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REVERSE ENGINEERING OF CENTRIFUGAL COMPRESSOR FLOW MAP

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Abstract

The modern design process is based on multi-criteria optimization methods. They require at the initial stage collecting a maximum amount of reliable information. In the case of centrifugal compressor would be desirable to obtain specified performance maps in the form of a digital array. High-resolution arrays are suitable to interpolate values between their nodes. Access to digital resources is often limited, because they are an intellectual property of the certain companies. As a temporary replacement is possible, the use of the characteristics published as illustrative or design characteristics published from solutions of the previous generations. Presented article takes the issue of adapting simplified compressor characteristics to the requirements of PMDO (preliminary multidisciplinary optimization) process. Selected characteristics due to the low density of the contour lines on the map field was not suitable for direct conversion into digital form Presented map was reconstructed by the method of approximation using a polynomials of nth degree. Reverse engineered map generates correct values at compressor contour map nodes. Chosen method is characterized by low demands in terms of computational power requirements, which makes it suitable to use also in embedded microprocessor control systems. Main advantage of presented method is allowed to create a working replacement of digital map that can be used until time when inputs will be complemented by experimental data.

Keywords: *compressor, centrifugal, flow map, performance, reverse engineering*

1. Introduction

The evolution of computer aided design and control systems is possible by the growing computing power of modern microprocessors. Available hardware resources allow to the introduction of algorithms: design and optimization, control software (digital engine control system). In aeroengine design – design and optimization are related to PMDO (Preliminary Multidisciplinary Design and Optimization, control software are related to DEC (Digital Engine Control) or FADEC (Full Authority Digital Engine Control) which are involved to design process also [10]. Both systems require data from performance models (Fig. 1). Previously widely used in performance models compressor turbine operation line was replaced by full characteristics of components [5, 7]. Main problem is related to the acquisition of data in digital form because often they are restricted by intellectual law [4]. Alternatively, it is possible to obtain data from the published characteristics. They are not as precise as digital ones because they are printed for illustrative purposes. Converted into digital form they are sufficiently accurate for preliminary design stage to improve the quality of solutions.

The research object is compressor designed by Borg-Warner model KKK2464 (Fig. 2) [2]. For selected compressor transition, process was presented from performance data on paper into the digital form. The calculations were performed in Matlab R2014a using Core i7 2600 cpu.

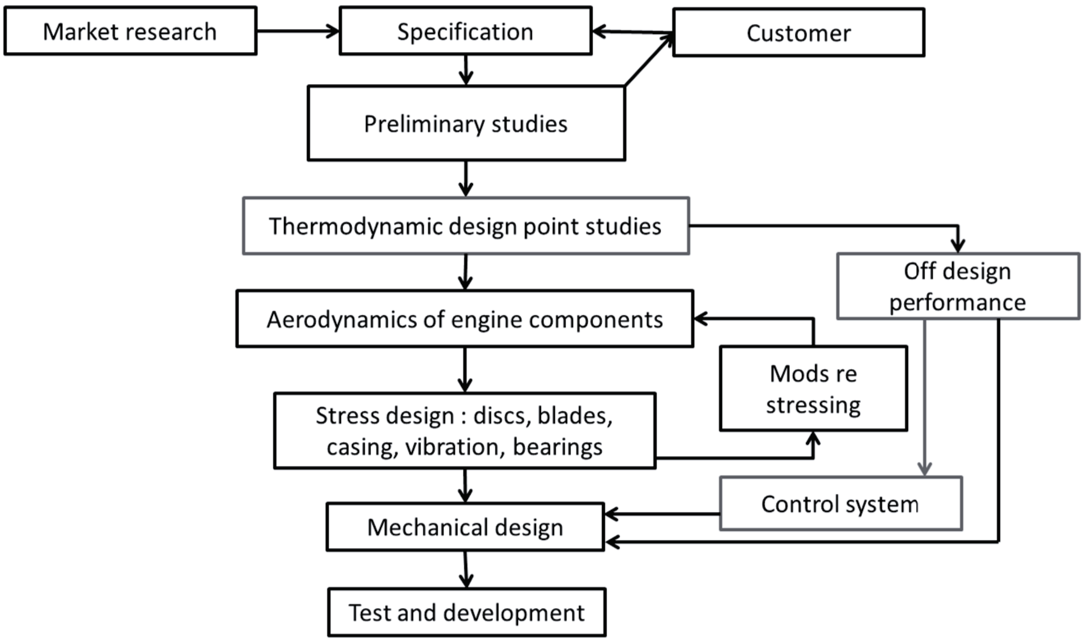

Fig. 1. PMDO gas turbine design steps [10]

2. KKK2464 compressor characteristics conversion

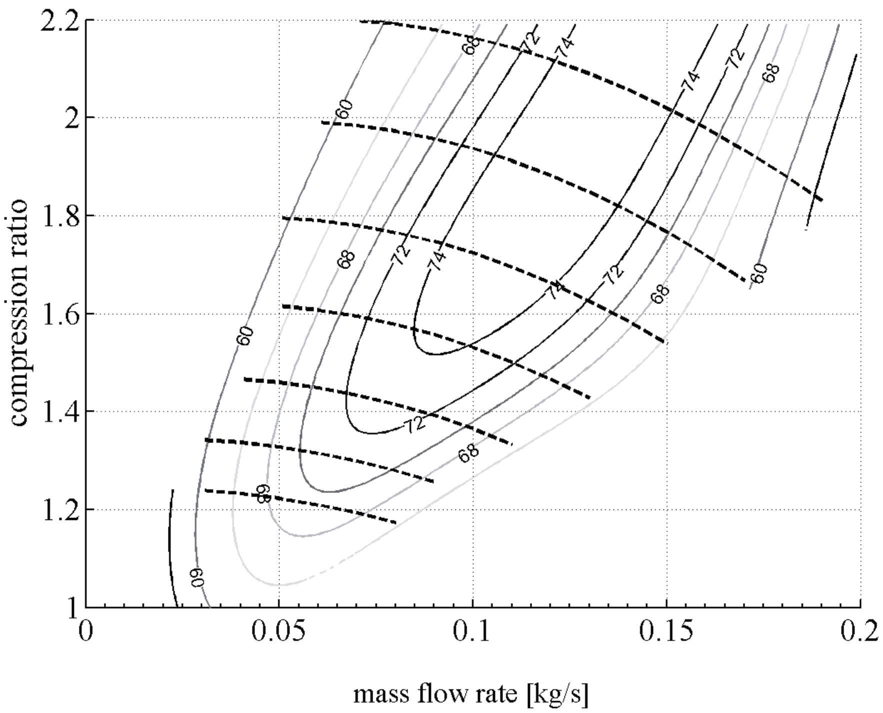

Fig. 2. Centrifugal compressor performance map [2]

Data conversion has been made with the following assumptions [3, 8]:

- input data are: rotational speed is n, mass flow of the working fluid through the channel compressor $\dot{m}$,
- restriction constitutes a line of stable operation of the compressor and the curve of maximum airflow,

– as a result of calculation is to estimate the compression ratio and efficiency for the selected input.

In detail conversion, process is presented below.

1. On the basis of the reduced rotational speed n_{zr} and the reduced mass flow rate $\dot{m_{zr}}$ compressor pressure ratio was calculated $\Pi_s{}^*(\dot{m_{zr}}, n_{zr})$.

Approximating of directional polynomial coefficients for given compressor speed is described by following equation:

$$A_n(n_{zr}) = a_{0n} + a_{1n} \cdot n_{zr} + a_{2n} \cdot n_{zr}{}^2 + a_{3n} \cdot n_{zr}{}^3 + a_{4n} \cdot n_{zr}{}^4, \tag{1}$$

where n_{ZR} – reduced compressor shaft speed.

Tab. 1. Directional coefficients of the equation compressor compression

n	a_{0n}	a_{1n}	a_{2n}	a_{3n}	a_{4n}
1	18.968	-1.653	0.0323	-0.000308	$1.0937*10^{-6}$
2	-2.721976	0.196	-0.00485546	$5.279*10^{-5}$	$-1.9179*10^{-7}$
3	1.091	-0.003768	0.00010397	0	0

Compressor pressure ratio was estimated by the equation:

$$\Pi_s{}^*(\dot{m_{zr}}, n_{zr}) = A_1(n_{zr}) \cdot \dot{m}_{zr}{}^2 + A_2(n_{zr}) \cdot \dot{m}_{zr} + A_3(n_{zr}), \tag{2}$$

where:

$\dot{m}_{zr}$ – reduced compressor mass flow rate.

2. Well-known limitations are explicitly excluded. Freedom from surge line $\dot{m_{zrpomp}}$ and limitation of compressor airflow $\dot{m_{zrgr}}$ are identified.

These restrictions are described by dependence:

$$\dot{m_{zrpomp}} = 0.049 \cdot \Pi_s{}^* - 0.039, \tag{3}$$

$$\dot{m_{zrgr}} = -0.11 \cdot \Pi_s{}^{*2} + 0.49 \cdot \Pi_s{}^* - 0.336. \tag{4}$$

3. On the basis of reduced rotational speed n_{zr} and the reduced mass flow rate $\dot{m_{zr}}$ compressor isentropic efficiency was calculated $\eta_s{}^*(\dot{m_{zr}}, n_{zr})$.

Approximating of directional polynomial coefficients for compressor isentropic efficiency is described by following equation:

$$B_n(n_{zr}) = b_{0n} + b_{1n} \cdot n_{zr} + b_{2n} \cdot n_{zr}{}^2 + b_{3n} \cdot n_{zr}{}^3 + b_{4n} \cdot n_{zr}{}^4. \tag{5}$$

Tab. 2. The directional coefficients of the equation of the compressor efficiency

n	b_{0n}	b_{1n}	b_{2n}	b_{3n}	b_{4n}
1	550996.15	-744686.96	354029.135	-61487.44	0
2	117503.77	155369.04	-79689.84	15836.63	0
3	6818.38	-10156.6	6802.9	-1660.96	0
4	-240.86	595.725	-423.49	97.2	0

Isentropic efficiency of the compressor stage is described by the equation:

$$\eta_s^*(\dot{m}_{zr}, n_{zr}) = B_1(n_{zr}) + B_2(n_{zr}) \cdot \dot{m}_{zr} + B_3(n_{zr}) \cdot \dot{m}_{zr}^{\ 2} + B_4(n_{zr}) \cdot \dot{m}_{zr}^{\ 3}. \tag{6}$$

The end result was characteristic presented into digital form (Fig. 2).

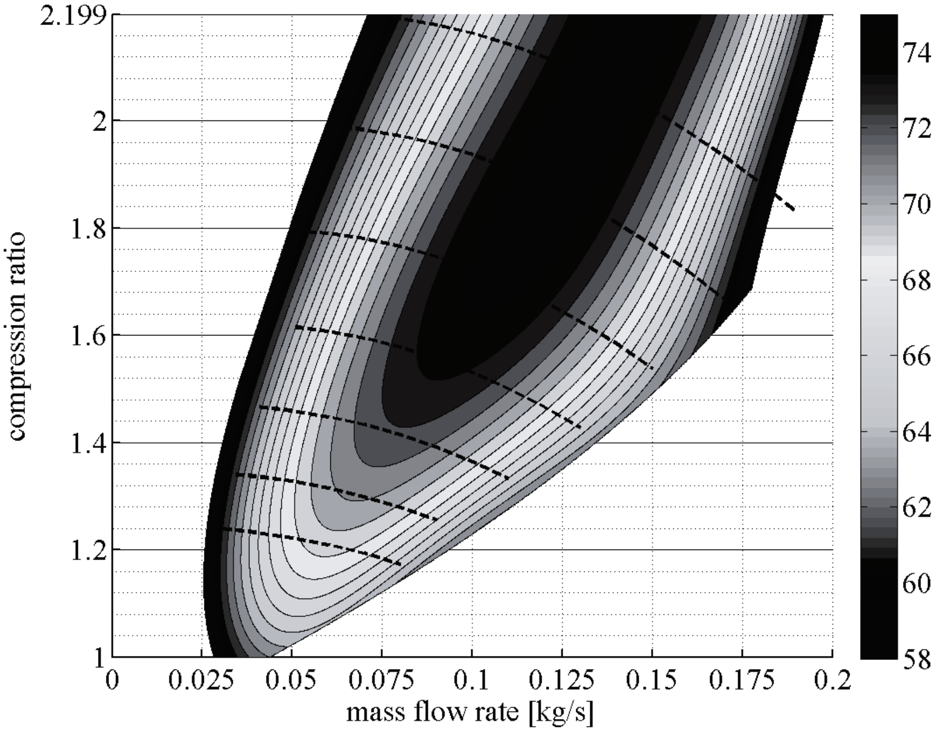

Fig. 3. KKK2464 compressor characteristics converted to the digital form (graph drawn for full range values of the contours)

Comparing the characteristics of the compressor stage shown in Fig. 2 stated that the digital model presented at Fig. 3 is correct in terms of quality.

3. Performance of digital model

Tests speed of the program is performed in order to determine the allowable time of the procedure. Bearing in mind that the algorithm approximates will be part of an extensive program, subjected to certain restrictions. Company specializing in the field of software for engineering calculations – ANSYS [1], has published guidelines for acceptable working time program. They are, respectively, depending on the type of task being performed: for design tasks – 1 hour, for analysis – 50 hours, research – 1000 hours. For further consideration two variants of computing was selected:

- with visualization of data (2 graphs image – enabled graphical user interface),
- without visualization.

The speed test was to use crude methods of “Monte Carlo”. Randomly generated points from the characteristics are based on parameters calculated according to the approximate thermo-gas dynamics. Comparing the relative time execution speed test should be noted that in the case of data visualization execution speed of the algorithm is clearly decreasing in the range above 2000 calculated points (Fig. 4).

Time calculations for centrifugal compressor characteristics can be estimated based on the relationship:

a) for the case of the calculation visualization:

$$t = 2.563 \cdot 10^{-8} \cdot n^3 + 1.239 \cdot 10^{-5} \cdot n^2 - 0.0018 \cdot n - 0.085, \tag{7}$$

b) for the case without the visualization:

$$t = 1.127 \cdot 10^{-11} \cdot n^3 + 2.846 \cdot 10^{-6} \cdot n^2 - 0.0006 \cdot n - 0.056. \tag{8}$$

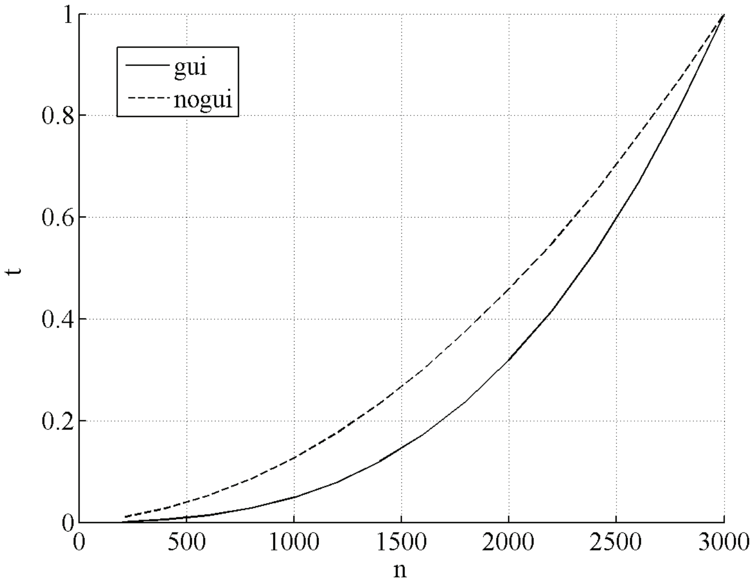

Fig. 4. Algorithm execution averaged time speed ~~t~~ for 3000 random chosen points

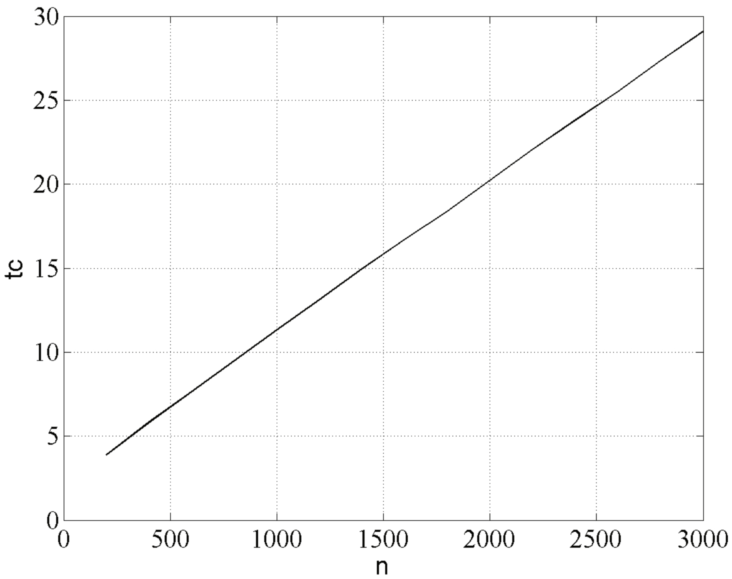

Fig. 5. Calculation visualisation slowing factor tc

It is important to determine the coefficient tc for estimation of time in computation process with enabled GUI in comparison to calculation without visualisation. This allows specifying number of points, which will be determined in restricted time, without losing data presentation. It is also possible to determine the probability of obtaining the optimum solution [9].

4. Summary

Developed procedure allowed reconstructing the map of the compressor (Fig. 2) with the difference of value at junctions between read and approximated data less than 0.4% of original value (Fig. 3). This compact approximation can be applied to electronic control units as thermo-gas dynamic parameter values can be calculated on the fly without the involvement of the memory subsystem and file system. An important fact is that the current data visualization slows down the speed of calculations more than 10 to 30 times (Fig. 5). For data visualization, computation time took 798 seconds, while without visualization only 24 seconds (7, 8). Enabling of visualization shows the weakness of computer's memory subsystem for more than 2000 generated points, because the time between successive points clearly extends. In conclusion to avoid slowing down the calculation is recommended to disable data visualization or present them at the selected time interval.

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