Creating a multi-level model of a centrifugal compressor for a digital analogue of the gas turbine engine

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Abstract. The paper presents the main ideas of the virtual test bench concept for rapid obtaining of the reliable characteristics of compressors based on a multi-level mathematical model with a two-step identification using data obtained from mathematical models with a high order of accuracy. One of the possible identification algorithms and the results of its successful testing are given on the example of a centrifugal compressor stage developed and tested at NASA.

Nomenclature

G	=	mass flow rate of the working fluid, kg/s
Z	=	Number of blades, pcs
K	=	scale factor;
l	=	2nd stage transformation ratio;
n	=	rotational speed, rpm;
Δ	=	displacement of the characteristics in the identification;
π^*	=	pressure ratio;
η	=	efficiency
$Y+$	=	non-dimensional wall distance
GTE	=	gas turbine engine;
CS	=	coordinate system;
FV	=	finite volume;
RW	=	rotor wheel
RD	=	radial diffuser
AD	=	axial diffuser
2D	=	referring to the simplified model;
3D	=	related to the model of high order accuracy.

1. Introduction

The compressor is an important component of a gas turbine engine that significantly affects the efficiency of the engine cycle, fuel efficiency, reliability and stability of work [1, 2]. To create a design that will be able to successfully compete with competitors today, it is not enough to obtain blades' shape that provides the best flow structure (which is in turn a difficult scientific and engineering problem). Modern compressor, in addition to providing the required pressure ratio with maximum efficiency, must:

- - withstand static and dynamic loads during the life cycle;
- - be cheap in production and operation;
- - have a low noise level;
- - be matched in the operation as the engine part;
- - show the required characteristics from the first delivery.

To successfully solve the problem of design and calculation development of the compressor at the modern level, it is necessary to involve a complex multi-physical model (considering gas dynamics, static and dynamic strength, manufacturing technology, cost, acoustic processes, etc.) of high accuracy (3/4D based on equations with minimum assumptions).

Summarizing the above, the task of designing or modernizing a compressor today is the search for the optimum of a multi-extreme, multi-criteria, multi-disciplinary function of a huge number of variables, the type and shape of which are not known, under the conditions of many restrictions. This task is not linear. It does not have a unique solution, and often the same design solutions made in different conditions lead to opposite results. For this reason, the creation of a modern compressor is one of the most difficult scientific and technical problems.

Finding the best combination of parameters describing the compressor by simply enumerating the options is the fortuity, not to mention that the human brain is not able to systematically comprehend and find the best combination of tens and hundreds of variables regarding constraints. Therefore, such a problem can be solved only with the use of mathematical optimization methods [6, 7, 8, 9].

The need to match the processes of the designed compressor with the engine process requires to determine in the calculation not just the values of the main parameters at the operating point, but to find its characteristic in a wide range of operating factors, conducting several dozen calculations for one combination of variable parameters. Since accurate multidisciplinary models require several hours to get a solution at one point, the time to determine the characteristics for one compressor variant will be calculated in days.

The application of complex multi-physical mathematical models described by hundreds of independent variables requires many iterations with the computational model. Considering the above, the search for the optimal solution of the task will require an unacceptably long time, even with the use of modern supercomputers. And the very problem of finding the extremum of a function with hundreds of variable parameters is a non-trivial task. If the compressor consists of several stages or it is necessary to design adjacent components (for example, a turbine), or it is required to carry out multi-criteria optimization, the described problem becomes even more complicated.

Thus, the key problem of designing modern compressors with outstanding characteristics is the creation of a coherent complex of multi-level mathematical models, which in a reasonable time can simulate the operation of a compressor and its elements at the earliest possible stages, prior to the production of a prototype, identifying potential defects and design variants that cannot meet the requirements of the technical specifications for some reasons. This complex performs the same functions as the test bench, so it can rightfully be called a "virtual compressor test bench".

A similar approach was developed by scientific group from led by Y.B Galerkin [10]. The researches apply so called "universal simulation method" to obtain the specifications of a centrifugal compressor with high accuracy.

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2. Algorithm of the Virtual Compressor Test Bench

To obtain data as close as possible to real ones in the calculation, it is necessary to apply precise 3/4D mathematical models describing the processes with minimal assumptions. Their main disadvantage is a great time for getting the result. At the same time, there are many simplified physical models (1/2D models, models with significant assumptions (for example, for gas dynamics — the Euler equations), etc.) that are not so accurate, but require a small calculation time (seconds and minutes).

According to the authors of the paper, the key technology that allows you to quickly and accurately get the desired compressor variant with outstanding performance (and will become the basis of a virtual compressor bench) that meets the set technical requirements is a coupled combination of the simplest "fast and cheap" and complex "slow and expensive" models. The main feature of the proposed version of the virtual test bench is that it is built based on a multi-level mathematical model with a two-stage identification according to data obtained from mathematical models with a high order of accuracy (Figure 1).

The core of the proposed methodology is a low order accuracy model (for example, 1/2D). In it, the characteristics of the compressor are calculated based on known geometric data of the compressor (in the form of a 3D model (often parametric)), a set of drawings of elements or an array of data containing information about the main geometric parameters of the elements of the flow path) and simulated conditions (from the experiment procedure). From the obtained data, a test results report is generated, a copy of which is archived.

The main disadvantage of the low-level model is that the resulting characteristics have a large error due to the strong simplification. Such models simplify the geometry of the model (the radii of curvature, the influence of the spatial alignment of elements, fillets, etc. are not considered), and they also do not properly simulate the energy losses.

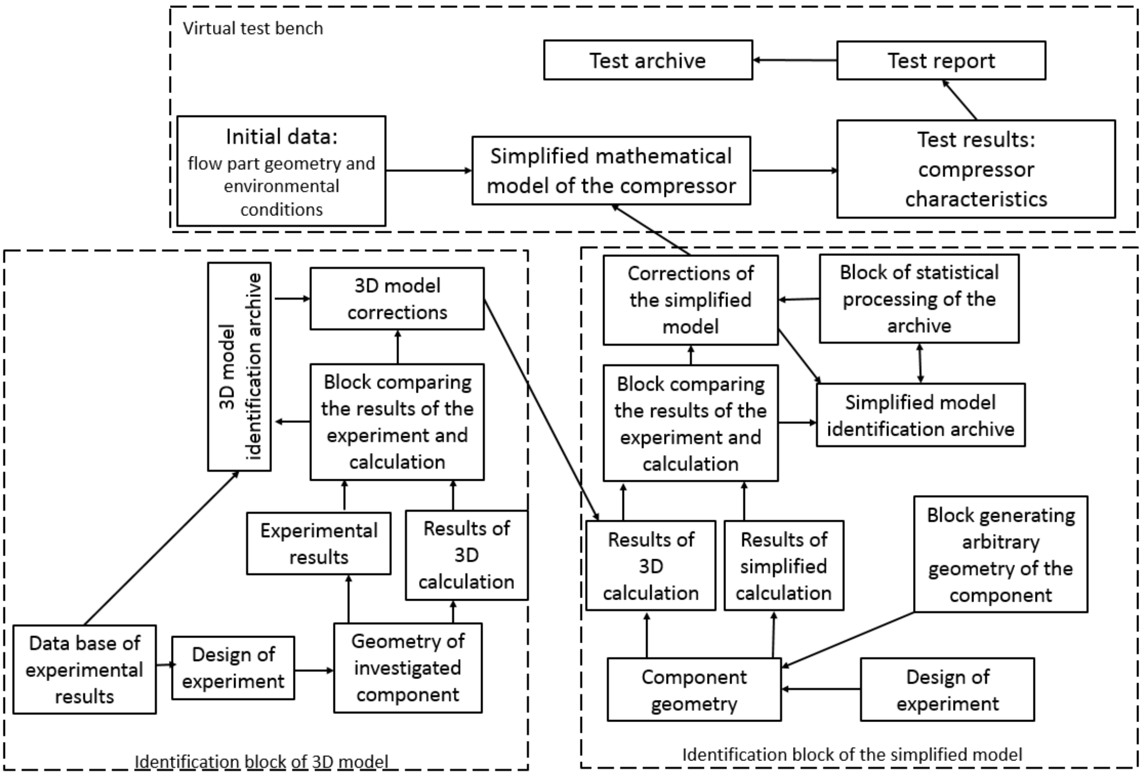

Figure 1. The principal flow diagram of the virtual test bench proposed by the authors for the investigation of the workflow of compressors.

To eliminate this drawback in the proposed version of the virtual stand, it is suggested to use the identification block of simplified computational models. The principle of its operation is to compare the results of the calculation of the same component using simplified methods and 3D (CFD) methods. The latter, as noted, have minimal assumptions, describe the geometry of the flow part without simplifications and show the best accuracy among the calculation methods known today. The calculation results obtained in two ways are compared with each other. As a result, corrections are found for a simple model, and further research of the compressor is carried out using characteristics calculated by the identified simplified model.

As various projects are completed, the geometry of the compressors and the results of their 3D and simplified calculations will be accumulated in the archive (database). As a result, an extensive identification database will be accumulated in a much wider range of geometric and operating parameters than the specific problem being solved. Statistical processing of archive data (creating regression models) can find universal corrections for simplified compressor models that can be used without conducting many initial 3D calculations of a specific task (one control calculation can be performed, which results will be recorded in the archive). Statistical processing of the archive must be conducted periodically at regular intervals, constantly updating the correction factors (teaching a simplified model). Moreover, the identification block can exist, work and "learn" independently from the virtual bench. To do this, a block must be implemented that will randomly generate the compressor geometry (with changes in the basic parameters in a wide range, screening options that are not possible for various reasons), carry out a simplified and 3D calculations of processes in them, record the results in the archive and periodically process it. Such an approach will allow obtaining continuously trained simplified models of compressor workflows that are able to calculate their reliable characteristics considering many features of the component geometry. Such a "training system" and the results of its operation is an independent product that may be of interest to compressor enterprises.

An important problem in identifying simplified models is the accuracy of 3D simulation, according to which the identification is carried out. To solve it, the proposed variant of the virtual test bench includes a block of identification of a 3D model based on the results of experiments, which must find corrections (settings) for 3D models that increase the accuracy of calculations. As can be seen from Figure 1, this block is created on the principle of identifying a simplified model. It is also possible to build an automatically functioning algorithm for identifying 3D models with periodically operating statistical processing of the archive (training models). However, its implementation is hampered by a small number of available experimental results and a rare update of their database.

3. Object for Creating a Pilot Variant of a Virtual Test

The construction and development of a pilot variant of the "virtual test bench" for testing compressors is carried out using the example of a single-stage centrifugal compressor. For this, a compressor designed by NASA is chosen, and which characteristics were comprehensively studied during the experiment [4].

The main parameters of the compressor at the design point are shown in Table 1. The main geometric parameters of the compressor meridional section are shown in Figure 2. Its three-dimensional model is shown in Figure 3. The experimental characteristics of the compressor obtained by NASA [4] are shown in Figure 6.

Table 1. The main parameters of the studied centrifugal compressor

Parameter	Designation	Units	Value
Rotor speed	n	rpm	22000
Air mass flow rate at the inlet	G	kg/s	5.1
Pressure ratio	π_c^*	-	4.5
Efficiency	η_c^*	-	0.8

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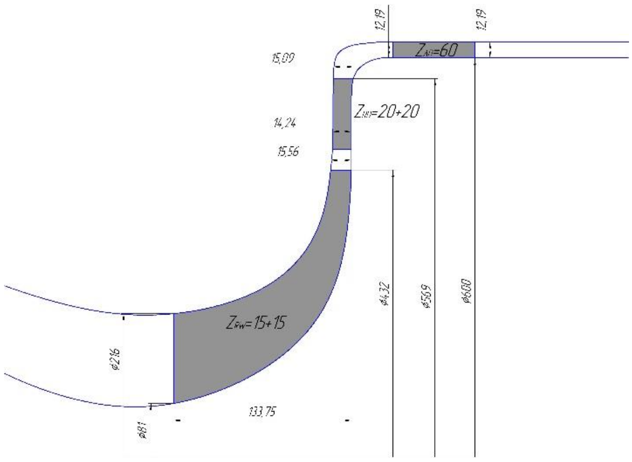


Figure 2. Meridional shape of a centrifugal compressor.

Figure 3. Three-dimensional model of the investigated centrifugal compressor.

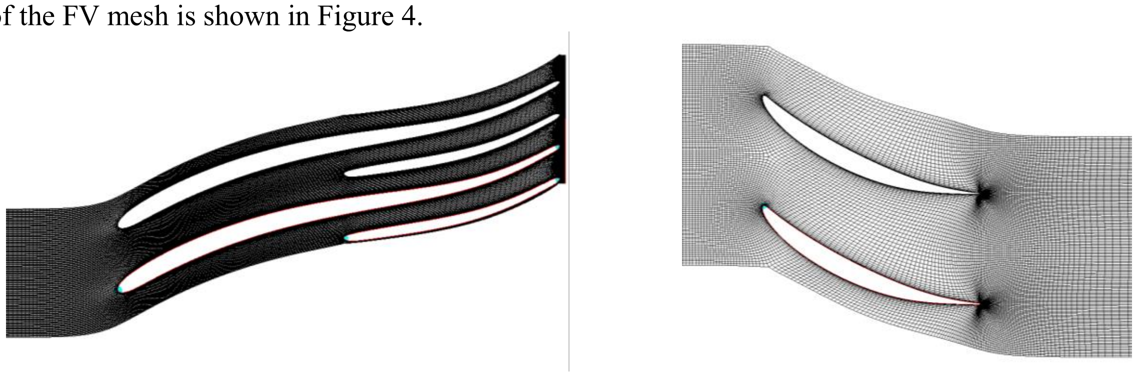
4. Creation and Verification of 3D Numerical Model of Compressor Workflow

Based on a detailed description of the compressor geometry and the results of its experimental studies [4], a 3D numerical model (high-level model) of its gas-dynamic processes is created in the *Numeca FineTurbo* [5].

The computational domain consists of three subdomains (rotor wheel, blade and axial diffusers). Each of the subregions consisted of one blade passage with periodic boundary conditions on the lateral surface. The RW domain is calculated in the moving coordinate system, rotating with the rotor speed, the other domains are considered in the fixed CS. Flow parameters between subdomains are transmitted using the *Full Non Matching Mixing Plane* interface, which averages in the circumferential direction the flow parameters at the outlet of one domain and transfers them to the inlet to the downstream domain as inlet boundary conditions.

As the boundary conditions at the inlet of the centrifugal compressor, the values of the total pressure (101325 Pa) and the total temperature (288 K) are set. At the outlet of the centrifugal compressor, the static pressure is set on the hub section. The value of static pressure is selected from the condition of providing the necessary point on the characteristics of the compressor.

The finite volumes mesh is created in such a way that the value of the parameter y_1^+ on the walls of the computational domain is equal to 1. The total number of elements is 3.2 million. The appearance of the FV mesh is shown in Figure 4.



Rotor wheel | Axial diffuser

Figure 4. Finite volume mesh of a 3D computational model of the centrifugal compressor**.**

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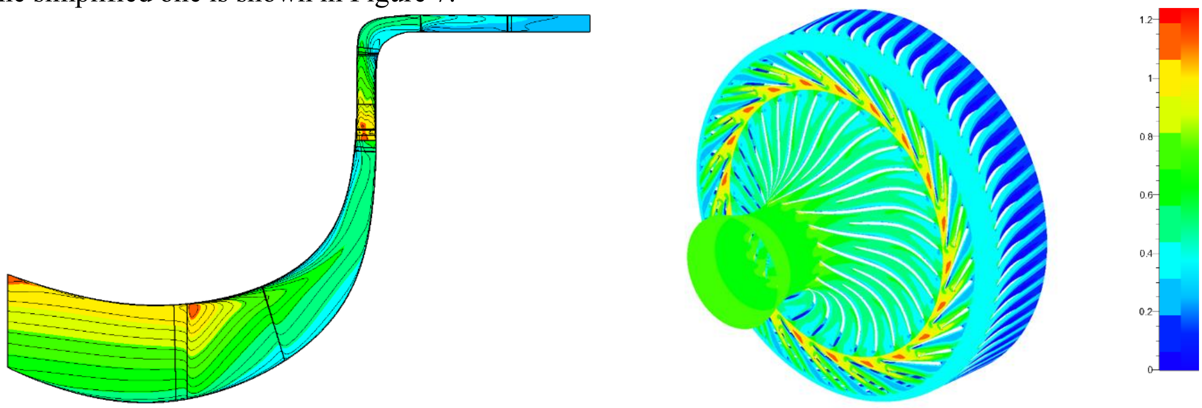
The flow structure (Mach numbers) in the compressor at the design point is shown in Figure 5.

Comparison of the pressure and efficiency characteristics obtained as a result of 3D calculations (Figure 6) at the rotor speed of $\bar{n} = 100\%$ with the corresponding experimental data indicates their good qualitative and quantitative coincidence. The appearance of the characteristics of the investigated compressor, obtained using the created computational 3D model, which will later be used to identify the simplified one is shown in Figure 7.

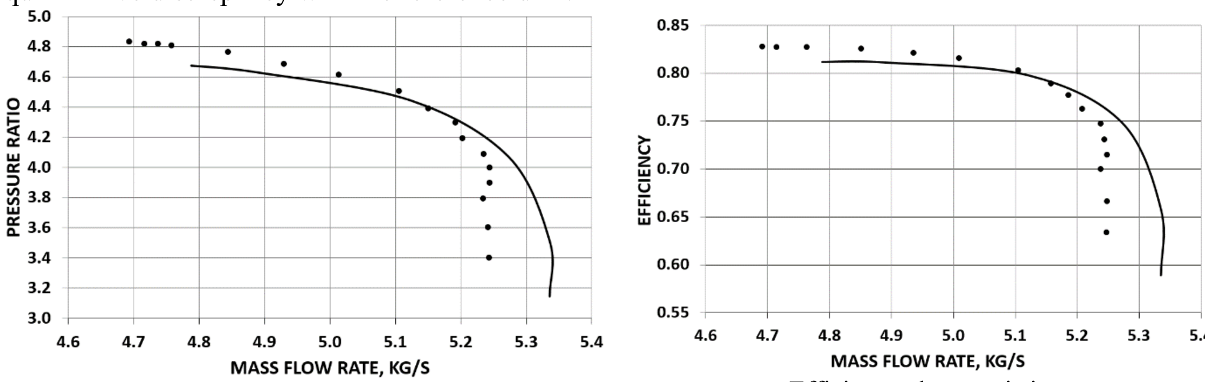


Averaged in the meridional section In the middle section

Figure 5. Calculated contours of Mach numbers in the relative motion at the design point, obtained for the compressor using computational 3D model.

5. Characteristics of the Centrifugal Compressor Created Using a Low-Level Design Model

For the centrifugal compressor taken as an example, a simplified 2D model of its workflow in it is created for the same initial data. With its help, the characteristics of the compressor are obtained. They are shown in Figure 7 in comparison with the characteristics obtained by the 3D model, verified by experimental data. As can be seen, the results of 2D modelling have a noticeable qualitative and quantitative discrepancy with the reference data.



Pressure characteristics Efficiency characteristics

- Results of 3D calculation; • - Experimental data

Figure 6. Comparison of the experimental and calculated (using a 3D model) characteristics of the centrifugal compressor at a rotor speed of 100%.

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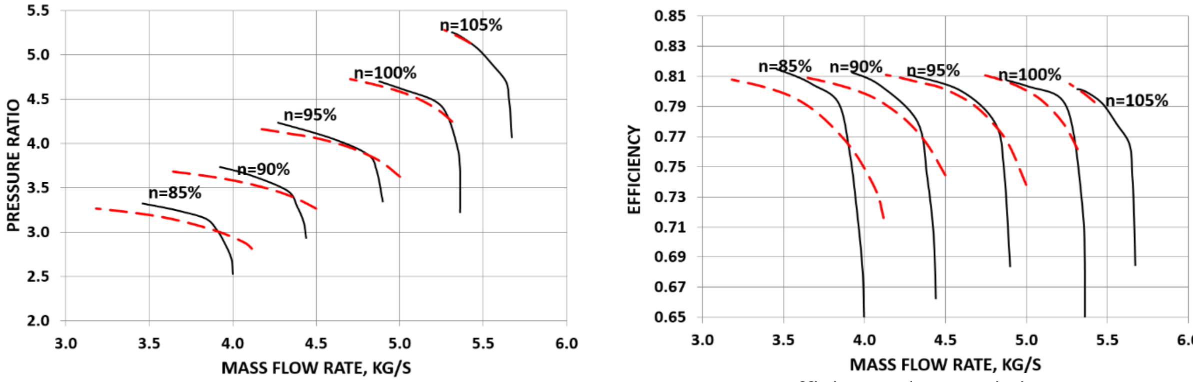


Pressure characteristics Efficiency characteristics

- Results of 3D calculation - Results of 2D calculation

Figure 7. Characteristics of the investigated centrifugal compressor obtained using 3D and a simplified 2D computational models of the workflow.

6. Description of the Implemented Algorithm for the Identification of Simple Mathematical Models by High-Level Models

The main purpose of identifying a mathematical model by a high-level design model is to find such corrections, the use of which will bring the results of the calculation of a low-level mathematical model as close as possible to the reference ones (obtained in the experiment or using an identified high-level model). In this case, the identifying corrections must be a function depending on many operational and geometric parameters. To obtain reliable universal correction factors that minimize the error in modelling an arbitrary problem, it is necessary to analyse a large database of matching results.

In relation to the current problem, identification (approximation of the design characteristics of the compressor to the reference ones) can be carried out in two principal ways:

- by the correction of empirical coefficients of the low-level mathematical model (firstly, the coefficients of the energy loss model);
- by the mechanical transformation of the characteristics obtained using the low-level model, so that it comes close to the reference.

The first approach looks more reasonable, but the second one can be implemented with lower costs. The latter will be further applied. The following describes the algorithm developed by the authors to identify a simplified mathematical model of a centrifugal compressor, described in Section 3, based on the results of a calculation using a 3D model used in constructing a pilot variant of a virtual test bench.

Figure 7 shows a comparison of compressor characteristics obtained using 2D mathematical model of the centrifugal compressor and the reference 3D model. To combine the corrected and reference characteristics, the first of them must be shifted and scaled along both coordinate axes. This manipulation must be done with both (π_c^* and efficiency) characteristics of the compressor.

The connection between the points of the original 2D and the adjusted characteristics at a constant rotor speed can be written as follows:

$$G_i^{cor} = G_i^{2d} + \Delta_G + \left(G_i^{2d} - G_{min}^{2d}\right)K_G; \quad (1)$$

$$\pi_{ci}^{cor} = \pi_{ci}^{2d} + \Delta_\pi + \left(\pi_{ci}^{2d} - \pi_{cmax}^{2d}\right)K_\pi; \quad (2)$$

$$\eta_{ci}^{cor} = \eta_{ci}^{2d} + \Delta_\eta + \left(\eta_{ci}^{2d} - \eta_{cmax}^{2d}\right)K_\eta, \quad (3)$$

where Δ_G, Δ_π, Δ_η –offset of characteristic lines;

K_G, K_π, K_η –scaling factors of the characteristic lines.

These coefficients for the fixed rotor speed are calculated as follows:

$$K_G = \frac{G^{3d}_{max} - G^{3d}_{min}}{G^{2d}_{max} - G^{2d}_{min}};\ K_\pi = \frac{\pi^{3d}_{cmax} - \pi^{3d}_{cmin}}{\pi^{2d}_{cmax} - \pi^{2d}_{cmin}};\ K_\eta = \frac{\eta^{3d}_{cmax} - \eta^{3d}_{cmin}}{\eta^{2d}_{cmax} - \eta^{2d}_{cmin}}; \tag{4}$$

$$\Delta_G = G^{3d}_{min} - G^{2d}_{min};\ \Delta_\pi = \pi^{3d}_{cmax} - \pi^{2d}_{cmax};\ \Delta_\eta = \eta^{3d}_{cmax} - \eta^{2d}_{cmax}. \tag{5}$$

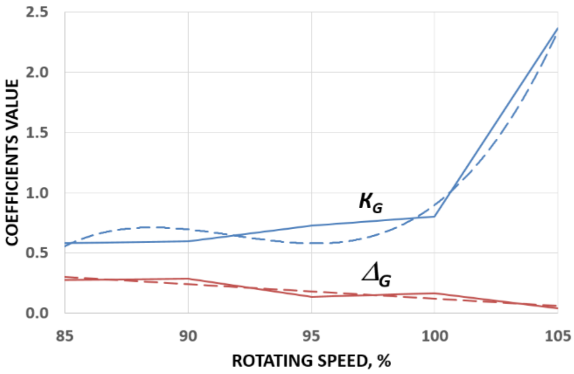
These coefficients are calculated for all pressure lines (lines of constant rotational speed). As a result, an array of data of the form K_G, K_π, K_η, Δ_G, Δ_π, Δ_η=f(n) is created. The data available in it is interpolated by some functions: $K_G = f(n)$, $K_\pi = f(n)$, $K_\eta = f(n)$, $\Delta_G = f(n)$, $\Delta_\pi = f(n)$, Δ_η=f(n).

Identification of 2D characteristics of the centrifugal compressor, carried out for an example compressor, showed that the displacement of the characteristic lines are most accurately interpolated by the function $\Delta_i = an + b$, and the scaling coefficients of the characteristic lines are a third-degree polynomial $K_i = cn^3 + dn^2 + en + f$. Examples of the obtained coefficients and their interpolation for the centrifugal compressor of a virtual prototype are shown in Figure 8.

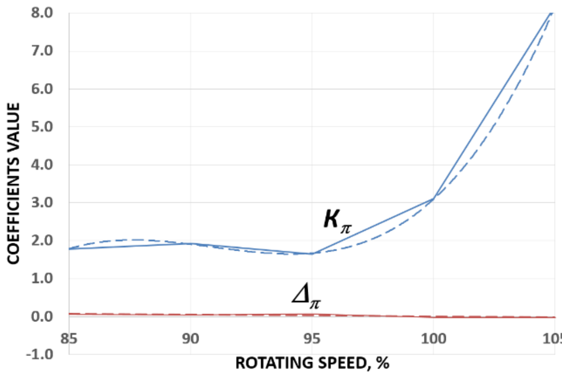
As can be seen from Figure 8, the interpolation equations are obtained only by 5 points, and show a relatively high error. It is obvious that the accumulation of identification statistics should significantly reduce it.

Using the found interpolation equations, the transformation coefficients are calculated and the original 2D characteristic is recalculated. The results of the described transformation are shown in Figure 9. As can be seen from the presented results, the corrected characteristics show good qualitative agreement, but at the same time, the quality is not satisfactory.

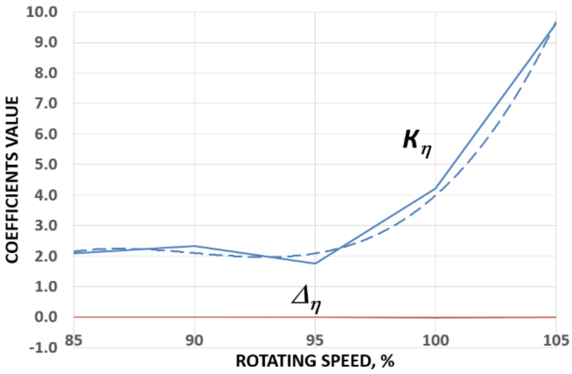
To solve this problem, the algorithm described above is upgraded. The essence of the modernization lies in the addition of the “qualitative correction” algorithm (the second stage of transformation), when a certain middle point of the calculated curve is combined with the same point of the reference curve.



For the mass flow rate through the compressor



For pressure ration



For efficiency

Figure 8. The results of calculating the transformation coefficients in identifying 2D characteristics of a virtual prototype (solid line) and their interpolation (dashed line).

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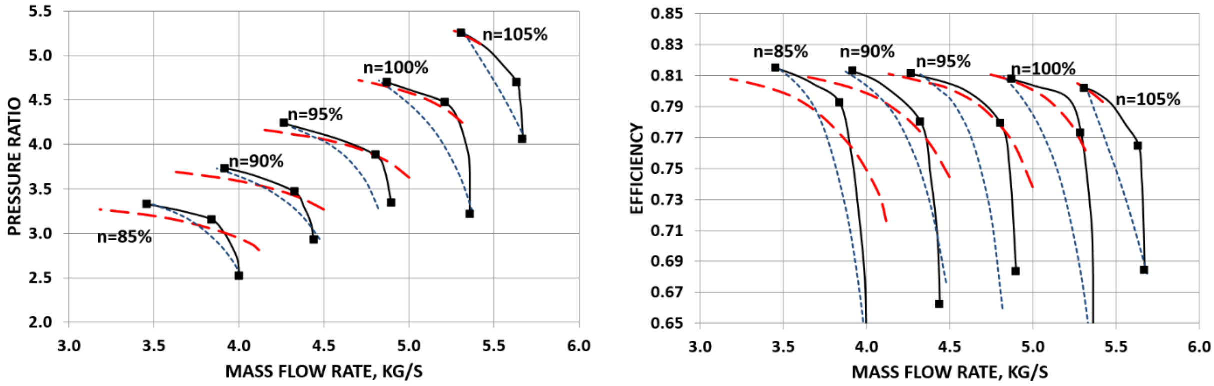


Pressure characteristics Efficiency characteristics

- Results of 3D calculation; - Results of 2D calculation Corrected 2D model (stage 1)

Figure 9. Transformation of compressor characteristics at the first stage of identification.

This algorithm works as follows. A "characteristic point" is selected on the reference curve (this point receives the index "mid") that is the point of discontinuity of the curve (indicated in Figure 9). To determine it, the tangents are calculated at the points describing the characteristic lines and their change when going from one point to the next in the direction of growth of the working fluid mass flow rate. In the place where the angle of inclination of the tangent is changed to the largest value is the point of maximum discontinuity (mid). Then, the angular coordinate of the found point in the polar coordinate system with the centre at the origin is calculated. The point with a close value of the angular coordinate in the same CS is on the transformed curve.

Further transformation of the characteristics can be carried out in the following way. At the second stage of the correction ("quality correction") occurs only along the vertical axes:

$$\pi_{ci}^{cor2stage} = \pi_{ci}^{cor1} l_{\pi i} = \left(\pi_{ci}^{2d} + \Delta_\pi + \left(\pi_{ci}^{2d} - \pi_{cmax}^{2d}\right)K_\pi\right) l_\pi; \tag{6}$$

$$\eta_{ci}^{cor2stage} = \eta_{ci}^{cor1} l_{\eta i} = \left(\eta_{ci}^{2d} + \Delta_\eta + \left(\eta_{ci}^{2d} - \eta_{cmax}^{2d}\right)K_\eta\right) l_\eta, \tag{7}$$

where $l_{\pi i}$, $l_{\eta i}$ are correction factors.

It is assumed that the value of the correction factors l_i with the change in flow rate varied in accordance with Figure 10. The change in the magnitude of the correction factor between the maximum and extreme values is assumed to be linear.

The value of the maximum correction factors is as follows:

$$l_{\pi max} = \frac{\pi_{cmid}^{3d}}{\pi_{cmid}^{2d}}; \; l_{\eta max} = \frac{\eta_{cmid}^{3d}}{\eta_{cmid}^{2d}}. \tag{8}$$

The maximum correction factors are found for all calculated lines corresponding to a constant rotation frequency and then interpolated by the function $l_{imax} = p \cdot n + q$.

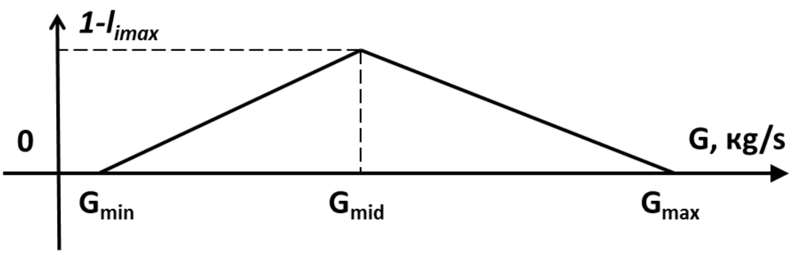


Figure 10. The adopted pattern of change of the correction factors l_i.

A flow diagram of the identification process used in the centrifugal compressor is shown in Figure 11.

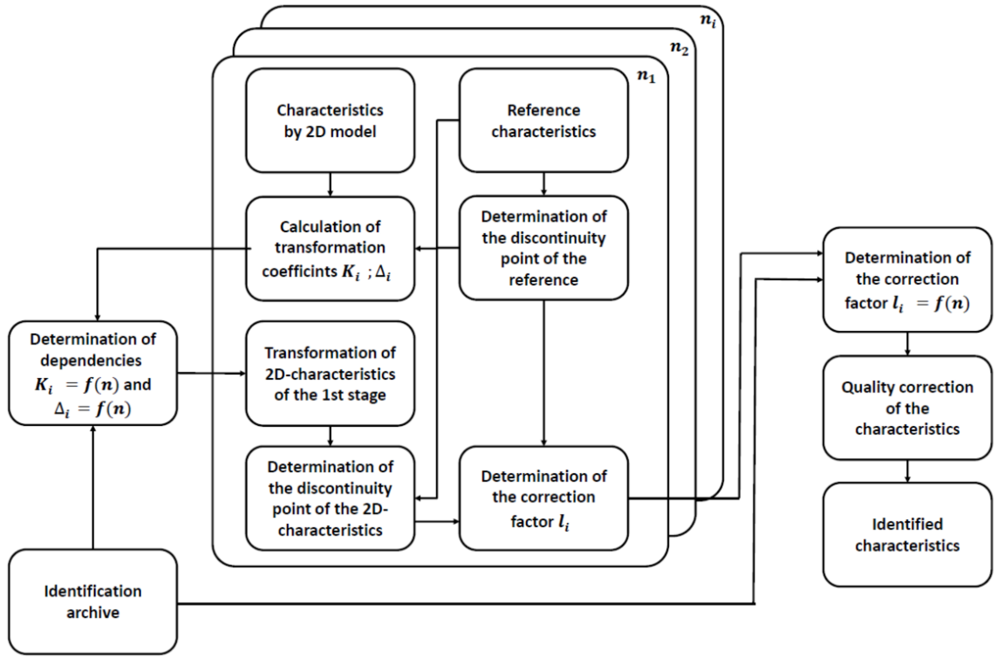
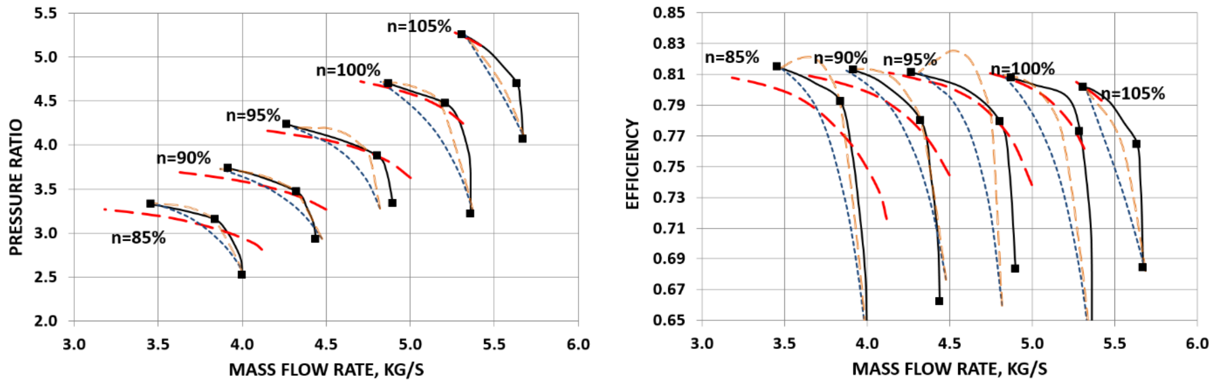


Figure 11. The flow diagram of the identification of mathematical models using the transformation characteristics.

The results of the transformation of the compressor characteristics after stage 2 are shown in Figure 12. As can be seen, the transformation allowed for a good agreement between the corrected and reference characteristics, especially for n=90 and 100%. The qualitative distortion of the characteristic lines at other rotor speeds is caused by a small number of calculation points, which introduced a significant error in the determination of the “maximum inflection point” (mid) on the 2D calculation curve.



Pressure characteristics Efficiency characteristics

- Results of 3D calculation; - Results of 2D calculation Corrected 2D model after the 1st transformation stage; - 2D model after the 1st transformation stage

Figure 12. The result of a two-step transformation of 2D characteristics during identification.

Conclusions

In the course of the project, the authors developed the concept of a virtual test bench based on simplified mathematical models with two-step identification by the results of calculations using high-level models and experimental data in order to obtain reliable characteristics of the compressor. According to this concept, characteristics obtained using 1/2D mathematical models of components are used to accelerate the obtaining of the results. They are based on relatively simple correlations and require a short calculation time but have significant error. To eliminate this drawback, 1/2D calculation models are identified by the results of 3D calculations. The latter have minimal assumptions and show the best accuracy among the calculation methods known today. Based on the comparison, corrective corrections are found for the 1/2D model. 3D models in turn are identified by the test results. When creating identification blocks, “learning” algorithms for 1/2D and 3D models are proposed.

An algorithm for identifying simplified models using high-level models is developed and successfully tested.

The developed algorithms and pilot samples of the virtual compressor test bench are the first steps of a fully featured “bench”, which will be able to replace most of the field tests. The virtual bench will allow to model a larger range of impacts on the object under study, including those that cannot be reproduced on existing benches or require huge material and energy costs. Modern development of automated tools and tools for the design of gas turbine engines, processing, management and accumulation of information allows us to believe in the successful solution of this problem and the achievement of a qualitative leap forward in the characteristics and capabilities of virtual test benches.

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