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DEFINITION OF MODELS TO DETERMINE THE GAS TEMTERATURE AT THE INLET OF THE TURBINE'S ROTOR IN A LIFE-TIME MONITORING SYSTEM

A life-time monitoring system is developed to predict the life-time of engines used in a gas pumping station. Four different models are presented to calculate the gas temperature at the inlet of the turbine's rotor, all the models are based on well known thermodynamic process taking place in the engine. Coefficients that include the not measured engine parameters are calculated by regression. The engine working cycle was simulated to generate data for model development and verification. Additional engine working cycle simulations were made taking into account three different defects for additional verification of the models. The model that describes the best the behavior of the gas temperature has been separated.

Key words: *gas turbine engine diagnostics, gas temperature, prediction.*

Introduction

The use of gas turbine engines to pump natural gas is widely used in present days. As any turbine engine is necessary to monitor the main engine parameters in order to ensure the proper running and durability of its main components. Contrary to gas turbine engines used in the aerospace industry, where exist typical working cycles (idle, take-off, cruise and landing), the gas turbines used in gas pumping stations have not a typical working cycle. The working cycle depends on the demand of the pipe line, making difficult to identify a general tendency, all the engines even at the same pumping station will run at different working conditions.

An efficient method for engine life-time monitoring has been developed at the Kharkov Aerospace University "KhAI" [1]. It is based on the use of models which give the possibility to determine the critical components of the thermal and stress state knowing engine parameters and the ambient conditions during flight. So, real maintenance conditions are taken into account and the life-time monitoring precision is increased.

Significant disadvantage of [1] and other existing approaches for engine components life-time monitoring is that they do not take into account individual properties of the engine caused by the components and unit variation and by the gas path deterioration in maintenance. This paper represents some effort to overcome this problem.

The main idea is to obtain a simple model which includes engine parameters that are easily measured in order to calculate the gas temperature at the inlet of the turbine's rotor (T_g). The proposed models are based on the thermodynamic working process of the engine [2]. In further an analogical model is to be formed for the cooling air temperature and for the blade thermal and stress state determination. The object of analysis is the engine GTU-12P, witch is a modification of the aero-engine PS-90 used in several gas pumping stations.

Nomenclature

C_{pg} – gas heat capacity, J/KgK;
C_p – air heat capacity, J/KgK;
T_H – atmospheric temperature, K;
T_C – compressor discharge temperature, K;
T_g – gas temperature at inlet of turbine rotor, K;
T_{HPT} –high pressure turbine discharge temperature, K;
T_{FT} –free turbine discharge temperature, K;
L_{HPT} – work of high pressure turbine, J/Kg;
π_{HPT} – pressure ratio of high pressure turbine;
η_{HPT} – efficiency of high pressure turbine;
Q_1 – heat added in the combustion chamber;
P_C – compressor discharge pressure, Pa;
P_g – pressure at the inlet of turbine rotor, Pa;
P_{HPT} –high pressure turbine discharge pressure, Pa;
F_g, F_{HPT} – cross section area in front of turbine rotor and after high pressure turbine, m^2;
$q(\lambda_g)$, $q(\lambda_{HPT})$ – gas dynamic function in front of the turbine rotor and after the high pressure turbine;
m – numeric flow coefficient;
Ne_{FT} – power of free turbine, W;
H_u – natural gas heat capacity, KJ/Kg;
C_i – coefficient that include unknown parameters;
η_m – high pressure rotor mechanical efficiency;
η_{comb} – combustion efficiency;
σ_{CC} – combustion chamber pressure factor;
$\nu = G_{air}/G_{gas}$ – air to gas flow ratio.

1. Data acquisition

The first step is to obtain the data that represent the general behavior of the engine, for such purpose was used the model that the chair 203 of the Kharkov Aerospace University made for such engine.

The engine cycle was simulated over the following combination of conditions:

atmospheric pressure – 80, 90 and 101,325 KPa;

atmospheric temperature – 243, 253, 268, 278, 288, 298, 303,308 and 318 K.

Free turbine power – 20, 40, 60, 80 and 100% of its full load. Figure 1 shows the main behavior of T_g. The data of faultless engine is then divided into group "a" and group "b". Group "a" is used for model developing and group "b" is used for model verification.

2. Model development

From thermodynamics four different models are proposed:

1) from high pressure rotor energy balance equation: check the formula

$$Cp_g\left(T_g - T_{HPT}\right)\eta_{m.HP} = L_C \cdot \nu\,; \qquad (1)$$

2) from turbine's work:

$$L_{HPT} = C_{pg}\cdot\left(T_g - T_{HPT}\right) = C_{pg}\cdot T_g\left(1-\frac{1}{\pi_{HPT}^{k-1/k}}\right)\eta_{HPT}\,; \qquad (2)$$

3) from combustion chamber's energy equation:

$$C_p{\cdot}T_C + Q_1 = c_{pg}\cdot T_g\,; \qquad (3)$$

4) from conservation of gas consumption at the inlet of turbine's rotor and after high pressure turbine:

$$m\frac{F_g\cdot q\left(\lambda_g\right)P_g}{\sqrt{T_g}} = m\frac{F_{HPT}\cdot q\left(\lambda_{HPT}\right)P_{HPT}}{\sqrt{T_{HPT}}}\,. \qquad (4)$$

In the four previous models, a lot of parameters are included in the engines measuring system; however there are some others that are unknown, those unknown parameters we propose to include them in coefficients C_i, the value of these coefficients are calculated using data from group "a" and a trend line is found. So, unmeasured factors are represented as functions of the engine operation mode. Compressor discharge temperature corrected to standard ambient conditions is used as mode representing parameter.

After some mathematical simplifications and correction to standard ambient conditions, the final models for corrected T_g are:

From high pressure rotor energy balance equation:

$$T_g = T_{HPT} + C_1\cdot\left(T_C - T_H\right)\,; \quad C_1 = \frac{C_p\cdot\nu}{C_{pg}\cdot\eta_{m\cdot HP}}\,. \qquad (5)$$

From HPT work:

$$T_g = \left(\frac{T_{HPT}}{1-\tilde{N}2}\right), \; C_2 = \left(1-\frac{1}{\pi_{HPT}^{k-1/k}}\right)\eta_{HPT}\,. \qquad (6)$$

From combustion chamber's energy equation:

$$T_g = C_{3.1}\cdot T_C + C_{3.2}\,,$$

$$C_{3.2} = \frac{H_u}{C_{p.g}}\eta_{comb}\left(1-\nu\right). \quad C_{3.1} = \frac{C_p}{C_{pg}}\nu\,. \qquad (7)$$

From conservation of gas consumption at the inlet of turbine's rotor and after high pressure turbine:

$$Tg = T_{HPT}\left[\frac{F_g}{F_{HPT}}\cdot\frac{P_C}{P_{HPT}}\cdot\frac{q\left(\lambda_g\right)}{q\left(\lambda_{HPT}\right)}C_4\right]^2; \; C_4 = \sigma_{CC}\,. \qquad (8)$$

From equation 8, all parameters are known, except for $q(\lambda_g)$ which is supposed to be 1 and $q(\lambda_{HPT})$ which was calculated as follows: the power of the free turbine is known, since the free turbine is not cooled, it's assumed that the gas consumption at the exit of the HPT is the same that at the inlet of the free turbine. Thus, we can calculate the gas consumption after HPT using the formula for power of free turbine and formula of Cristianovich to obtain $q(\lambda_{HPT})$:

$$G_{g.HPT} = \frac{Ne_{.FT}}{Cp_g\left(T_{HPT} - T_{FT}\right)}\,, q\left(\lambda_{HPT}\right) = \frac{G_{g\cdot HPT}\sqrt{T_{HPT}}}{m\cdot F_{HPT}\cdot P_{HPT}}\,.$$

Coefficients C_i are dimensionless and composed of the unmeasured parameters of the engine working fluid. Mainly, they cannot be supposed as constants independent on the engine operational mode. So we represent them as polynomial functions of some parameter of operational mode. Corrected compressor discharge temperature $T_{C.cor}$ was used as this parameter. Polynomials that describe these functions were obtained using the mentioned above group "a" of initial data:

$$C_1 = -7{,}029\cdot 10^{-7}T_{C.cor}^2 + 1{,}328\cdot 10^{-3}\cdot T_{C,cor} + 0{,}5203\,;$$

$$C_2 = -1{,}951\cdot 10^{-8}\cdot T_{C.cor}^2 - 1{,}748\cdot 10^{-5}\cdot T_{C.cor} + 0{,}2788\,;$$

$$C_{3.1} = 7{,}109\cdot 10^{-8}\cdot T_{C.cor}^2 - 1{,}395\cdot 10^{-4}\cdot T_{C.cor} + 1{,}093\,;$$

$$C_{3.2} = 3{,}31\cdot 10^{-4}\cdot T_{C.cor}^2 + 1{,}848\cdot T_{C.cor} - 726{,}7\,;$$

$$C_4 = -1{,}982\cdot 10^{-7}T_{C.cor}^2 + 3{,}372\cdot 10^{-4}\cdot T_{C.cor} + 0{,}1718\,.$$

Precision of this approximation is represented in chart 1.

Chart 1

Precision of polynomial approximation

Parameters of precision	Coefficients				
	C_1	C_2	$C_{3.1}$	$C_{3.2}$	C_4
Mean square error	0,012	0,003	0,001	50,52	0,005
Max "+" deviation	0,020	0,008	0,002	140,96	0,008
Max "-" deviation	0,026	0,006	0,002	110,77	0,010

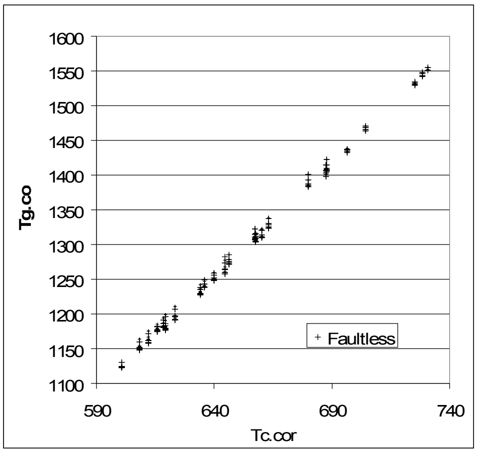

Figure 1. T_g of faultless engine

3. Model verification

There are two stages in model verification. In the first stage, the models are verified against a faultless engine. The results are presented in figure 2.

In the second stage, models are verified against an engine with faults, for such purpose the engine working cycle is again simulated using the same combination of initial conditions used in the faultless engine, but this time adding the following faults:

$\delta G_{C.cor}$ -0,03, $\delta\eta_C$ -0,03 and $\delta F_{HPT.NB}$ +0,03.

As an example is presented in figure 3 the value of prediction of T_g for an engine with fault $\delta\eta_C$ -0,03. Similar graphics were obtained for the other models.

The chart 2 shows the maximum and minimum difference in the prediction of gas temperature.

Chart 2

Difference in the prediction

	Maximum difference, K			
Equation	Faultless	$\delta\eta_C$ -0,03	$\delta G_{C.cor}$ -0,03	$\delta F_{HPT.NB}$ 0,03
1	-5/8	-6/8	-5/8	-7/5
2	-13/14	-13/13	-13/14	-23/2
3	-10/17	-9/17	-9/17	13/38
4	-55/146	-84/76	-87/75	-1/153

4. Conclusions

From chart 2 is seen that the model 1 is the one that describes the best the faultless engine, the models 2 and 3 have a middle performance in describing the gas temperature, model 4 is the one that describes the worst.

When verifying the models against engine with faults, the same results were found, being the model one performing the best.

The model 1 depends only from Tc.cor, making a very simple and easy model that might be used in a life-time monitoring system.

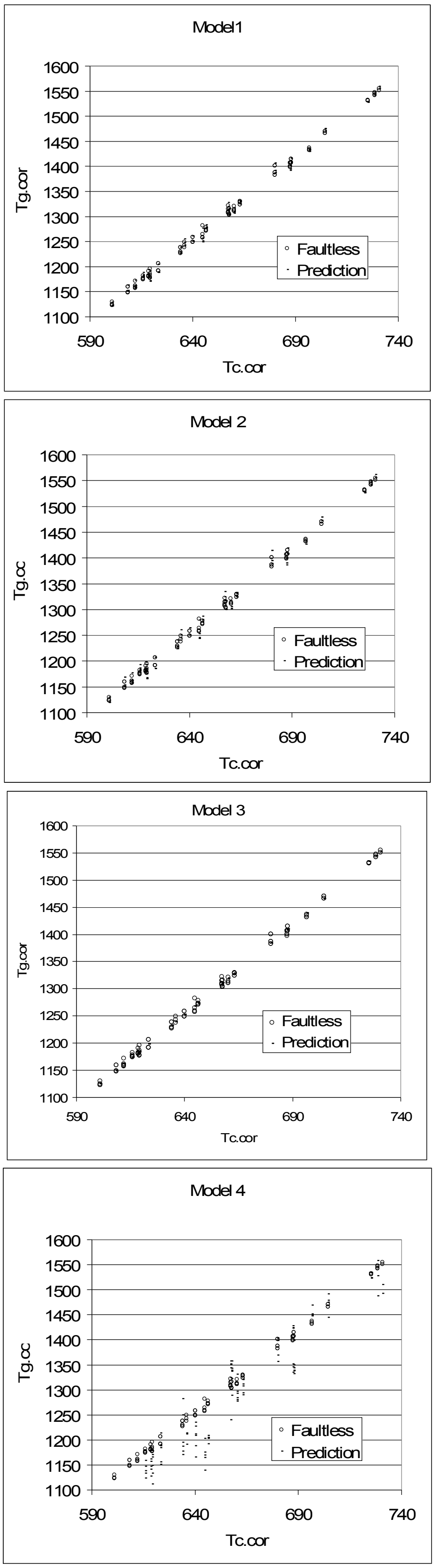

Figure 2. Model verification for faultless engine

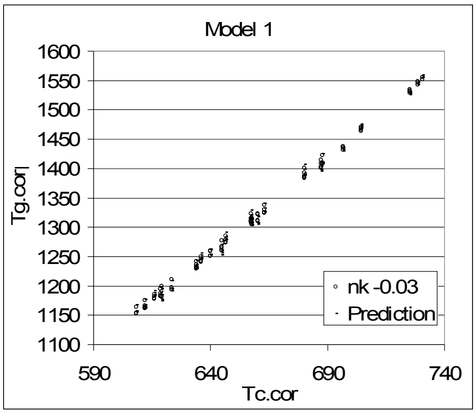

Figure 3. Model verification for engine with fault $\delta\eta_C$ -0,03

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ФОРМУВАННЯ МОДЕЛІ ДЛЯ ВИЗНАЧЕННЯ ТЕМПЕРАТУРИ ГАЗУ НА ВХОДІ ДО РОБОЧОГО КОЛЕСА ТУРБІНИ В СИСТЕМІ МОНІТОРИНГУ РЕСУРСУ

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Розробляється система моніторингу ресурсу привідних газотурбінних двигунів газоперекачувальних агрегатів. Розглянуто моделі для визначення температуру газу на вході до робочого колеса турбіни за відомими значеннями вимірюваних параметрів. Всі ці моделі базуються на використанні термогазодинамічних рівнянь робочого процесу. Значення коефіцієнтів цих рівнянь, які об'єднують не вимірювані параметри; подані регресійними залежностями від режиму. Для визначення цих залежностей і аналізу результатів використано нелінійну по вузлову модель двигуна. Додаткові розрахунки дозволили проаналізувати вилив на точність визначення температуру газу трьох дефектів проточної частини. У результаті визначено найкращу з розглянутих моделей.

Ключові слова: газотурбінний двигун, діагностування, прогнозування температури газу

ФОРМИРОВАНИЕ МОДЕЛИ ДЛЯ ОПРЕДЕЛЕНИЯ ТЕМПЕРАТУРЫ ГАЗА НА ВХОДЕ В РАБОЧЕЕ КОЛЕСО ТУРБИНЫ В СИСТЕМЕ МОНИТОРИНГА РЕСУРСА

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Разрабатывается система мониторинга ресурса приводных газотурбинных двигателей газоперекачивающих агрегатов. Рассмотрены четыре модели для определения температуры газа на входе в рабочее колесо турбины по известные значениям измеряемых параметров. Все эти модели основаны на использовании термогазодинамических уравнений рабочего процесса. Значения коэффициентов этих уравнений, объединяющих не измеряемые параметров, представлены регрессионными зависимостями от режима. Для определения этих зависимостей и анализа результатов использована нелинейная поузловая модель двигателя. Дополнительные расчеты позволили проанализировать влияние на точность определения температуры газа для трех дефектов проточной части. В результате определена лучшая из рассмотренных моделей.

Ключевые слова: газотурбинный двигатель, диагностирование, прогнозирование температуры газа.

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