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Integrated Environment for Gas Turbine Preliminary Design

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ABSTRACT

This paper presents structure and capabilities of new integrated environment for axial and radial turbines and compressors preliminary design. The environment makes possible to find number of different designs with inverse task solver, basing on initially specified boundary conditions, closing conditions and design variables. Design space explorer provides easy and visual comparison for range of obtained design in customizable coordinate axes. Solution filtering on different parameters, such as number of stages, meridional and axial dimensions, maximal blades weight, saving the time to choose from thousands obtained solutions the only one right design.

Flexibility of presented approach allows to built-up complete gas turbine flow path from consequence of individual elements: stationary and rotating elements, ducts, heat exchangers, and analyze it in common environment. Joint turbine and compressor performances calculation “on the fly” is the next essential step of gas turbine or aircraft engine design and performances analysis to evaluate their operating modes and working ranges lines. Complete control of all aspects of aerodynamic flow path quality, structural reliability, and integral performances on design and off-design conditions is performing throughout all design process. This gives full interaction between user and system for immediate correction and enhancement of current design data using various optimization capabilities to feel the impact of changes on each design step.

Proposed system significantly shortening the design cycle time from initial machine concept to finalized design with all off-design performances details already calculated.

NOMENCLATURE

c	velocity in absolute frame	m/s
F	area	m^2
H	rothalpy	J/kg
i	enthalpy	J/kg
G	mass flow rate	kg/s
p	pressure	Pa
R	reaction	-
s	entropy	J/kgK
u	circumferential velocity	m/s
w	velocity in relative frame	m/s
α	flow angle in absolute frame	deg
β	flow angle in relative frame	deg
η	efficiency	-
φ	stator velocity coefficient	-
ψ	rotor velocity coefficient	-
ρ	density	kg/m^3
ω	rotation speed	s^{-1}
$\bar{\varpi}$	total pressure loss coefficient	-

Subscripts

0	inlet to machine, station upstream stator
1	station downstream stator
a	axial velocity component
w	relative movement

INTRODUCTION

World’s increasing demands in energy, as well as transportation market growth emerges gas turbine manufacturers to be proactive. They have to design machines, that satisfies today’s requirements of highest efficiency (i.e. minimal fuel consumption), ability to operate in some certain range of conditions, weight restrictions, which are critical for transport applications. To be as much competitive as possible, design cycle shortening and intensifying is necessarily too. That’s why question creation of new generation of gas turbine preliminary design environment raised up high last years.

As it well-known, most of machine’s geometrical properties selects on phase of preliminary design and remain almost unchangeable throughout next design phases, predefining its layout significantly. Therefore, preliminary design task is basis, that should be selected very carefully. But from other side, it can be a number of different options that also can be found useful and need to be considered.

This paper is describing theoretical backgrounds and internal structure of integrated gas turbine preliminary design system. At the end some practical usage examples are illustrating its work and results.

REQUIREMENTS FOR GAS TURBINE INTEGRATED DESIGN ENVIRONMENT

Before design system creation is started, its developers have to outline obligatory requirements, which make such software concept satisfying end-users needs and meets modern turbomachinery design standards. Overview of different theoretical sources [1-4] and a real design system, implemented in companies [5-7], were made to establish new design system requirements. Mainly, preliminary design system should be integrated with aerodynamic performances analysis to perform study of designed machine and have capabilities to alternate between created designs to make refinement, basing on design generated. Additional, but useful features for it can be design of repeating stages, capability to maintain specific design diameter, specification of stages reaction ranges for design, capability to stay in limited axial sizes ranges and weight ranges.

Proper selection of project architecture and theoretical basis for such system is crucial question that is predetermining system’s functionality and usability in terms of real tasks application. One of the main requirements for such system is fast turnaround time with ability to create and consider extensive number of various designs, be able to find trade-off between existing constraints and required outputs. Machine's various layout configurations and additional elements, such as ducts, exhaust diffusers, surge valves and others, can be used in gas turbine and effect its performances, thus they have to be present and taken into account as part of system design process.

Underlining all statements made above, main requirements for gas turbine preliminary design system can be summarized as follows:

1. Flexibility of usage, possibility to generate flow path designs for different configurations of machine elements and parameters from scratch, satisfying existing constraints.
2. Fast response time, ability to generate and review large number of design candidates in short time on their design mode, as well as off-design modes performances evaluation.
3. Integration and interaction between design system elements and modules, responsible for different steps of design process.
4. Provide to user convenient mechanism of data managing with selection of additional elements for precise simulations of complex machines (ducts, diffusers, heat exchangers)

It is clear that system need to have a finished preliminary design cycle starting from scratch and ending up with 3D flow path geometry, but current paper aim is to describe components, related to preliminary design and sizing, as most innovative ones. As it follows from requirements stated above for preliminary design environment, it can't be based on 3D CFD ideology, because it requires extensive time to accomplish, even with current computational power speeding up. Also, due to its nature 3D CFD can't be reliably applied for designing turbomachines from scratch, as well as it has many other limitations in preliminary design phase.

Therefore, some different approach has to be applied in this type of system. The most appropriate approach in this case is system architecture with principle from general to special. Such design system should use fast meanline codes for preliminary sizing and designs evaluation, and increase complication with axisymmetric and quasi-3D codes, while it's moving from general concepts to particular machine details on higher design process levels.

The detailed theoretical background and structure of preliminary design and sizing part of the system is reviewed in next parts of current paper.

MACHINE ELEMENTS ARCHITECTURE

To establish design system, it's necessary to create proper hierarchy of objects to be used in its structure. A few major levels, that describe different project components depending on their complications, are created. The levels, used in system are next:

1. Machine – represents complete turbomachine of any available type (axial, radial turbine or compressor, or combined – axial-radial machine), that can consist from a few modules, and elements between them.
2. Module – represents individual stage or group of stages that can be combined basing on their common properties: belongs to same machine component (e.g. HP, LP cylinder), equal specific diameters, repeating configuration, similar rotation speed etc. Module can combine only stages of similar type: axial or radial.
3. Stage level represents layout of single individual stage or components between the stages. The axial stage can consist from stator and rotor, radial stage layout can include impeller, diffuser and volute. Stage level includes different inter-stage components, as heat exchangers, inlet and outlet elements.
4. Component level is lowest one and represents minimal units of machine, such as rows (rotation or stationary), ducts and any other individual elements that can be necessary.

Machine elements architecture schematic representation shown in figure 1 below, and it makes possible to create almost any layout with versatile elements, combined in any consequence.

TURBOMACHINERY FLOW PATH SYNTHESIS PROCEDURE

Task Formulation

Turbomachinery flow path design task consists in new flow path designs generation using basic boundary conditions and design variables inputs obtaining maximum of selected target criterion (power, efficiency etc). Capability of results comparison, selection of proper designs basing on specific criteria with further evaluation of obtained solutions to determine their off-design parameters is mandatory requirement to simplify obtained results post-processing.

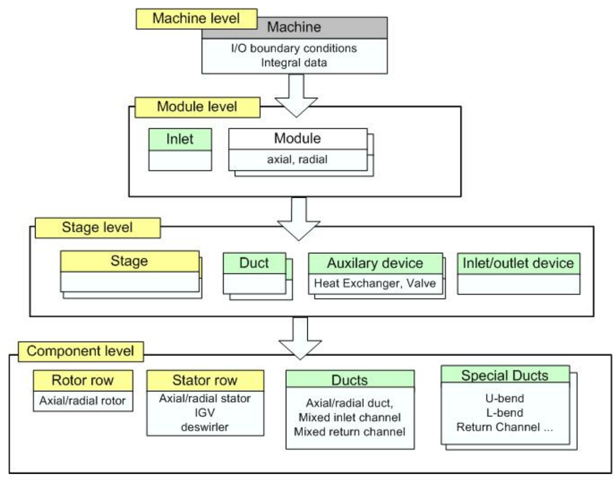

Fig.1. Machine structure layout

System Background Mathematical Description

Integrated system uses similar mathematical background independently on type of turbomachine, which is going to be designed or calculated. Basically, it can be described by next equations, such as energy equation:

$$H = i + \frac{w^2 - u^2}{2} \tag{1}$$

Continuity equation:

$$G = \rho \cdot F \cdot w_a \tag{2}$$

Process equation based on velocity loss coefficient:

$$s_0 = S\left(P, \frac{1}{\psi^2}\left(i - \left(1-\psi^2\right) i^*_{0w}\right)\right) \tag{3}$$

and based on total pressure loss coefficient:

$$s_0 = S\left(\frac{p^*_w - \bar{\varpi} \cdot p_0}{1-\bar{\varpi}}, i^*_w - \frac{u^2}{2} + \frac{u_0^2}{2}\right) \tag{4}$$

Equations of state:

$$\rho = P(p,i);\ s = S(P,i);\ p = P(i,s);\ i = I(p,s) \tag{5}$$

Depending on closing conditions applied, two types of tasks can be considered:

- *Inverse task* – task of geometry selection (diameters, angles, heights) basing on specified inlet and outlet boundary conditions, when pressure drop (raise) between stages applies as closing conditions
- *Direct task* – task of flow path thermodynamic calculation, when geometry (heights, diameters) is known and angles are applied as closing conditions

Boundary conditions can be represented as:

1. Machine inlet total pressure and enthalpy, p^*_0, i^*_0
2. Inlet flow angle, α_0
3. Pressure downstream machine, p_2
4. Rotation speed, ω
5. Mass flow rate, G

For inverse task stages' pressure drop (raise) on stages can be applied as closing condition, geometry parameters are set as range of design variables, where search is to be done. Design approach uniformity is based on idea that all machine types can be designed using the same equations, presented above. Current article provides representation for newly created integrated structure that can combine next machine types by this uniform approach: axial turbine, axial compressor, radial turbine, centrifugal compressor and mixed (axial-radial) types. The only difference is in design variables parameters combination, i.e. type of boundary conditions and specific geometry constraints applied depending on each particular machine type (turbine or compressor, axial or radial).

Preliminary Design with Meanline Inverse Task

Preliminary design is procedure of flow path geometry obtaining using predefined set of boundary conditions and design variable ranges. For purposes of machine geometry generation and evaluation in preliminary design, inverse task was selected because of possibility to quick review of number of designs, without certainly defined geometry, that matching selected criteria. Uniform approach can be applied to all types of machines described above, but different design parameters combinations should be used for each particular one. Consequence of preliminary design steps is next:

1. Design parameters combination setting for selected machine type
2. Design parameters variation in selected ranges
3. Geometry generation from selected set of parameters and constraints verification
4. Inverse task calculation
5. Selection of best design basing on criteria chosen

As it stated above, meanline inverse task was selected as most satisfactory for rapid and flexible preliminary design generation procedure. Depending on machine type, selection of design variables combination is different, and for axial machines it can be described by next data:

- Number of stages
- Specific diameter (hub, mean, tip)
- Geometry constraints (blade height, gauging angle, diameter/blade height ratio)
- Velocity ratio or work coefficient
- Axial velocity ratio distribution between stages
- Additional constraints on flow path diameters and axial sizes, which can be applied to restrict search to more specific ranges

For radial machines set of input design parameters is next:

- Rotor inlet mean diameter
- Outlet/inlet diameter ratio
- Inlet flow factor (c_{1a}/U_1)
- Stage configuration setup - diffuser and volute type selection
- Additional constraints: blade metal angle, diffuser outlet diameter

Design generation should be performed basing on some initial set of parameters. Set of multiple design variables should be studied and all possible design combination considered, so different approaches could be used for this operation to cover whole range. Proposed method is LPτ search, that generates quasi-random sequences. These are uniformly distributed sets of $L=M^N$ points in N-dimensional unit cube I^N. The advantage of algorithm selected is that unlike pseudo-random sequences, quasi-random sequences provide uniform distribution in spaces. This also makes possible to increase search points density by setting additional parameters.

From selected set of parameters geometry is generated and evaluated in inverse task solver. Additional parameters, such as clearances, chords, number of blades are selecting basing on prescription given for specific machine type and sizing ranges, specified above.

General theoretical overview of presented approach methodology for axial turbine and compressor is given in [8] and in [9] for centrifugal compressor.

The essence of the inverse task calculation is solving of equation set to find unknown angles α_1 and β_2, when velocity coefficients φ and ψ (i.e. losses) supposed to be predefined basing on some known correlations or prescribed efficiency charts (such as Spencer-Cotton, Smith, Baines diagrams). The task of α_1 and β_2 angles determination is such way to find search criterion maximum as function from set of design variables:

$$\max \eta_i(\vec{u}) \quad (6)$$

To improve design selection flexibility, best possible solution can be chosen basing on predefined search criteria, such as: internal or polytropic efficiency maximum, maximal (turbine) or minimal (compressor) power. Process chain described below is representing machine synthesis procedure.

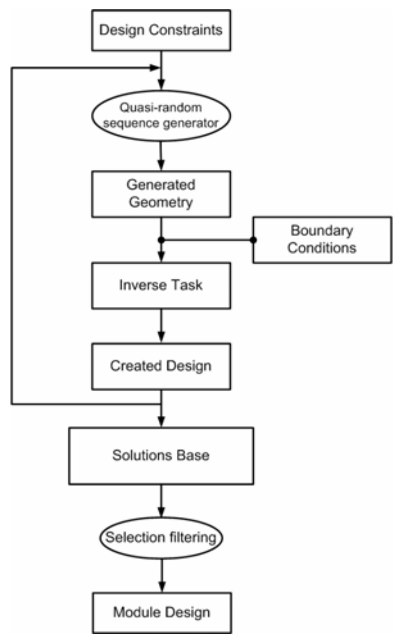

Fig.2. Design procedure scheme

Design Option by Modules

Generation of complicated flow paths with significant thermodynamic or geometric properties difference between groups of stages (flow extractions and inductions, reheat and intercooling, etc), as well as combinations for different kind of mixed (axial-radial) machines, required additional option to solve preliminary design task for multiple modules and combine them in one machine as result of preliminary design study. Each module can have unique inlet and outlet boundary conditions and design variables. Modules can be designed all together in one procedure or individually, that gives flexibility to select different boundary conditions variations before each module, such as:

- Inherit outlet conditions from previous module
- Inherit pressure from previous module, temperature can be specified additionally
- Set specific pressure and temperature for each module

In case of significant temperature difference between modules designed, design system automatically inserts heat exchanger and selects approximate temperature required to make this difference.

Design Results Post-processing

Convenient postprocessing with capability to filter results is crucial requirement for such system type. Design space explorer contains all generated designs for current machine or module depending on procedure selected on previous step. Important trade-offs between power, efficiency and number of stages, velocity ratio and geometric design constraints can be easily found. Example of design space charts with comparison between number of stages, efficiency, machine axial dimensions.

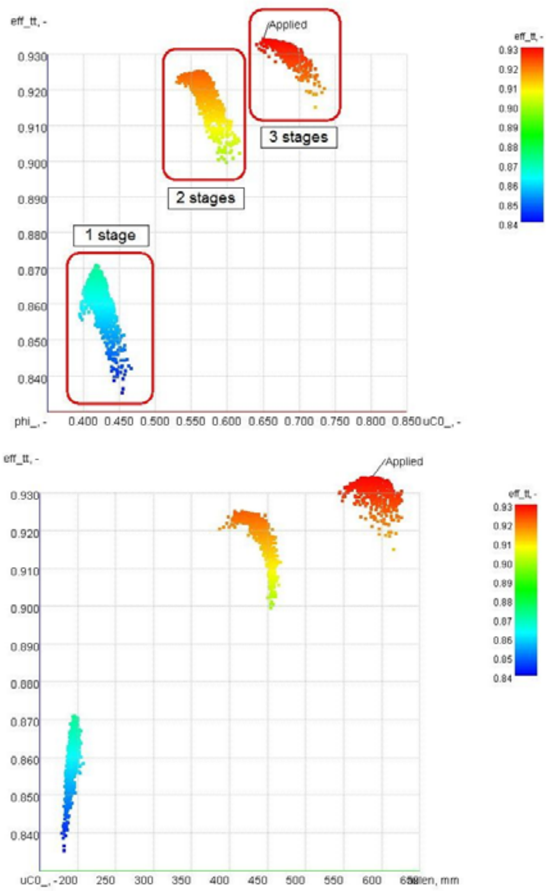

Fig.3. Solution explorer space with generated axial turbine designs (Efficiency vs velocity ratio and axial length)

Table 1. Gas Turbine Preliminary Design Data

Number of stages	Total-total efficiency	Power, MW	Axial length, mm
1 stage	0.8709	66.47	206
2 stages	0.9251	76.60	460
3 stages	0.9341	77.87	626

These charts clearly represent challenges designer faces while selecting layout and potential compromises between them. Applying additional constraints designer can narrow range with additional parameters selection, such as:

- Number of stages = 2;
- Flow outlet angle in absolute movement = from 85 to 95 deg;

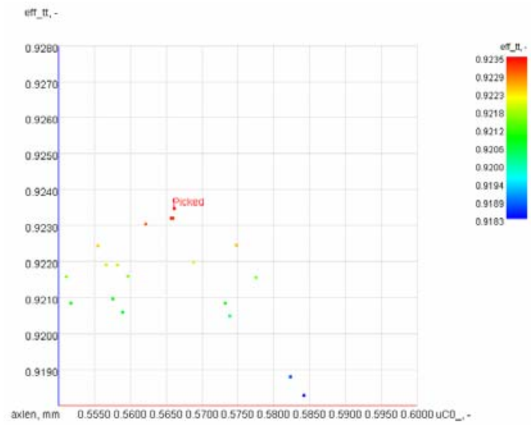

Fig.4. Final designs selection

Evaluation of Created Design in Direct Task

Inverse task accomplished on initial phase of design study having used some simplified approach for losses and efficiency estimation, that can lead to differences between preliminary and final design results. When design geometry (diameters, angles) is defined and known, direct task calculation can be performed to confirm resulting conditions. Direct task uses the same equations (1-5) with angles applied as closing conditions. In direct task unknown variables are: c_1, w_2 and G.

To enhance results quality, empiric losses models can be applied to determine real cascade velocity coefficients (i.e. losses) instead of fixed coefficients or efficiency charts, used in inverse task. This makes possible to assign appropriate losses models for machine elements and bring additional option to add various elements on phase of direct task analysis. Capability to add flow path elements (ducts of different configurations between stages, inlet and outlet channels, volutes) for designed machines is desired for precise simulations of complicated flow paths.

Summary: Design Procedure Organization

Summarizing all the details mentioned above, the statement about multilayer system structure can be made. Main three layers are:

1. Equation layer that contains basic equations (1-5), similar for all type of machines.
2. Specific machine thermodynamic solvers layer, that uses equations with design parameters combination, applied to specific machine type.
3. Loss models layer that contains set of loss (profile, secondary losses) and other empirical models (deviation angle models, blockage models) for each machine type.

OFF-DESIGN PERFORMANCES STUDY FOR SYNTHESIZED MACHINE

Off-design Study Theoretical Background

Off-design conditions study and comparison of generated designs is additional point of interest. Off-design calculation requires only variation of boundary conditions: pressure, rotation speed and others for the fixed geometry in direct task. This makes no principal difference between direct task calculation on design and off-design modes in presented approach.

As it was discussed above, specific empirical losses models can be applied in direct task for each machine. After applying proper loss models it's possible to take into account variation of number of important effects, such as profile and secondary losses change depending on off-design conditions, deviation angle variation and calculate critical off-design incidence angles for compressor stall prediction for selected profile geometry.

Maps are especially critical in case of compressor stages designs comparison, where they can have significant influence on design application. Other important question is correct operation ranges prediction. This problem also can be solved by application of real losses models and loss limits to calculation in direct task. Equation set solving results in some discrepancy accuracy on each step, and depending on selected accuracy limits and number of iteration steps performed, different accuracy could be obtained, that indicates stability of current calculated mode. In case if no steady solution exist for current operational conditions, this point can be identified as non-existing or non-stable (stalled) operation condition for real machine too. Of course, question of proper loss and deviation models selection, as well as applying correct limits and scale coefficient, is crucial for correct operating range determination for each machine type, but it can be resolved to determine right models through model evaluation and comparison with experiment.

Study Example

Study example presents importance of off-design conditions understanding on preliminary design phase. Three points represents different designs performances characteristics for range of flow rates applicable for current design.

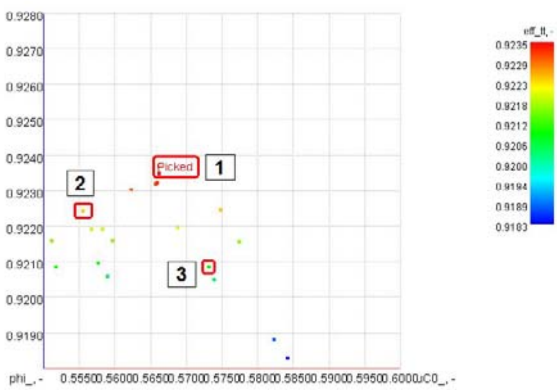

Fig.5. Off-design performances comparison for gas turbine designs (efficiency vs velocity ratio)

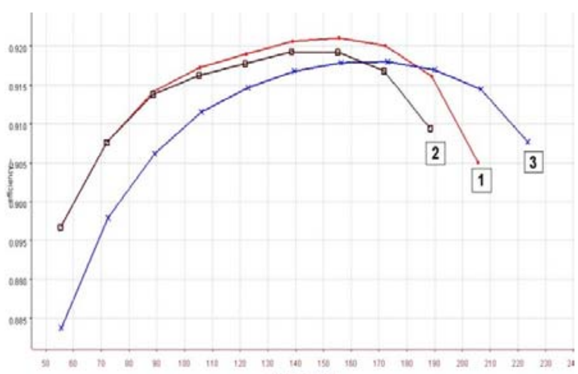

Fig.6. Off-design performances comparison for gas turbine designs (efficiency vs mass flow for selected designs)

AXIAL-RADIAL COMPRESSOR DESIGN IN INTEGRATED ENVINRONMENT

Integrated environment for gas turbine design was used for “X-Engine” (Kutrieb Research) aerodynamic concept development and optimization. Current article presents mixed (axial-radial) compressor development to illustrate practical application of created system.

Design Point Technical Requirements

Temperature at inlet = 15 C
Pressure at inlet = 98700 Pa
Mass flow rate = 1.827 kg/s
Total pressure at outlet = 592000 Pa
Rotation speed = 40000 rpm

Empirical Models Applied for Design

The next empirical losses and deviation models were used for axial-radial compressor design and calculation procedure:

- Axial compressor profile losses – by Lieblein [10]
- Axial compressor deviation – by Howell [11], [12]
- Radial compressor profile losses – by Aungier [13]
- Radial compressor deviation - by Wiesner (for impeller) [14], by Aungier (for vaned diffuser) [13]

These models initially been evaluated on axial single-stage (Rotor 37 [15]) and multistage (General Electric E3 engine [16], [17]) compressors, “Radiver” radial compressor [18] and shown a good correlation for experimental data.

Preliminary Sizing

To achieve required pressure ratio within minimal possible sizing and engine weight, mixed compressor concept was selected. The aim of preliminary design phase is to select optimal number of stages and pressure distribution between them. Compressor was divided on 2 modules: axial and radial, where geometry parameters selection was made for each of them to obtain optimal design. Selection of optimal pressure ratio between modules and number of stages within existing limits is task of preliminary design procedure. On initial design concept phase it was necessary to find the difference between usage of 3 or 4-stage axial compressor. The range of pressure ratios for axial compressor was selected between 220000 and 250000 Pa, to divide it approximately equally between axial and radial groups. For centrifugal stage configuration with impeller and vaned diffuser was selected. In case if preliminary design for both modules performs in one procedure, it satisfies matching between axial and radial modules and selects optimal pressure ratio for each one automatically.

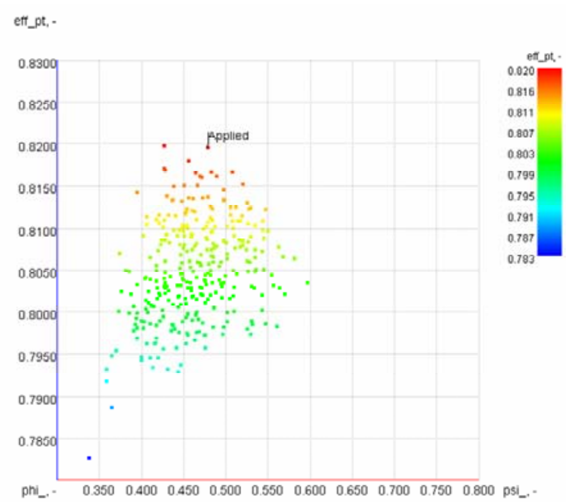

Fig.7. Polytropic efficiency vs work coefficient (4 axial + 1 radial compressor stages)

Maximal polytropic efficiency obtained for designs with 4 axial stages is 0.8196. Maximal efficiency of 0.8089 is obtained for design with 3 axial stages as it shown in figure below.

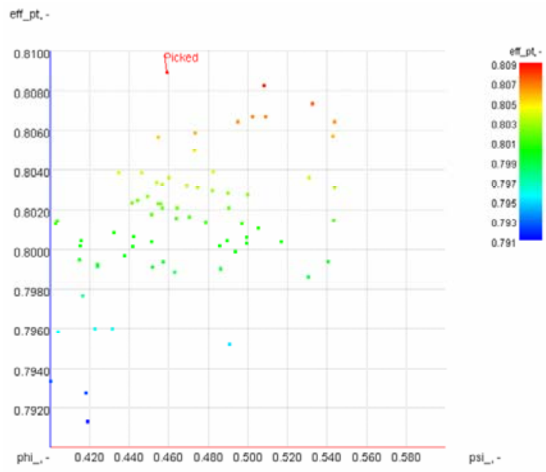

Fig.8. Polytropic efficiency vs work coefficient (3 axial + 1 radial compressor stages)

Comparison of these designs with 4 or 3 axial stages and 1 radial was performed to determine operation at 40,000 rpm. Consideration of efficiency difference on 1.07% comparing to weight and size increase caused by additional stage, decision to make 3 stages compressor was made.

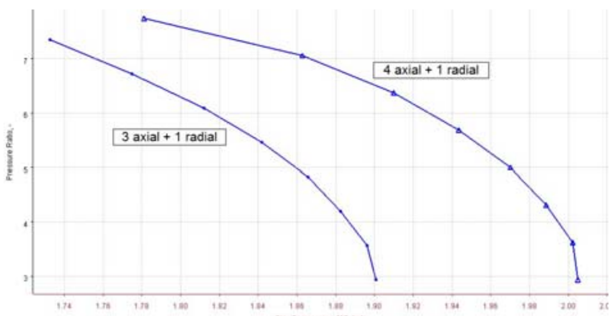

Fig.9. Performances maps with 3 and 4 stages designs comparison

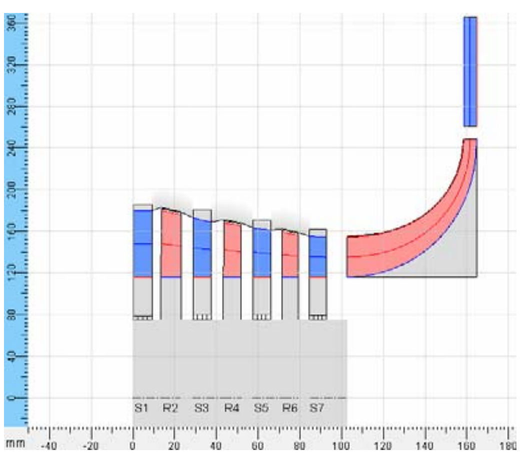

Fig.10. Axial-radial compressor finished design

Velocity triangles for designed compressor stages is in figure below. As it clear from this picture, axial compressor stages are designed to be identical (congruent).

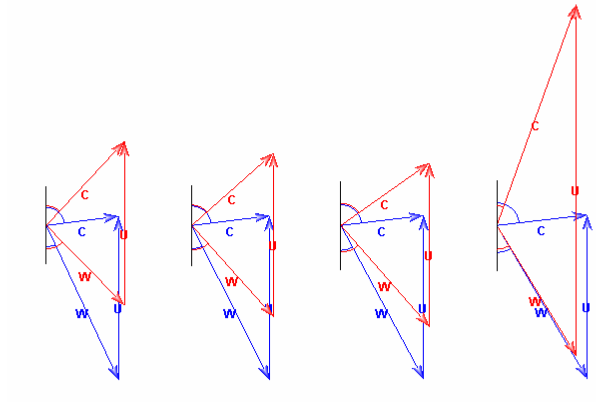

Fig.11. Compressor velocity triangles

For created machine performances maps generation in range of expected machine operation was performed. Performances curves in fig. below represent rotation speeds from 24,000 to 40,000 rpm.

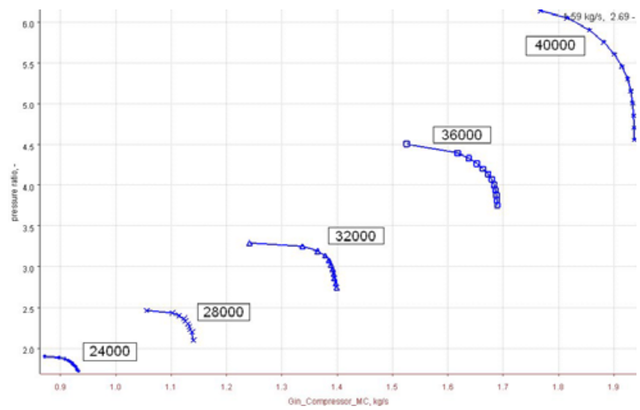

Fig.12. Performances curves for pressure ratio vs mass flow rate

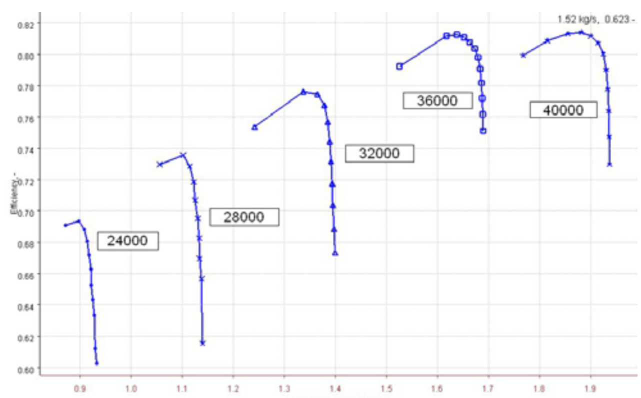

Fig.13. Performances curves for efficiency vs mass flow rate

Final Design

Basing on initially sized geometry, flow path dimensions and angles, final 3D geometry for compressor was created in the same integrated environment, exported and manufactured by Kutrieb Research (www.kutriebresearch.com)

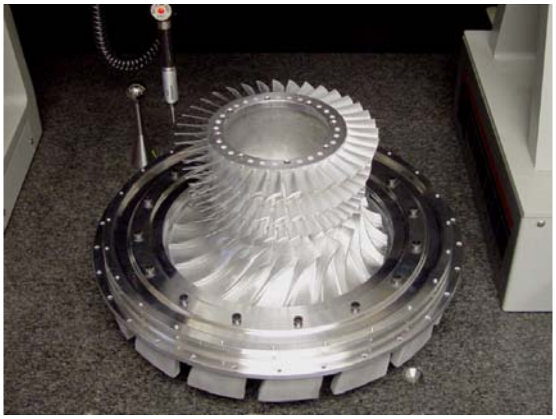

Fig.14. Compressor and diffuser

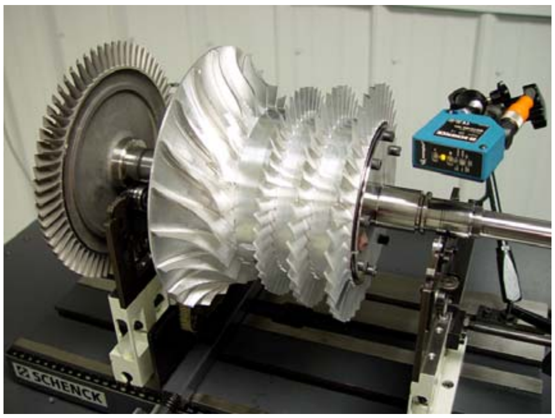

Fig.15. “X-Engine” rotating assembly

CONCLUSIONS

This article establishes main requirements for gas turbine design integrated design environment. The idea of design approach uniformity and selection of different design parameters for discussed types of machines. Basic set of equations used for calculation is similar, but depending on variables and boundary conditions applied, it can be presented in two basic forms: inverse and direct tasks that have advantages for preliminary design generation and existing machine performances evaluation respectively. Flexible design geometry generation approach is presented, that makes possible to form machines of different complexity from set of individual modules and add auxiliary elements. This ability of rapid flow paths synthesis is supplemented by off-design performances calculation and comparison for selection of final design candidates.

BIBLIOGRAPHY

[1] Boyko A. V., Govorushchenko Y.N., 1989, Theoretical Basis of Axial-Flow Turbines Optimal Design, Kharkov, Visha Shkola (in russian)

[2] Govorushchenko Y.N., Romanov G.L., Skibina E.E., 1991, Automated Preliminary Design of Multistage Steam Turbine Flow Paths (in russian), Thermal Energetics

[3] Aungier, R.H., 2003, Axial-Flow Compressors: A Strategy for Aerodynamic Design and Analysis. New York: ASME Press

[4] Baines N., 2005, Radial Turbines: An Integrated Design Approach. Concepts NREC

[5] Karl A., Hansen R., 2002, Computer Based Optimization And Automation Of Analysis And Design Processes In Aero Engine Development, GT-2002-30498, Proceedings of Turbo Expo 2002: Land, Sea and Air, 3 – 6 June 2002, Amsterdam

[6] Cunningham T., Medlock A., Sandefur M., Rowse J., 2005, High-Productivity, Low-Cost, Gas Turbine System Modeling Software, GT2005-68424, Proceedings of ASME Turbo Expo 2005: Power for Land, Sea and Air, June 6-9, 2005, Reno-Tahoe, Nevada, USA

[7] Prado P., Panchenko Y., Tr´epanier J-Y, Tribes C., 2005, Preliminary Multidisciplinary Design Optimization System: A Software Solution For Early Gas Turbine Conception, GT2005-69021, Proceedings of ASME Turbo Expo 2005: Power for Land, Sea and Air, June 6-9, 2005, Reno-Tahoe, Nevada, USA

[8] Moroz L., Govorushchenko Y., Pagur P., 2006, A Uniform Approach to Conceptual Design of Axial Turbine/Compressor Flow Path, Future of Gas Turbine Technology, 3rd International Conference, Brussels, Belgium

[9] Moroz L., Govorushchenko Y., Pagur P., Romamenko L., 2008, Integrated Conceptual Design Environment For Centrifugal Compressors Flow Path Design”, IMECE2008-69122, Proceedings of IMECE2008, ASME International Mechanical Engineering Congress and Exposition, October 31-November 6, 2008, Boston, MA, USA

[10] Lieblein S., 1959, “Loss and Stall Analysis of Compressor Cascades”, Journal of Basic Engineering, ASME, Vol. 81, Sept. pp 387-400

[11] Howell A.R., 1942, “The Present Basis of Axial Flow Compressor Design; Part 1 – Cascade Theory and Performance”, R&M 2095, British Aeronautical Research Council, London, United Kingdom

[12] Howell A.R., 1947, “Development of the British Gas Turbine Unit”, Lecture: Fluid Dynamics of Axial Compressors, ASME Reprint, New York

[13] Aungier R.H., 2000, “Centrifugal Compressors, A Strategy for Aerodynamic Design and Analysis”, ASME Press, New York

[14] Wiesner F.J., 1967, “A Review of Slip Factors for Centrifugal Impellers”, Transactions ASME, Journal of Engineering for Power

[15] Moore R.D., Reid L., 1980, “Performance of Single-Stage Axial Flow Transonic Compressor With Rotor and Stator Aspect Ratios of 1019 and 1.26, Respectively, And With Design Pressure Ratio of 2.05”, NASA Technical Paper 1659, Lewis Research Center

[16] Holloway, P. R.; Koch, C. C.; Knight, G. L.; Shaffer, S. L., 1982, “Energy Efficient Engine. High Pressure Compressor. Detail Design Report”, NASA Lewis Research Center, CR-165558

[17] Cline S.J., Fesler W., Liu H.S., Lovell R.C., Shaffer S.J., 1983, “Energy Efficient Engine. High Pressure Compressor. Component Performance Report”, NASA Lewis Research Center, CR-168245

[18] Ziegler K.U., Gallus H.E., Niehuis R., 2002, “A Study on Impeller-Diffuser Interaction” Part 1, 2, GT-2002-30381, Proceedings of ASME TURBO-EXPO 2002, Amsterdam, The Netherlands