Efficient Coding Techniques for Propulsion Systems

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ABSTRACT

Overengineering is a common practice in modern consumer electronics. It is easier to add : additional memory or a more powerful CPU, than optimize and focus on program code efficiency. Aerospace electronics in comparison to commercial solutions have longer lifespan, up to 40 years. According to PT6 component manufacturer Pratt&Whitney AeroPower Rzeszow, electronic components are produced in 10 years period. After that time they reach EOL status. This article focuses on efficient coding of compressor and turbine performance maps using a polynomial approximation. As an example, the K24 compressor map and genuine GasTurb turbine map was select. The generated numerical map had proper directional efficiency island distribution according do qualitative evaluation. Obtained solutions could be successfully applied to 8-bit microcontrollers due to low resources requirements. Pure mathematical approaches guarantee easy applicability and flexibility for any programmer. Using this method, it is possible to add a component map to ECU or to generate backup a map, increasing safety in the event of data corruption. Presented approach offers to store backbone of the system in short understandable paper form.

1.0 INTRODUCTION

Engine control units evolved from hydrodynamic control units (HCU) to full authority digital engine control units (FADEC) which are modern approach for gas turbine control systems. Digitization have advantages - ease of system configuration and upgradeability, which is essential for commercial applications [1,2,3,4]. Military applications are in some aspects, victims of that trend, without a deep understanding of operator needs and military operator requirements. Unlike for commercial applications, military ECU are exposed to: ground fire , operation in hostile environment, electronic warfare conditions, and even nuclear radiation and electromagnetic pulse (EMP). Considering these aspects, the most reliable in warfare environment would be an HCU which would operate until engine stops. The disadvantage of this system would be complicated process of diagnostics and regular maintenance [2,5]. DEC or FADEC unit requires additional testing for reliability and stability. A key factor is a microcontroller which must operate efficiently in hostile conditions according to standard electronics application. Additional requirements are also related to logistics. HCU could be, overhauled easily using the simplest tools and could be carried out by average mechanical shop[2]. Helicopters and aircrafts operated by military operators have a service lives of up to 40 years of operation. There is a legitimate concern about the availability of certified electronic components. Today there is even a demand for sustained source of engines configured in HCU configuration only according to maintainability requirements. Electronics components generate additional cost due to cybersecurity they need to pay for software and security updates. A compromise between cost, survivability and reliability would be simple 8-bit electronics without possibility to update microcode easily[3].

2.0 MATERIALS AND METHODS

Calculating gas turbine performance requires additional information about behaviour of engine components. This information could be obtain from performance/test rig tests or from CFD simulations [6,7,8]. The scientific problem concerns how to store efficiently data from component maps and make it easily to reproduce and even reconstruct original data in case losing it. As an example two component maps would be selected. Compressor map from GT60 gas turbine engine , and turbine map from GasTurb performance software[6].

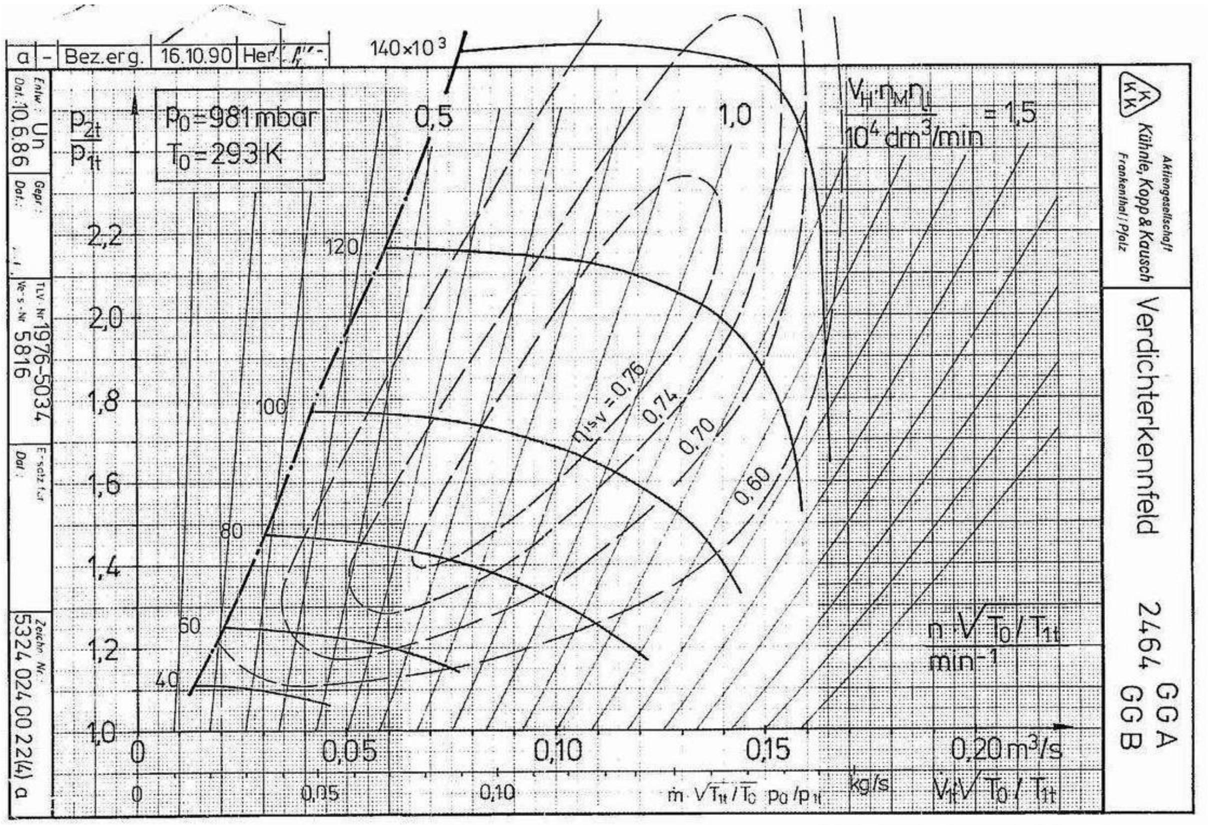

Figure 1: Borg-warner KKK K24 – compressor map.

In general, a method of estimation compressor parameters (for performance modelling) is based on identification of impeller rotational speed (Figure 1). Then one of the additional parameters must be selected : π_C – pressure ratio or airflow – $\dot{m}_{cor}$. As a result compressor efficiency η_C – is predicted.

The first step is requires to recreate external boundary conditions. Considering compressor map boundaries we could divided into two parts : surge line boundary and maximum airflow boundary.

Surge line boundary is represented by a straight line which is approximate by equation :

$$\dot{m}_{b1} = 0{,}0049 - \pi_c - 0{,}039 \tag{1}$$

Maximum airflow boundary is represented by second order polynomial:

$$\dot{m}_{b2} = -0{,}11 \cdot {\pi_C}^2 + 0{,}49 \cdot \pi_C - 0{,}0336 \tag{2}$$

From a gas turbine performance modelling point of view, interesting would be an only area of efficiency islands between those two lines. Estimated pressure ratio is a variable dependable on corrected mass flow rate and corrected speed. Corrected speed line would be approximate using directional coefficient that can be found in Table 1.

Table 1. Coefficient for K24 compressor pressure estimation by speed lines.

i	a_{0i}	a_{1i}	a_{2i}	a_{3i}	a_{4i}
1	18,968	-1,653	0,0323	-0,000308	$1{,}0937 \cdot 10^{-6}$
2	-2,721976	0,196	-0,00485546	$5{,}279 \cdot 10^{-5}$	$-1{,}9179 \cdot 10^{-7}$
3	1,091	-0,003768	0,00010397	0	0

Directional polynomial for selected corrected compressor speed is presented by formula:

$$A_i(n_{cor}) = a_{0i} + a_{1i} \cdot n_{cor} + a_{2i} \cdot n_{cor}^2 + a_{3i} \cdot n_{cor}^3 + a_{4i} \cdot n_{cor}^4 \tag{3}$$

Following data presented on Table 2, there is requirement to approximate a set of three polynomials.

$$A_1(n_{cor}) = 18{,}968 - 1{,}653 \cdot n_{cor} + 0{,}0323 \cdot n_{cor}^2 - 0{,}000308 \cdot n_{cor}^3 + 1{,}0937 \cdot 10^{-6} \cdot n_{cor}^4 \tag{3.1}$$

$$A_2(n_{cor}) = -2{,}722 + 0{,}196 \cdot n_{cor} - 0{,}004855 \cdot n_{cor}^2 + 5{,}279 \cdot 10^{-5} \cdot n_{cor}^3 - 1{,}9179 \cdot 10^{-7} \cdot n_{cor}^4 \tag{3.2}$$

$$A_3(n_{cor}) = 1{,}091 - 0{,}003768 \cdot n_{cor} + 0{,}00010397 \cdot n_{cor}^2 \tag{3.3}$$

Compressor pressure ratio would be a function of corrected speed and corrected mass flow ratio.

$$\pi_C(\dot{m}_{cor}, n_{cor}) = A_1(n_{cor}) \cdot \dot{m}_{cor}^2 + A_2(n_{cor}) \cdot \dot{m}_{cor} + A_3(n_{cor}) \tag{4}$$

Using the same approach described below isentropic efficiency is approximated. Directional coefficients for component efficiency are identified using a given compressor map.

Table 2. Coefficient for K24 compressor efficiency estimation by speed lines.

i	b_{0i}	b_{1i}	b_{2i}	b_{3i}
1	550996,15	-744686,96	354029,135	-61487,44
2	117503,77	155369,04	-79689,84	15836,63
3	6818,38	-10156,6	6802,9	-1660,96
4	-240,86	595,725	-423,49	97,2

$$B_i(n_{cor}) = b_{0i} + b_{1i} \cdot n_{cor} + b_{2i} \cdot n_{cor}^2 + b_{3i} \cdot n_{cor}^3 \tag{5}$$

For compressor map efficiency, four coefficient need to be approximated

$$B_1(n_{cor}) = 550996{,}15 - 744686{,}96 \cdot n_{cor} + 354029{,}135 \cdot n_{cor}^2 - 61487{,}44 \cdot n_{cor}^3 \tag{5.1}$$

$$B_2(n_{cor}) = 117503{,}77 + 155369{,}04 \cdot n_{cor} - 79689{,}84 \cdot n_{cor}^2 + 15836{,}63 \cdot n_{cor}^3 \tag{5.2}$$

$$B_3(n_{cor}) = 6818{,}38 - 10156{,}6 \cdot n_{cor} + 6802{,}9 \cdot n_{cor}^2 - 1660{,}96 \cdot n_{cor}^3 \tag{5.3}$$

$$B_4(n_{cor}) = -240{,}86 + 595{,}725 \cdot n_{cor} - 423{,}49 \cdot n_{cor}^2 + 97{,}2 \cdot n_{cor}^3 \tag{5.4}$$

The final equation for efficiency approximation is described by following polynomial

$$\eta_C(\dot{m}_{cor}, n_{cor}) = B_1(n_{cor}) + B_2(n_{cor}) \cdot \dot{m}_{cor} + B_3(n_{cor}) \cdot \dot{m}_{cor}^2 + B_4(n_{cor}) \cdot \dot{m}_{cor}^3 \tag{6}$$

A similar approach could be applied to the axial turbine performance map. There are some changes in procedure which are consequence of gas turbine performance calculation. Knowing turbine expansion ratio π_T would be estimated as a function of relative speed and relative mass flow ratio. Using relative values makes this genuine performance map easily applied for preliminary calculation[7,8].

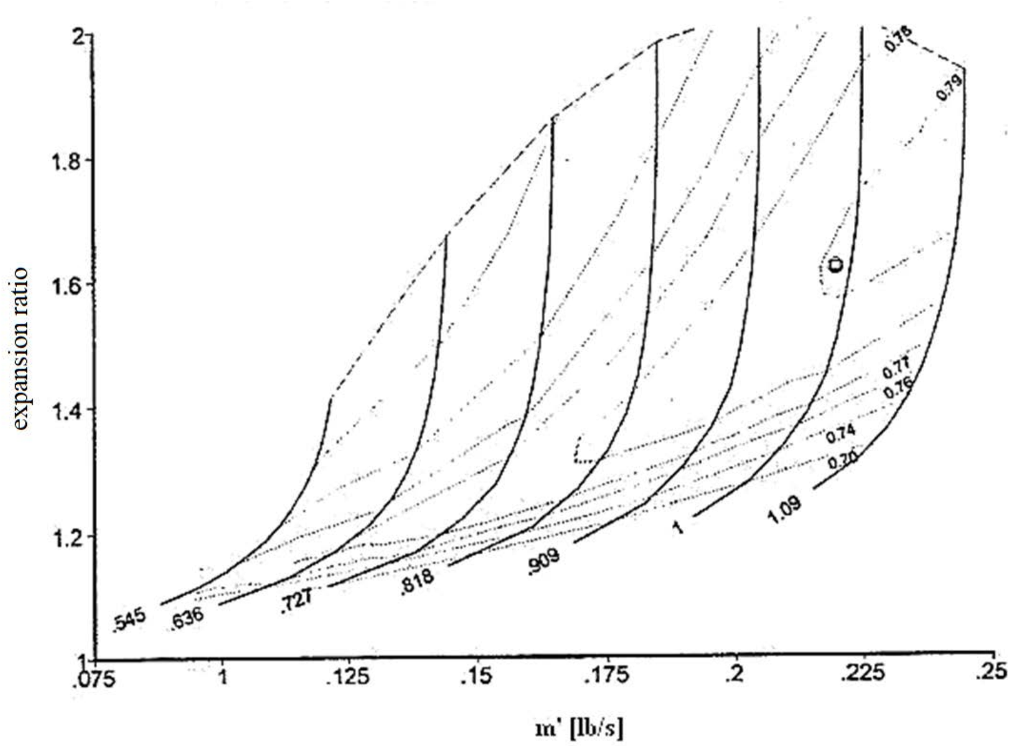

Figure 2. GasTurb – axial turbine performance map [6].

Procedure starts from identification lines that correspond to minimum turbine expansion ratio π_{Tmin} and maximum expansion ratio π_{Tmax} which are limiting factor for approximation.

$$\pi_{Tmin}(\overline{m'}) = 1{,}146 - 0{,}328 \cdot \overline{m'} + 0{,}496 \cdot (\overline{m'})^2 \tag{7}$$

$$\pi_{Tmax}(\overline{m'}) = 1{,}099 - 2{,}611 \cdot \overline{m'} + 7{,}567 \cdot (\overline{m'})^2 - 3{,}396 \cdot (\overline{m'})^3 \tag{8}$$

where :

$\overline{m'}$- relative mass flow rate of exhaust gases (range from 0,6 up to 1,2)

Polynomial required to approximate relative mass flow though turbine stage requires only two sets of coefficients according to Table 3. There is only one change in formula, corrected speed is replaced by relative value as is presented on Figure 2.

$$A_i(\pi_T) = a_{0i} + a_{1i} \cdot \pi_T + a_{2i} \cdot {\pi_T}^2 + a_{3i} \cdot {\pi_T}^3 + a_{4i} \cdot {\pi_T}^4 \tag{9}$$

Table 3. Coefficient for Gasturb turbine relative airflow estimation by turbine expansion ratio.

i	a_{0i}	a_{1i}	a_{2i}
1	0,609	-0,68	0,1864
2	-1,789	3,433	1,008

$$A_1(\pi_T) = 0{,}609 - 0{,}68 \cdot \pi_T + 0{,}1864 \cdot {\pi_T}^2 \tag{9.1}$$

$$A_2(\pi_T) = -1{,}789 - 3{,}433 \cdot \pi_T + 1{,}008 \cdot {\pi_T}^2 \tag{9.2}$$

Relative mass flow rate through turbine stage represent equation :

$$\overline{m'}(\bar{n}, \pi_T) = A_1(\pi_T) \cdot \bar{n}^2 + A_2(\pi_T) \cdot \bar{n} + A_3(\pi_T) \tag{10}$$

To approximate turbine stage efficiency directional sets of coefficients are required (Table 4). In general form formula for directional coefficients for turbine represents as follows :

$$B_i(\pi_T) = b_{0i} + b_{1i} \cdot \pi_T + b_{2i} \cdot {\pi_T}^2 + b_{3i} \cdot {\pi_T}^3 + b_{4i} \cdot {\pi_T}^4 + +b_{5i} \cdot {\pi_T}^5 + +b_{6i} \cdot {\pi_T}^6 \tag{11}$$

Table 4. Coefficient for GasTurb turbine efficiency estimation by turbine expansion ratio. Presented values requires multiplication by 10^6

i	b_{0i}	b_{1i}	b_{2i}	b_{3i}	b_{4i}	b_{5i}	b_{6i}
1	45,63297	-184,025	308,3894	-274,888	137,4583	-36,5619	4,041366
2	-166,821	672,9834	-1128,3	1006,278	-503,514	134,0259	-14,8268
3	203,1576	-819,81	1375	-1226,9	614,2713	-163,619	18,11476
4	-82,3209	332,2286	-557,343	497,4762	-249,178	66,40735	-7,35677

$$B_1(\pi_T) = 45{,}63297 \cdot 10^6 - 184{,}025 \cdot 10^6 \cdot \pi_T + 308{,}3894 \cdot 10^6 \cdot {\pi_T}^2 - 274{,}888 \cdot 10^6 \cdot {\pi_T}^3 + 137{,}4583 \cdot 10^6 \cdot {\pi_T}^4 - 36{,}5619 \cdot 10^6 \cdot {\pi_T}^5 + 4{,}041366 \cdot 10^6 \cdot {\pi_T}^6 \tag{11.1}$$

$$B_2(\pi_T) = -166{,}821 \cdot 10^6 + 672{,}9834 \cdot 10^6 \cdot \pi_T - 1128{,}3 \cdot 10^6 \cdot {\pi_T}^2 + 1006{,}278 \cdot 10^6 \cdot {\pi_T}^3 - 503{,}514 \cdot 10^6 \cdot {\pi_T}^4 + 134{,}0259 \cdot 10^6 \cdot {\pi_T}^5 - 14{,}8268 \cdot 10^6 \cdot {\pi_T}^6 \tag{11.2}$$

$$B_3(\pi_T) = 203{,}1576 \cdot 10^6 - 819{,}81 \cdot 10^6 \cdot \pi_T + 1375 \cdot 10^6 \cdot {\pi_T}^2 - 1226{,}9 \cdot 10^6 \cdot {\pi_T}^3 - 614{,}2713 \cdot 10^6 \cdot {\pi_T}^4 - 163{,}619 \cdot 10^6 \cdot {\pi_T}^5 + 18{,}11476 \cdot 10^6 \cdot {\pi_T}^6 \tag{11.3}$$

$$B_4(\pi_T) = -82{,}3209 \cdot 10^6 + 332{,}2286 \cdot 10^6 \cdot \pi_T - 557{,}343 \cdot 10^6 \cdot {\pi_T}^2 497{,}47 \cdot 10^6 \cdot {\pi_T}^3 - 249{,}178 \cdot 10^6 \cdot {\pi_T}^4 + 66.407 \cdot 10^6 \cdot {\pi_T}^5 - 7.35677 \cdot 10^6 \cdot {\pi_T}^6 \tag{11.4}$$

Final formula for turbine estimation is presented below :

$$\eta_T{}^*(\overline{m'}, {\Pi_T}^*) = B_1({\Pi_T}^*) + B_2({\Pi_T}^*) \cdot \overline{m'} + B_3({\Pi_T}^*) \cdot (\overline{m'})^2 + B_4({\Pi_T}^*) \cdot (\overline{m'})^3 \tag{12}$$

3.0 RESULTS AND DISCUSSION

Presented method allows to recreate compressor K24 compressor map. Due to condition of source map only qualitative evaluation could be applied (Figure 1).

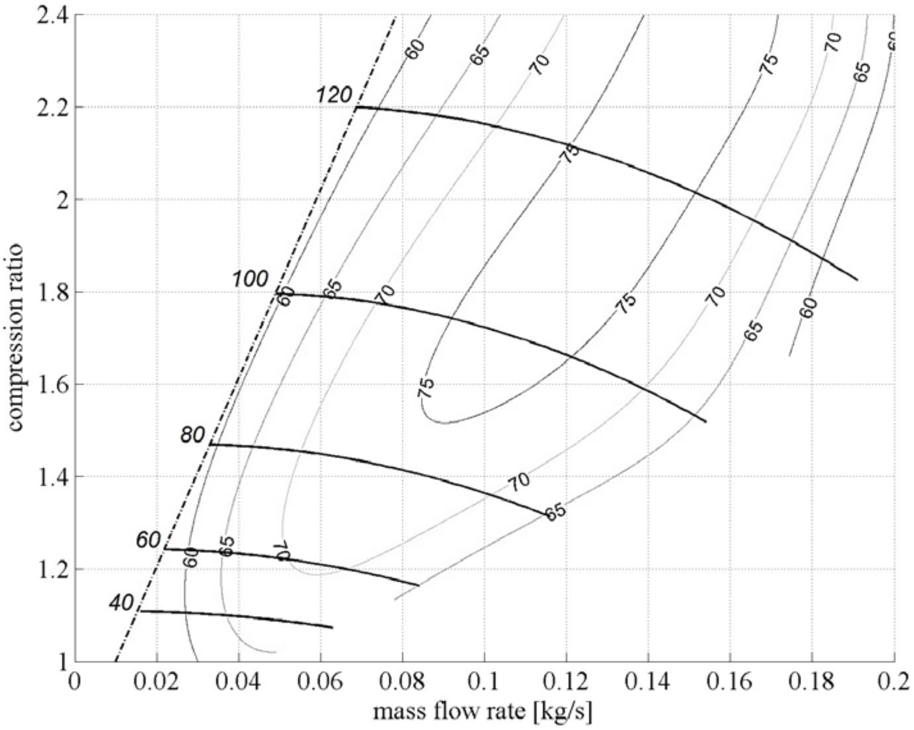

Figure 3. K24 initial map – low density.

Considering directional arrangement of efficiency island is correct in comparison to the original map (Figure 1). Corrected speed lines distribution at low speed range up 80000 rpm is correct. Difference in speed lines shape is observed below 70% efficiency island (Figure 4 – right hand side) The approximation coefficients need to be corrected for high speed line range when full recreation would be required.

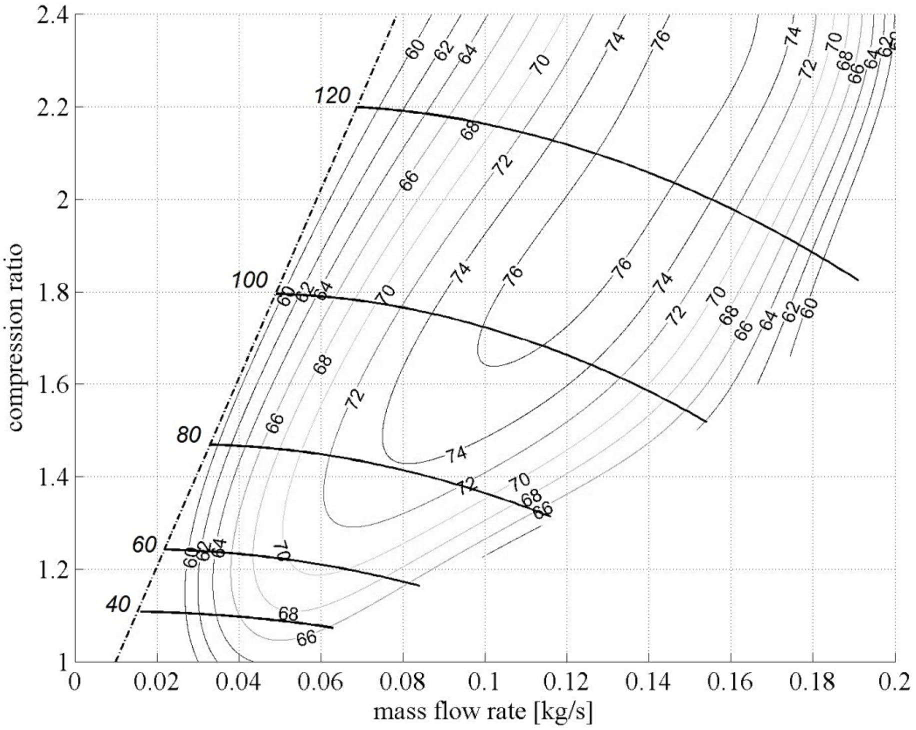

Figure 4. K24 initial map – high density.

Chosen method is also flexible and suitable to recreate additional efficiency lines that are missing in source map due a readability of the compressor map (Figure 4).

Selected approach was applied to the turbine map (Figure 2). Main purpose of this application was to evaluate suitability for other gas turbine components.

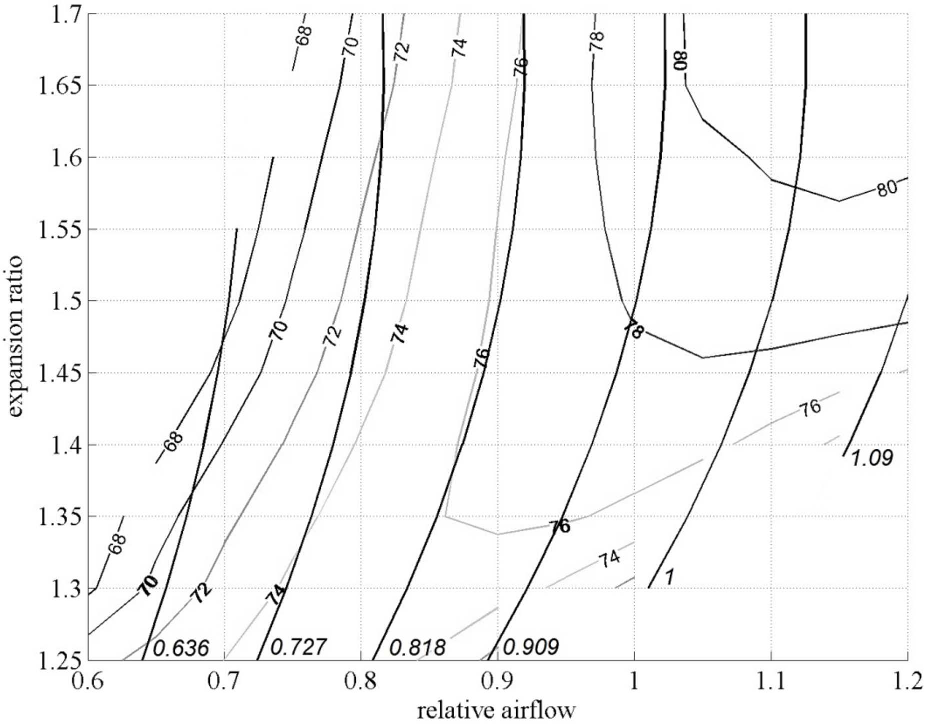

Figure 5. GasTurb turbine performance map.

Application method was successful and comparing to the source map (Figure 2) , directional agreement and efficiency island trend is correct.

Presented method of program coding is robust and efficient. As a proof of concept compressor map code was programmed in Atari Basic which is slow Basic language interpreter. Using interpreter was also an penalty in comparison to compiled code. Running code was able to calculate K24 compressor parameters in loop with stable frequency of 8 Hz. This 8-bit computer was powered by 1,74 MHz MOS 6502 CPU. Using compiled code could speed up execution of code by 200%. Now there is available versions of 6502 CPU with speed up to 14 MHz.

Advance of selected method is form of its presentation that is purely mathematical. Coded performance map could be used at all stage of gas turbine development. Compact size allows to store component data in internal controller memory. Risk of error is limited due skipping input and output operation when ECU requires external data file with performance map data.

Disadvantage of chosen approach is related to additional work requires to approximate component map. Quality of results depends on work hours dedicated to approximation process.

4.0 CONCLUSIONS

In modern times there is a need to divide engineering programming from commercial programing. There is a continuous trend to promote programming language like a fashion. For example in 1975 popular languages was fortran/cobol/lisp, 1985 was dominated by pascal/C/ada, 1995 C/C++/Fortran by 2005 we had Java, Java Script, PHP and finally 2015 Java,Java Script, Python. Whole philosophy has changed. Software become service (subscription method) rather than product. Short live of a platform is a business strategy, which is unacceptable in aerospace. For example NASA still requires Fortran programmers. Last concern is a cyber security issue. Up to mid-90s microprocessors had closed infrastructure, there was no backdoor possibility. Nowadays even tiny microcontrollers could be backdoor by “payload injection”. For engine and control application there’s no need to use more advanced micro controller unit (MCU) larger than 8 bit with closed architecture. Small amount of random access memory (RAM) up to 64k offers ability to track any form of backdoor code. Finally there is always risk of losing data. Presented method allows to store performance maps in compact report and offers rapid way of code recreation. That shortens development procedure to *implementation and validation* without problematic *translation reimplementation and validation* approach.

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