Turbomachinery quasi-one-dimensional and quasi-dimensional mathematical models for design of turbocharged piston engines' air-gas channel: CAE model hierarchy and methodology of parameter identification

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Abstract. In the presented paper, requirements for mathematical models of turbomachinery as elements of turbocharged piston engines' air-gas channels are analyzed. A necessity for models' calibration (through an identification of their parameters) for an application in design calculations and a consequent demand for a parameterization of turbomachinery models at different levels are discussed. Modular and hierarchical model architecture, which is adopted with a consideration of software implementation of turbomachinery models, is described using an example of turbine's model. Accepted approach to an identification of model parameters with an implementation of test bench testing data of turbocharged piston engine is justified.

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Introduction

A numerical simulation of a process in *air-gas channel* (AGC) of turbocharged piston engine has an objective of proposing recommendations for a development and a refinement of AGC design. In analysis, *direct problem* of a process's characteristics prediction is solved. Its solution is necessary for *analysis* of AGC perfection and it serves as a basis for a solution of *inverse problem – synthesis* [1-3].

Nowadays, specialized *computer-aided engineering* (CAE) software packages are used as tools for a simulation of processes in engine's AGC. They implement standard mathematical models and computational procedures for CAD of objects in a specific engineering field. It is necessary, that CAE software package would allow to effectively solve routine problems of various stages of design and development (life-cycle) – problems of model's calibration, parametric (and structural) optimization of an object. CAE software package, which meets that requirement (a quite general one), can be an element of CAD/CAE systems for turbounits, gas-turbine engines, turbocharged piston engines and their turbocharge units.

It is substantial that a support of inverse problem solutions at a level mathematical models' libraries should be implemented (and in sufficient and efficient manner) in CAE software package. With the same purpose, in the first place, models libraries in specialized CAE software packages must be based on hierarchical software architecture, which must be developed as a result of analysis of specific requirements. In the following, using example of models, which describe flow through turbines' stages, adopted approach for a creation of turbomachinery models for application models library of modern CAE software package is demonstrated.

Main part

Nowadays, in computational analysis and synthesis of gas-turbine and combined engines the mathematical models of processes with reduced spatial dimension – quasi-one-dimensional [4-6] and even quasi-dimensional mathematical model are used. Their use in design is determined by (a) immediacy of calculations, and (b) simplicity of a parameterization of such models. The aforementioned parameters are critical for inverse problems' solution.

High reliability of AGC process description is, in principle, achievable in calculations using models of three-dimensional flow as the most detailed and versatile. Use of such models, however, deprives calculations of flexibility and immediacy. Therefore, even in a case of a development of air-gas channel, calculations are conducted with use of models, which allow fast conduction of calculations (quasi-one-dimensional and quasi-dimensional classes). Acceptable reliability of results is achieved by means of models calibration, for example, through *parametric identification* (PI).

Requirements for turbomachinery stages' models for CAE. Thus, a presence of models of processes, which are based on quasi-dimensional and quasi-one-dimensional description of working medium flow, in CAE software packages is determined by a demand for completeness of CAE applied model libraries and practical circumstances. Models of elements of AGC of types of compressors and turbines serve as *closure models*. Such models can contain only the dependencies which describe quasi-static flow conditions. From a variety of such models of turbomachinery, models can be singled out, in which for closure stages' *performance characteristics* of classic type are used – in the presented mode parameters; for compressor stage:

$$\pi^*_{c\,s} = \pi^*_{c\,s}(G_{corr}, n_{corr}),\; \eta^*_{c\,s} = \eta^*_{c\,s}(G_{corr}, n_{corr}),$$

and for turbine stage:

$$G_{corr} = G_{corr}(\pi^*_{t\,s}, n_{corr}),\; \eta^*_{t\,s} = \eta^*_{t\,s}(\pi^*_{t\,s}, n_{corr}); \quad (1)$$

there for brevity $G_{corr} = G\sqrt{T^*_1}/p^*_1$, $n_{corr} = n/\sqrt{T^*_1}$, where p^*_1 and T^*_1 – stagnation pressure and temperature at inlet of a stage. For the turbine in (1) $\pi^*_{t\,s} = p^*_{t1}/p^*_{t2}$ – operational mode parameter, $\eta^*_{t\,s} = l^*_t / l^*_{t\,s}$ – indicator of performance. With an assumption of adiabatic flow $l^*_t = c_p(T^*_{t1} - T^*_{t2})$ and $l^*_{t\,s} = c_p T^*_{t1}\left[1-(1/\pi^*_{t\,s})^{(\gamma-1)/\gamma}\right]$.

In turn, performance of turbomachinery stage by their performance characteristics are calculated using closure models. First, those are models, which approximate performance characteristics by points obtained through full-scale experiment (or calculated using 3D models) for a specified AGC design. Second, those are models, which calculate performance of a stage by means of flow calculation in AGC of a stage in an accepted scheme of a model. Thus, in modules of application software a variety of specific closure models of the discussed level is implemented. Each of those models must support a specific method of "local" calibration (with use of an experiment's data on performance of a turbomachinery stage itself in different modes).

It is substantial that flow model calibration in AGC of heat engine can also be carried out on using data on performance characteristic of engine. In that regard, it is important that the implemented models of turbomachinery support that type of calibration ("global" mathematical model) – also through PI parameters of a stage's model. Such PI must be based on a rational approach, which allows to introduce "free" parameters, which are applicable for PI, in a model.

Thus, in CAE software package the models of turbomachinery stages are necessary, which support a rational approach to PI model – for a model's calibration using experimental data on performance characteristics of a heat engine as a whole and its units of turbomachinery.

Aforementioned considerations formed a basis for hierarchical modular software implementation of a stage's model. For a case of a model of turbine stage, the scheme of the adopted architecture is presented in Fig.1.

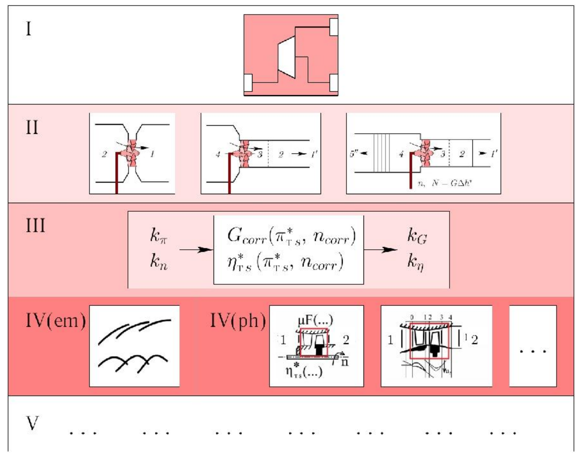

Fig.1. Architecture of TURBINE model; following levels are shown:
I – interfaces to TURBINE model; II – calculation procedures for quasi-dimensional and quasi-one-dimensional models of AGC; III – interfaces' performance characteristics ("calibration unit"); IV – models of characteristics of *empirical* (em) and *phenomenological* (ph) types; V – auxiliary procedures and data.

Hierarchical architecture of TURBINE model. On an upper level (I, in Fig.1) of hierarchy – software modules that implement in CAE software package all types of interfaces between a model of process in AGC and "lower" specific models. There a connection of a model to design diagram of (quasi-dimensional or quasi-one-dimensional) model for a process in AGC of a heat engine, editing of original data of a stage's model via graphic user interface, an invocation of calculation procedures of a model in a calculation, etc. are provided.

The next level (II, Fig.1) – procedures, which ensure correctness of calculations with quasi-static model, based on a characteristic of a stage (1) in numerical calculation of a process in AGC. Thus, in a calculation with quasi-one-dimensional model, which takes into account wave effects, a turbine's characteristic is included in a system of non-linear equations, which describe interactions of elementary waves with internal boundary cross-section of that kind in a computational domain [6, 7].

For example, for a turbine's stage located at a point where two sub-regions of *channel* type (Fig.2) in a model of an engine's AGC, a system of nonlinear equations is solved

$$\frac{p''_5}{p'_1} = \frac{\pi'(M_2)}{\pi''(M_4)} \cdot \frac{\pi(M_4)}{\pi(M_3)} \cdot \pi^*_{t\,s}, \qquad (2)$$

$$\frac{c''_5}{c'_1} = \frac{\alpha'(M_2)}{\alpha''(M_4)} \cdot \frac{M_2}{M_3} \cdot \frac{\alpha(M_4)}{\alpha(M_3)} \cdot \left\{1 - \eta^*_{t\,s}\left[1 - \left(1/\pi^*_{t\,s}\right)^{(\gamma-1)/\gamma}\right]\right\} \qquad (3)$$

$$\frac{F_5}{F_1} = \frac{q(M_3)}{q(M_4)} \cdot \frac{1}{\pi^*_{t\,s}} \cdot \left\{1 - \eta^*_{t\,s}\left[1 - \left(1/\pi^*_{t\,s}\right)^{(\gamma-1)/\gamma}\right]\right\}. \qquad (4)$$

There

$$\pi' = \frac{p}{p'} = (\alpha')^{2\gamma/(\gamma-1)} = \left(\frac{c}{c'}\right)^{2\gamma/(\gamma-1)} = \left(1 - \frac{\gamma-1}{2}M\right)^{2\gamma/(1-\gamma)},$$

$$\pi'' = \frac{p}{p''} = (\alpha'')^{2\gamma/(\gamma-1)} = \left(\frac{c}{c''}\right)^{2\gamma/(\gamma-1)} = \left(1 + \frac{\gamma-1}{2}M\right)^{2\gamma/(1-\gamma)},$$

$$\pi = \frac{p}{p^*} = (\alpha) = \left(\frac{c}{c^*}\right)^{2\gamma/(\gamma-1)} = \left(1 + \frac{\gamma-1}{2}M^2\right)^{\gamma/(1-\gamma)},$$

$$q = \frac{G\sqrt{T^*}}{mp^*F}, \quad M = \frac{u}{c},$$

where G – mass flow rate, F – cross-sectional area. An iterative procedure of a calculation with (2) – (4) is described in detail in [7] and for a similar model and a procedure for a stage of compressor – in [8].

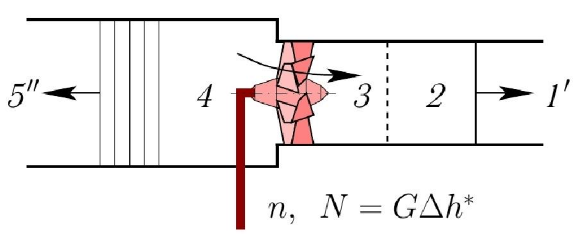

Fig.2. Design diagram of Riemann problem for a correct connection of quasi-static TURBINE model with a numerical calculation of wave motion in channels.

Hierarchy level III (Fig.1) – modules that implement an interface for a calculation of performance characteristic of a turbine stages by any of lower models and "calibration unit". The latter allows to implement basic support for PI model of a stage in such a way that, on the one hand, to ensure calibration of "global" mathematical model of an engine, and, on the other hand, not to interfere with an implementation of one of many (located lower in the hierarchy) models for a calculation of performance characteristics.

A rational approach to calibration of model there (at "global" level of a model's process, for an entire ACG of heat engine) – also PI relationships from the presented "mode" parameters for models of turbomachinery. Parametrized relationships should be created on a basis of parameters and factors of "reference" mode ('0'), the deviation from which is taken into account by normalized "mode" factors, for example, in a form of power polynomial (if there is no justification of a semiempirical form). Results of calculations and measurements (performance of turbomachinery and of engine as a whole and also their "mode" parameters) should be expressed in the corrected values.

One of possible ways to calibrate such stage models:

$$\pi^*_{t\,s} = (\pi^*_{t\,s})'/k_\pi, \quad n_{corr} = (n_{corr})'/k_n, \qquad (5)$$

$$(G_{corr})' = k_G G_{corr}, \quad (\eta^*_{t\,s})' = k_\eta \eta. \qquad (6)$$

The specified calibration method is implemented in modules of the developed library as a base one (which meets needs of the major part of most design work).

In (5) values of mode parameters of stage are calibrated; in (6) – value of factors of stage; (1) specifies overall view of universal performance characteristic in a representation by any model of a stage of an accepted class. Values, that are conventionally considered as calibrated ones, are $(\pi^*_{t\,s})'$, $(n_{corr})'$, $(G_{corr})'$ and $(\eta^*_{t\,s})'$, which are transmitted from/to the outside of a module, which implements the "calibration unit" (5), (6) for (1). Values k_π, k_n, k_G и k_η in (5) and (6) can be adjusted by PI directly, or related to the "mode" parameters of a unit, using linear and other relationships with parameters for determination by PI. A rational approach implies a normalization of variables relatively to values of parameters and factors of reference mode AGC element (there – turbomachinery stage). Then, for example, a linear relationship of each k_i, $i = 1, \ldots, 4$ in (5) and (6) with parameters of flow mode through a stage can have following form:

$$\overline{k}_i = k_{\overline{\pi}} \cdot \overline{\pi}^*_{t\,s\,i} + k_{\overline{n}} \cdot \overline{n}_{corr\ i}, \qquad (7)$$

where

$$\overline{k}_i = (k_i - k_{i\,0}) / k_{i\,0},$$

$$\overline{\pi}^*_{t\,s\,i} = (\pi^*_{t\,s\,i} - \pi^*_{t\,s\,i\,0}) / \pi^*_{t\,s\,i\,0},$$

$$\overline{n}_{corr\ i} = (n_{corr\ i} - \overline{n}_{corr\ i\,0}) / \overline{n}_{corr\ i\,0}.$$

Relationships of type (7) contain 5 parameters each ($k_{\overline{\pi}\,i}$, $k_{\overline{n}\,i}$, $k_{i\,0}$, $\pi^*_{t\,s\,i\,0}$, $\overline{n}_{corr\ i\,0}$), which are used for a stage's model identification in a field of its modes, first three of them set a point of "reference" mode in (7) for $\overline{k}_i$. Noticing, that for an entire model of a turbocharged engine (not only stage boost unit), calibrations, such as (5) – (7), are explicitly or implicitly made during design work; in this regard it's reasonable to implement in CAE software package a support of such method of PI for a model of type (5) – (7) not only in a stage's model, but also at "global" level of mathematical model for a model of a process in ACG of an engine.

A calibration of (5) – (7) for any model for (1) is simple to use and does not require refactoring of all modules of a level lower III in Fig.1, which implements (1). But an absence in (5) and (6) of physical meaning is also obvious; more "deep", in that regard, model's calibration should be allowed by calculation models for (1), which implement fluid dynamics calculation of performance characteristic of a stage using a certain model schemes of flow in AGC. On a scheme's elements of a stage, such a model is closed by (semi-empirical in meaning) relationships on a selected elements of its ACG. For discussed purposes, it is closure relationships (in dimensionless parameters) that should be parameterized and made their "free" parameters available for procedures of PI for a calibration of models – both at "local" (by a stage characteristic) and at "global" (by an engine's characteristic) levels.

Level IV (Fig.1) – an implementation of specific models, which allow to calculate a stage's performance parameters by a current values of its "mode" parameters. Over the past decades models of that class were created, fine-tuned and used in calculations [1, 3]. At that level of the hierarchy of turbomachinery models (models for a represent1ation of their characteristics), a number of models must be included into a standard library; also, a possibility of a connection of external ("user defined") models of that class must be provided.

It is at that level (or at a lower level), where a support should be implemented for PI models of "local" calibration of model characteristics of stages according to experimental data on performance parameters of a stage in a function of its mode parameters. That calibration is implemented by means of models of characteristics themselves, at that, both purely "empirical" (approximating) models of characteristics and "phenomenological" models (considering structural dimensions in a calculation).

It is necessary, that PI in models, which are included in a standard library, was implemented on a basis of a standard rational approach. The adopted approach comprises the fact, that at each level (hierarchy of a process's model), parameterized for PI of models their closure sub-models are taken in a form of expressions in generalized variables (according to the theory of dimensions and similarity). Thus, performance characteristics of models stages, in fact, represent a ratio of that type, which are parameterized for PI. Then, phenomenological models of stages' performance characteristic, which are based on model schemes of flow in ACG of a stage, contain such closure relationships for a certain models of flow on an independent elements of ACG of a stage. In those relationships key parameters – local "mode" a parameters of hydrodynamic similarity; for a parameterization of such relationships in order to conduct PI in them corresponding "free" parameters are introduced. The accepted approach contributes to a preservation of universal nature of a model of a stage, which was calibrated, i.e. with acceptably small deviations during an analysis of a process in ACG of turbocharged piston engine, even with significant deviations of parameters of problems from "reference" values (conforming to calibration conditions).

Requirements for CAE software package on a support of solution of inverse problems. In mature CAE software package for analysis and synthesis of processes in systems, effective and universal tools for a parameterization of models and a solution multiparameter problems (including inverse problems) must be included. That is a quite general requirement for a modern CAE software package, which is intended for use as a design tool for engineering systems. In such CAE software package applied models libraries that support a parameterization of a model by "free" parameters for its calibration, on a basis of (described above) rational approach. And this is a necessary, but not sufficient condition for a provision of effective design calculations of systems.

Rather simple simulation software can be easily adapted for multiparameter problems of analysis, identification and synthesis (with an implementation of external software tools) with a use of applied models of that type. For a simulation software to be applicable to solving engineering inverse problems, it is absolutely necessary to create internal tools of models parameterization, at all levels – from "core" of CAE software package to graphic (and other) interfaces for models data – relatively to discussed problems. For that, it is necessary to provide for a solution of such tasks a separate level of software, design and implement to a special subject-invariant library of software components.

Thus, design and implementation of interacting at different levels components of software is necessary. In a case of the implementation, parallel or serial approaches can be used. However, in a case of any approach, good software architecture contributes to success, taking into account requirements, which are defined by problems of design calculations of engineering systems.

Practial development of software with a consideration of the requirements. Models of flow through stages of turbomachinery are perfected for an application in ALLBEA software package [9]. The package is designed for computational analysis of the processes in complex engineering systems. Modules of application software for ALLBEA, which implement the discussed models, are developed as a part of models library ***gasdyn*** [10]. It should be noted that models and procedures implemented can be correctly applied to a calculation of quasi-dimensional or quasi-one-dimensional class models of a process in ACG (as a part of a certain computational software).

Capabilities of the models, the described approach to an identification of their parameters and methods of its implementation, in relation to the discussed engineering field, must be confirmed with practical calculations. In order to do that, models and procedures, which are intended for an inclusion into ALLBEA as a part of gasdyn model library, their PI is perfected as a part of a specially created ALLBEA TURBO software. In the program a calculation of steady-state engine mode enlarged model of quasi-dimensional class is impended (Fig.3).

ALLBEA TURBO software allows to perfect not only quasi-dimensional class models of elements of turbocharged piston engine' AGC. In ALLBEA TURBO a software implementation of a methodology for a solution of inverse problems in design calculations is also perfected. The software components created as a result of this research (models and components of software support of standard design methodologies) are planned to be integrated in application software [10] and the service software of ALLBEA software package [9, 11].

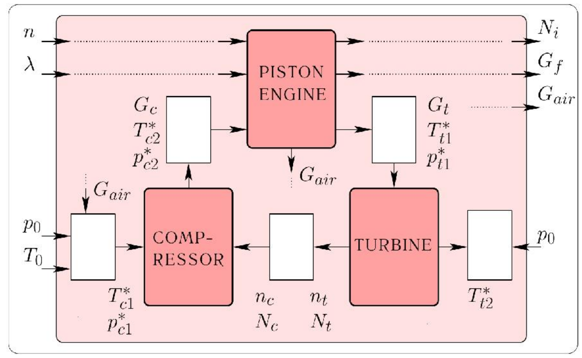

Fig.3. Composition of a model of a turbocharged engine in ALLBEA TURBO software

Currently, with use of ALLBEA TURBO, a technology of model calibration of quasi-dimensional class process in ACG of a turbocharged engine in a broad range of engine operation parameters is perfected – (n, λ), see Fig.3. For more information about the example of an implementation of the developed technology and obtained results please refer to the paper [11].

Conclusions

The results of the presented study allow to draw following conclusions:

1. Problems of design calculations of engineering systems have heterogeneous requirements for computational analysis and synthesis tools; two groups of requirements that are critical for a creation of effective tools are marked out:

(a) An implementation of a rational approach to a calibration, which is based on an identification of a model's parameters (at different levels of model hierarchy);

(b) An implementation of that approach, as well as universal tools of routine multiparameter problems' solution (including inverse problems) in main components of the developed application package – at all levels of its software architecture.

2. With a respect to models of processes in turbocharged piston engines, a specific architecture of turbomachinery models is proposed, which implements a rational approach and the identification of model parameters (on two levels).

3. The proposed approach to an identification of model parameters and the architecture are used in a development of ALLBEA software application package.

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