible to compare the actual value of the air flow rate with the base with the minimum error in the range of operating frequencies of the high pressure cascade rotor.

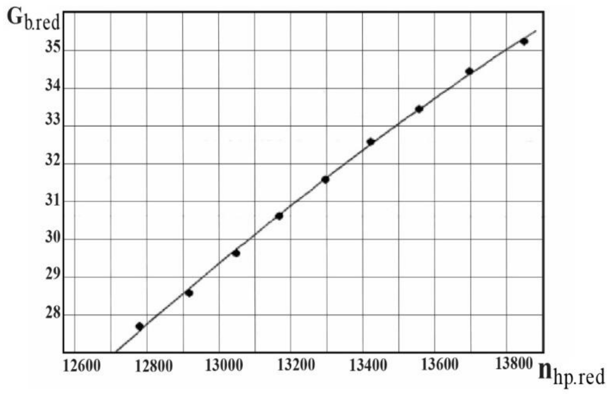

Fig. 2. Graphical representation of the basic characteristic

1.2. Algorithm for the measuring the air flow rate through the GTD

The algorithm for assessing the technical condition of the compressor is shown in Fig. 3.

In accordance with the algorithm, a software was done. It includes:

– program of diagnostics and installation of the technical part of the system;

– the software for calculating air flow rate and recording the results of measurements.

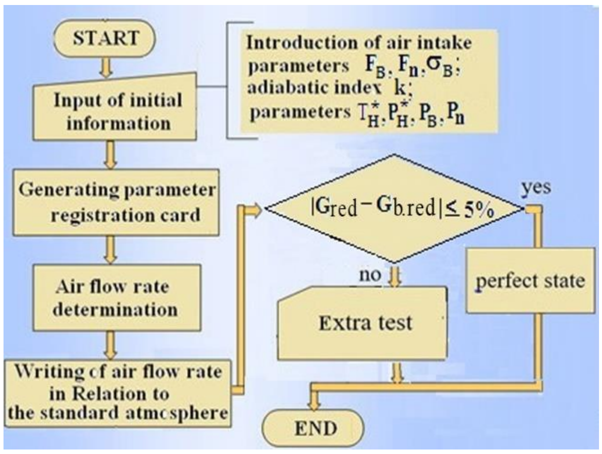

Fig. 3. The algorithm for determining the air flow by an automated system

1.3. Automated system for measuring air flow through the gas turbine engine compressor

Automation system for measuring the air flow rate through the gas turbine engine compressor (Fig. 4) minimizes the operator's participation in the processing of the data. It implements the algorithm of air flow rate measurement method [4]. The method of determining the change of the air flow through the compressor and

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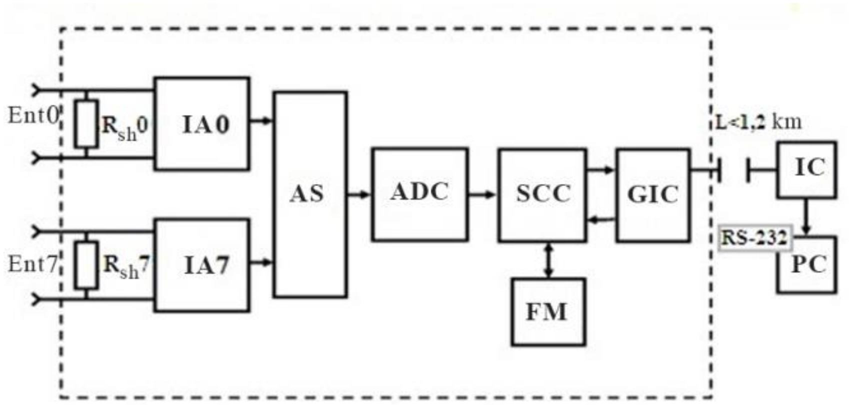

Fig. 4. Functional scheme of the automated system for measuring air flow rate through the compressor

consists of:

– sets of primary signal converters, (receivers, sensors) installed on the gas turbine engine;

– eight-channel communication with the object module;

– electric cable;

– data interface controller RS-422A/RS-485;

– portable PC-based workstation;

– software;

– technical documentation.

In Fig. 4 the object communication module (MSO) is selected with the dashed line, where Ent0 ... Ent7 – analog inputs from sensors; IA0 .... IA7 – input amplifiers; AS – analog switching unit; ADC – analog-digital Converter; SCC – single-chip controller; FM – flash memory; GIC – galvanic isolated Converter; other modules of the system: KI – interface Converter; PC – workstation based on personal computer.

System specifications:

– input signal from sensors – current 4…20 mA;

– supply voltage – 220 V;

– power consumption – no more than 30 W;

– number of measurements per second – no more than 20;

– error – 0,05 %;

– distinguishing ability – 16 bit;

– isolation voltage – 2500 To;

– ambient temperature – from -10 to +70 °C.

The primary converters are - temperature sensor and two pressure sensors. Each GTU has a standard temperature sensor, the signal from which can be used in the system. To measure the air temperature before GTU it is advisable to use a sensor type KVANT - DDTVN 5303/4B2A (-50...+ 650 °C), and to measure the static pressure in the air intake – sensors such as MDD-1-1000, MDD-Te-220-780, Метran-100-DIF Vn1350, Safir 2415, Honeywell 307536667-000 and etc.

The pressure sensors of the type MDD-1-1000, MDD-Te-220-780, in particular used in the flight recorders, require a special converter to convert the analog signal into digital. Besides this their metrological characteristic requires testing of sensors once a year, so it's better to apply the sensors with more stable metrological characteristics and digital output like types Metran-100-DIF Vn1350, [6] Safir 2415, Honeywell 307536667-000.

Pressure sensors “Safir” have been made in Ukraine by Private JSC “Manometr-Kharkiv” since 1998 in accordance with the specification U24275859.002-99. They designed for continuous conversion of liquid and gas pressure into a unified electrical signal. The sensors “Safir” minimized the shortcomings of sensors such as “Sapfir-22” and its Russian analogs. The error associated with the influence of temperature and static pressure was reduced. Resistance to one-way overloads was increased. Structurally, the sensor is a device in which two units can be selected: the measuring unit and the electronic unit. Sensors for various parameters have a unified electronic unit. The sensor works follows: the pressure of the working fluid is transferred from the pressure receiver into the chamber (chambers) of the measuring unit where it is converted into the deformation of the sensing element associated with the strain gauge, which leads to a change in the electrical resistance of the strain gauges. The electronic unit converts this resistance change into a constant current signal output. The upper limits of measurements are shown in table 2.

The maximum permissible displacement of “zero” (change in the output signal at zero pressure) as a percentage of the range of displacement of the output signal, which occurs due to changes in ambient temperature from the boundaries in the range of 23±2 °C to another temperature in the operating temperature range for every 10 °C, is determined by:

$$\Delta_{ot} = \pm\, \Delta'_{ot}[1+0{,}5(P'_{max}/ P_{max})],$$

where Δ'_{ot} – values taken from the table 2;

P'_{max} – maximum upper limit of measurement for this sensor type;

P_{max} – the actual value of the upper limit of measurements for this sensor type.

Table 2

The upper limits of measurings

Measured physical quantity	Type of sensor	The upper limits of measurings, kPa
Pressure difference	2415	0,63; 1,00; 1,60; 2,50; 4,00; 6,30

The relative change in the output signal range Δ'_{dt}, which occurs due to changes in ambient temperature 23±2 °C to another temperature in the operating temperature range for every 10 °C, does not exceed $\pm\Delta'_{dt}$ (given in table 3).

Table 3

Changing the output signal due to the influence of operational factors

Sensors with limits of acceptable basic error	Δ'_{ot}, %	Δ'_{dt}, %
± 0,20	0,06	0,10
± 0,25	0,08	0,12
± 0,50	0,15	0,20

The change in the output signal of sensors with a range of 4…20 mA, which occurs due to a change in the voltage of the power source from 15 to 42 V does not exceed ± 0,005 % of the range of the output signal for each 1V change in electrical voltage. The change in the output signal of the sensors for changes in load resistance does not exceed ± 0,01 % of the range of the output signal for every 100 Ω change in load resistance. The sensors remain in operating condition when the maximum permissible pressure is exceeded by 1,5 times. The service life of the sensors is 12 years. The mass of the sensor is 5,8 kg. Metrological characteristics of sensors «Safir» (Fig. 5), «Metran» (Fig. 6), "Honeywell" (Fig. 7) are given below.

As the switch of the automated system, you can apply a switch-type F7071 as analog-to-digital converter (ADC) – F7078, communication devices, and read-only memory (ROM) – K573RF, electronic computers – computer class Pentium 133.

The signals of the primary converters are fed to the ADC, which converts the analog signal to digital by the method of double integration. The digital signal is supplied to the ROM via galvanic ally-isolated elements and Protocol serial communication to a computer. The computer operates in real time and cyclically take the sensors readings. in the case of changes in the initial data the air flow is calculated according to the algorithm shown in Fig. 3.

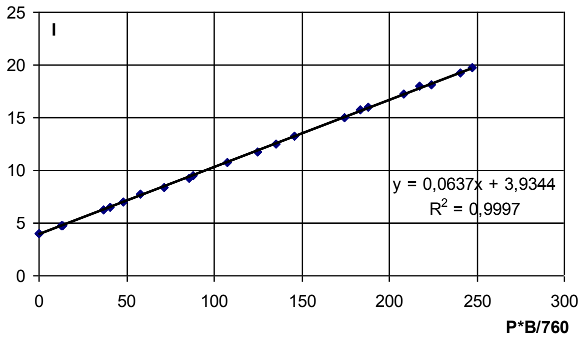

Fig. 5. Metrological characteristics of the pressure sensor “Safir” model 2415 №12179094

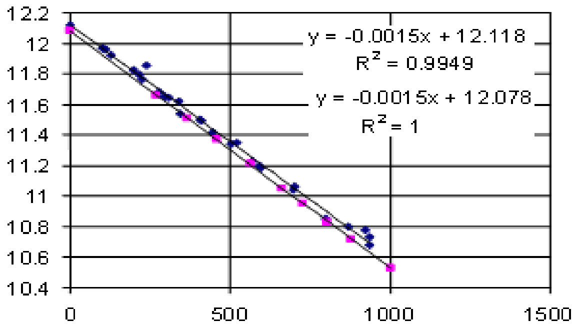

Fig. 6. Metrological characteristics of the pressure sensor Metran-100-DIF Vn 1350 №23748

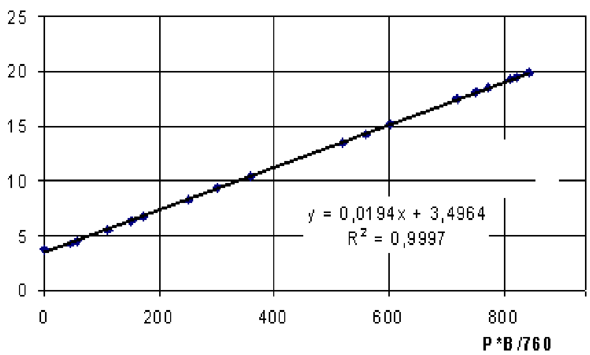

Fig.7. Metrological characteristics of the pressure sensor Honeywell 307536667-000

Parameters written by the system are automatically counted and presented as a flow characteristic by using the program SVZ_1.EXE. Characteristics can be approximated with the standard program Excel, as a result of which we get the flow characteristics in both analytical and graphical forms, that allows to compare them. The initial (basic) characteristic is taken as the characteristic of the washed engine, that allows to evaluate

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divergence of parameter

$$\Delta G = \frac{G_{wash} - G_{filt}}{G_{wash}} 100\%.$$

Using the data of the test report, the air flow rates through the polluted engine and the same engine after washing are reduced to standard atmosphere (table 4).

According to this table, we approximate the obtained data and get a graphical and analytical representation of the flow characteristics before and after the engine washing. From the obtained data , it can be seen that the point of the first value of flow is significantly allocated among the General distribution, which is explained by the operation of the compressor bypass valves. Excluding these points, the approximation gives a linear distribution of the data (Fig. 8).

Table 4

Data of the test report

$n_{red\ pt}$, rev/min	$G_{red\ filt}$, kg/s	$n_{red\ pt}$, rev/min	$G_{red\ wash}$, kg/s
5500	15,785	5550	15,197
6060	15,949	6050	15,631
6570	17,311	6520	16,489
7030	18,457	7020	17,962
6550	17,211	6510	16,582
6090	15,909	6040	15,356
5550	14,484	5550	14,123

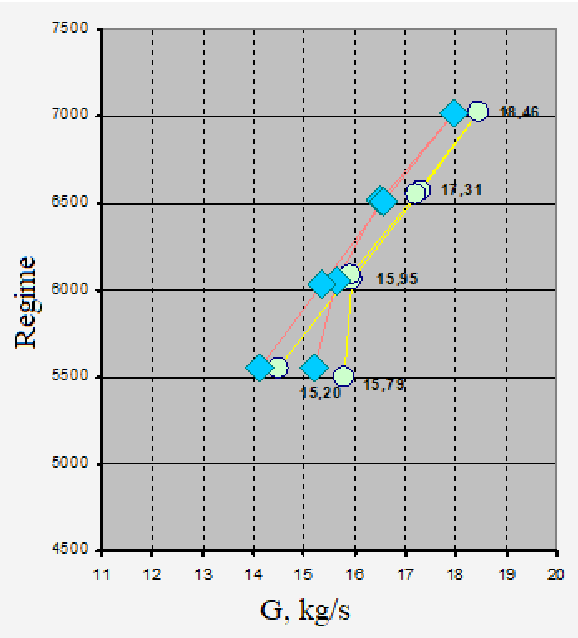

Fig. 8. Distribution of approximation data

With further comparison of the compressor flow characteristics of the polluted and washed engine, it is seen that an almost equidistant displacement of the engine flow characteristics in the entire range of its operating regimes. The maximum deviation of the characteristics is approximately 5 %, which is inherent in the tolerance of the algorithm for evaluation performances of the compressor.

Conclusion

The automated control system of the technical condition of the gas turbine engine compressor described in the article has been tested at the engine test centre "Motor Sich", as well as at the underground gas storage in Dashava. The system has shown its efficiency, it does not cause in changes to the design of the engine and does not affect its gas-dynamic parameters, the margin of stability. It can be used on helicopters and ground gas turbine units with a lemniscate air intake.

The developed system allows for express control (operational control) in the current time.

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АВТОМАТИЗИРОВАННАЯ СИСТЕМА КОНТРОЛЯ ТЕХНИЧЕСКОГО СОСТОЯНИЯ КОМПРЕССОРА ГАЗОТУРБИННОГО ДВИГАТЕЛЯ

Н. С. Кулик, В. В. Козлов, Л. Г. Волянская

Статья посвящена одному из подходов к построению автоматизированной системы для решения задач диагностики и контроля проточной части авиационных газотурбинных двигателей и газотурбинных установок. Своевременное выявление неисправностей и последующий контроль за их развитием в эксплуатации возможны благодаря автоматизированным системам оценки технического состояния двигателей. Особенно актуальным это является в условиях эксплуатации, так как знание технического состояния двигателя необходимо в любой системе технического обслуживания двигателей, так как позволяет выбрать содержание и сроки технического обслуживания, текущего ремонта узлов проточной части газотурбинных двигателей и газотурбинных установок, а также наладочных работ.

Рассматривается инженерная методика, которая может быть применена при выполнении технического обслуживания, а также на этапах испытаний и доводки авиационных двигателей. Автоматизированная система реализует способ измерения расхода воздуха через компрессор и данную методику оценки технического состояния компрессора по относительному изменению расхода воздуха.

Для определения расхода воздуха, проходящего через ГТД достаточно провести измерения только статических значений давления в проточной части, приёмники статических значений давления располагаются на внешней поверхности проточной части и не затеняют её, и тем самым не влияют на запас газодинамической устойчивости компрессора. Участок для измерения параметров выбирают в проточной части воздухозаборника. На данном участке измеряется статическое давление в максимальном и минимальном сечениях, максимальная площадь сечения проточной части; полная температура воздуха измеряется снаружи воздухозаборника штатной системой контроля силовой установки. Для определения расхода воздуха используют функциональную зависимость расхода воздуха от статических давлений.

Алгоритм контроля и диагностики технического состояния двигателя базируется на сравнении действительных значений расхода воздуха со значениями расхода определёнными при проведении контрольно-сдаточных испытаний или при использовании адаптированной для данного газотурбинного двигателя математической модели.

Положительный эффект от использования предлагаемой автоматизированной системы контроля технического состояния заключается в том, что измеренный в эксплуатационных условиях расход воздуха существенно повысит объективность контроля работы и оценки технического состояния двигателя.

Ключевые слова: автоматизированная система; первичные преобразователи; метрологические характеристики; расход воздуха; компрессор; газотурбинный двигатель; оценка технического состояния; алгоритм; метрологические характеристики; функциональная схема; апробация.

АВТОМАТИЗОВАНА СИСТЕМА КОНТРОЛЮ ТЕХНІЧНОГО СТАНУ КОМПРЕСОРА ГАЗОТУРБІННИХ ДВИГУНІВ

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Стаття присвячена одному з підходів до побудови автоматизованої системи для вирішення завдань діагностики та контролю проточної частини авіаційних газотурбінних двигунів і газотурбінних установок. Своєчасне виявлення несправностей і подальший контроль за їх розвитком в експлуатації можливі завдяки автоматизованим системам оцінки технічного стану двигунів. Особливо актуальним це є в умовах експлуатації, тому що знання технічного стану двигуна, необхідно в будь-якій системі технічного обслуговування двигунів і дозволяє вибрати зміст та терміни технічного обслуговування, поточного ремонту проточної час-

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тини газотурбінних двигунів і газотурбінних установок, а також налагоджувальних робіт.

Розглядається інженерна методика, яка може бути застосована при виконанні технічного обслуговування, а також на етапах випробувань і доведення авіаційних двигунів. Автоматизована система реалізує спосіб вимірювання витрати повітря через компресор і методику оцінки технічного стану компресора по відносній зміні витрати повітря.

Для визначення витрати повітря, що проходить через ГТД, достатньо провести вимірювання тільки статичних значень тиску в проточній частині. Приймачі статичних значень тиску розташовуються зовні проточній частини і не затінюють її, і тим самим не впливають на запас газодинамічної стійкості компресора. Ділянку для виміру вибирають в проточній частині повітрозабірника. На обраної ділянці вимірюється статичний тиск в максимальному і мінімальному перерізах, максимальна площа перерізу проточної частини, але повна температура повітряного потоку вимірюється зовні повітрозабірника штатною системою контролю силової установки. Для визначення витрати повітря використовують функціональну залежність витрати повітря від статичного тиску.

Алгоритм контролю і діагностики технічного стану двигуна базується на порівнянні фактичних значень витрати повітря зі значеннями витрати, що визначені при проведенні контрольно-здавальних випробувань або при використанні адаптованої для даного газотурбінного двигуна математичної моделі.

Позитивний ефект від використання запропонованої автоматизованої системи контролю технічного стану полягає в тому, що виміряна в експлуатаційних умовах витрата повітря суттєво підвищить об'єктивність контролю роботи і технічного стану двигуна.

Ключові слова: автоматизована система; первинні перетворювачі; метрологічні характеристики; витрата повітря; компресор; газотурбінний двигун; оцінка технічного стану; алгоритм; метрологічні характеристики; функціональна схема; апробація.

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