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The Method of Selecting Aircraft Conceptual Design Parameters at the Stage of Feasibility Study

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Abstract: *The article, proposed by the authors describes the method of multidimensional ordered parametrization in the aircraft design. An important part of the methodology is the ability to consider design features at the early stages of design, in particular, comparing and analyzing a large number of design alternatives, as well as searching for the optimal solution according to the selected performance criteria.*

Keywords: *aircraft, parameter selection, aircraft conceptual design, parametric synthesis, vector of parameters, multiparametric approach, conceptual model.*

I. INTRODUCTION

The preliminary design stage, called the development of a technical proposal (preliminary design, advance project), involves selecting a scheme and determining the most advantageous combination of the main parameters of the aircraft based on the analysis of existing samples, designer ideas, experience, and recommendations of previously designed aircraft, formulated as a conceptual model and implemented in the form of an advance project [1]. The modern civil aircraft industry is based on several characteristic conceptual components that form the basis for the aircraft design, assuming a sketch drawing of the future object. For this purpose, a special mathematical apparatus and software are used which allow analyzing and systematizing the results of special flight tests, as well as conceptual design technologies based on a consistently increasing scientific and technical background, and methods of statistical analysis. However, so far, the problem of finding a rational design solution for forming the aircraft conceptual design (aircraft general shape), different from the traditional aerodynamic layout, has not been implemented holistically in the form of applications software [2]. Using the method of scientific cognition to study the existing views on the creation of aerial vehicles (AV) with an increased flying range, and their elements, it is revealed that the essence of the term "concept" is interpreted by the authors as the structure of an object with indicators of purposeful action targeted to various hierarchical levels and elements, which can be presented in the list of performance criteria (thesaurus) with an importance factor, characteristic at given level [3].

$$\{(X_i, y_j)\} \tag{1}$$

where X_i is the i-th efficiency criterion; y_j is the i-th importance factor (contribution of the parameter).

Working with the structure of AV in the form of a thesaurus leads to the fact that the block-hierarchical approach inherent in such a concept does not allow evaluating the effectiveness by the selected criteria indicators at the *K*-th level of the hierarchy, since the work is carried out with an insufficiently defined object. It is impossible to achieve a certain indicator of "optimality" without coordination between the levels of the hierarchy. Because at the early phases and design stages, the basic scheme of the AV is used, which shows the projections in the first approximation, obtaining a "schematic dimensionless drawing of the AV" begins with the processing of statistical data of analogs. This approach does not allow determining the advantage of using partial solutions in the sketch, [4], i.e. only global aspects are taken into account, which often does not allow achieving the required performance indicators.

II. THE PROBLEM STATEMENT AND THE MAIN POINTS

At the moment, the design of the AV is carried out according to empirical dependencies using a large number of statistical data. It is rational to design the "element" in the same context but not to consider it separately from the AV on which it is installed but describe all the AV using some individual model. Information about the design solution of the AV and its elements appears as the project is detailed by clarifying the formal information models of the AV both at the design stages and within each stage. An important factor is registering the experimental results obtained during the transition from one model to another [5]. Thus, the experimental results are in good agreement at the simulation stage. The results of flow around process visualization presented in the form of surface, band, and vector charts, as well as streamlines, particle trajectories linked to the original geometry, including animation, data on parameters and variables of model equations, graphical dependencies, derived quantities (drag and lift coefficients, etc.), give the designer an idea of the characteristics and processes of flow around the designed aircraft. The software used in such analysis is just a tool. This software is not able to form a design solution. Based on the received cumulative modeling information, the designer must decide on the correction of the AV geometry.

The method proposed in the present article includes the traditional principles of design, software-implemented in a single information environment and combined with methods of statistical information processing, namely, correlation and factor analysis, and subsequent construction of polynomial models, as well as forecasting using the Brandon method, which allows finding a vector of parameters that would meet the requirements and restrictions imposed on the AV at the selected performance criterion at the preliminary design stage.

Forming the aircraft conceptual design of the mainline aircraft at the stage of development of the feasibility assessment can be formulated as follows: to find a vector of parameters that characterizes the shape, structure, and size of the AV, which would ensure the satisfaction of the requirements and restrictions imposed on the AV and achievement of the minimum (maximum) of the target function (Fig. 1). The take-off mass of the AV, m_0 is chosen as a global efficiency criterion since the flight range, cruising speed, payload, cost, and resource of parts, as well as the intended runway length, are commensurate.

Particular criteria for technical efficiency are the aerodynamic quality at the cruising flight mode K_{cruis} and the fuel efficiency G_{fuel}. The set of parameters to be calculated and optimized forms a vector of parameters that characterizes the aircraft conceptual design

$$\vec{\mathbf{X}} = (x_1, x_2, x_3, \dots x_m) \quad (2)$$

The characteristics of the AV, dependent on the parameters $x_1, x_2, x_3, \dots x_m$ form a vector of the characteristics of the AV

$$\vec{\mathbf{Y}} = (y_1, y_2, y_3, \dots y_n) \quad (3)$$

The aircraft conceptual design parameters and characteristics are related through certain dependencies. The mathematical formulation is represented by a system of constraints consisting of a vector of parameters $\vec{\mathbf{X}}$ and a vector $\vec{\mathbf{Y}}$, written as a system of inequalities

$$\begin{cases} x_i^L \le x_i \le x_i^U, i = 1, 2, 3, \dots m \\ y_j^L \le y_j(\vec{X}) \le y_i^U, j = 1, 2, 3, \dots n \end{cases} \quad (4)$$

where x_i^L is the lower permissible limit of the shape parameter; x_i^U is the upper permissible limit of the shape parameter; y_j^L is the lower permissible limit of the characteristic; y_i^U is the upper permissible limit of the characteristic.

Any vector $\vec{\mathbf{X}}$ belonging to the domain of acceptable solutions ($\vec{\mathbf{X}} \in \vec{\mathbf{X}}_{add}$), defines a valid design alternative of the AV. Then, with the selected efficiency criterion m_0, among the acceptable options for the design alternatives of the AV, there may be a vector of parameters $\vec{\mathbf{X}}$ that provides the extremum of the optimality criterion, at which $m_0 \to min$, while preserving the vector of characteristics $\vec{\mathbf{Y}}$ that meets the requirements within the selected constraints. This vector takes the form

$$\vec{\mathbf{X}}_{add} = min_{\vec{X} \in \vec{X}_{add}} F(\vec{\mathbf{X}}, \vec{\mathbf{Y}}) \quad (5)$$

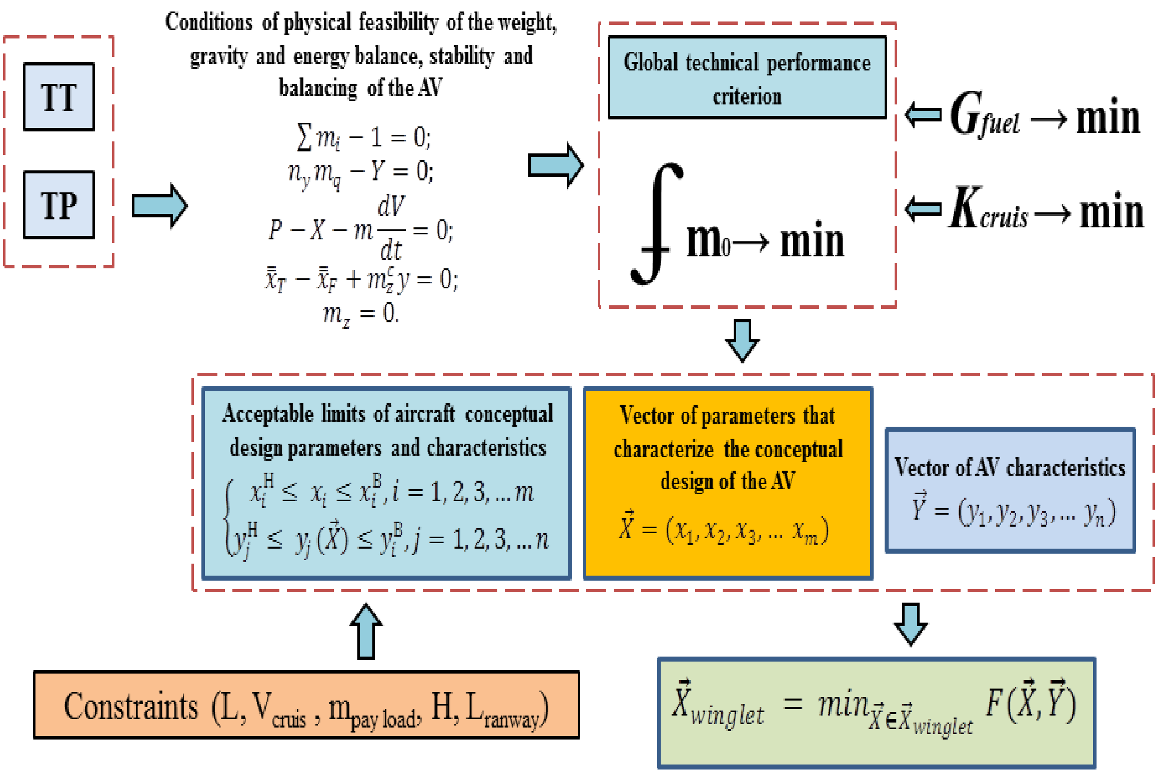

Fig. 1 The traditional approach to the problem of forming the mainline aircraft conceptual design at the stage of development of the feasibility assessment

In the current context, there is a need to develop a new approach, as well as a methodology whose construction principles would not be rigidly tied to empirical dependencies and existing calculation formulas (Fig. 2). At that, it is necessary to ensure the relationship with the validation basis to assess the compliance of the characteristics of the design alternative within the embedded physical meaning and boundary conditions.

To establish new relationships between design variables and design techniques, it is necessary to apply synergistic methods that allow conducting analysis and synthesis of data using a certain model based on statistical information and results of R&D.

In the classical approach, a sketch (drawing, picture) is used to assess the suitability of fulfilling the design goal, which shows the projections of the AV and its elements. Obtaining such a sketch begins with the processing of statistical data (analogs of the designed AV). At this stage, it is impossible to determine the advantage of using particular solutions in the sketch, such as, for example, the shape of the wing-to-body fairing, the type of additional aerodynamic surface (AAS) (winglets), stagger and shape of the engine pod, etc. Considering the presence of a winglet in the aircraft conceptual design begins when determining the weight of the AV in the first approximation. Optimization of the design parameters that affect the aerodynamic characteristics is carried out immediately after determining the take-off weight, while the evaluation of the aerodynamic characteristics is carried out after preparing layout drawings and weight reports.

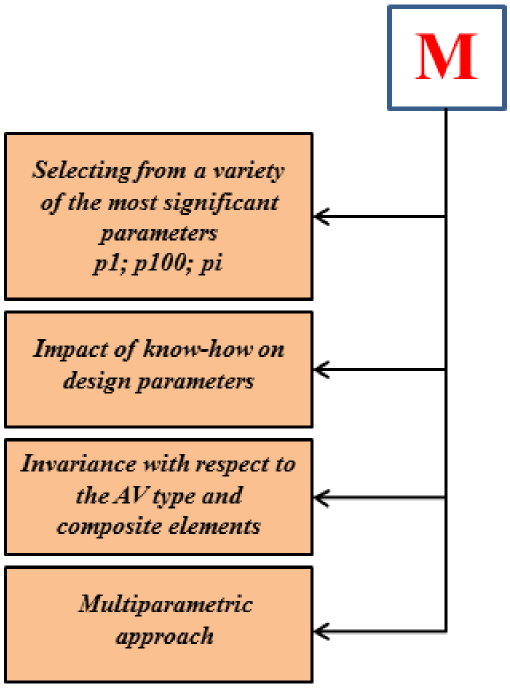

Fig. 2 Factors affecting the performance indicators of the project alternative in the course of developing a feasibility assessment and necessary for simultaneous consideration, combined into the model

That is, the influence of know-how on the aerodynamic characteristics of the AV is taken into account at too late design stages when several important decisions have already been made. The proposed approach to the joint design process makes it possible to analyze and select the composition of design parameters at the stages preceding the calculation of the take-off weight. This approach allows considering a significant amount of source data while highlighting the basic parameters, which makes it possible to reduce the dimension of the problem to be solved (Fig. 3).

The projections of individual units, obtained at the design stage of the elements of the mainline AV are combined into a single electronic geometric 3D model, forming a detailed design of the AV. The detailed design allows evaluating the aerodynamic and energy characteristics of the designed AV. In case if the selected performance criteria are met, the transition to the next design stage is carried out, otherwise, the process is repeated considering the shortcomings identified based on the results of simulation modeling.

The stages of preliminary design, detailed design, and design of elements are in organic interaction, and in the aggregate represent iterative processes on the synthesis of the design solution within the given constraints.

Considering the nature of the effect of AAS on the wing characteristics is a complicated scientific problem, whose solution at this stage of design is either difficult or impossible due to the lack of a mathematical apparatus that would allow accurate calculations of aerodynamics using computer technology. Therefore, here it is advisable to use the results of R&D, as well as design and development work. In other cases, designers resort to using know-how.

In the course of synthesis and formalization of the design process of the AV and its elements, it is necessary to consider as many parameters that define its conceptual design as possible. However, considering a large number of geometric parameters is not always justified, since the computational process is significantly complicated as well as the amount of initial information that is not available at the stages of preliminary and detailed design, and therefore, it is impossible to use rationally some capacious, relative, dimensionless, and absolute parameters.

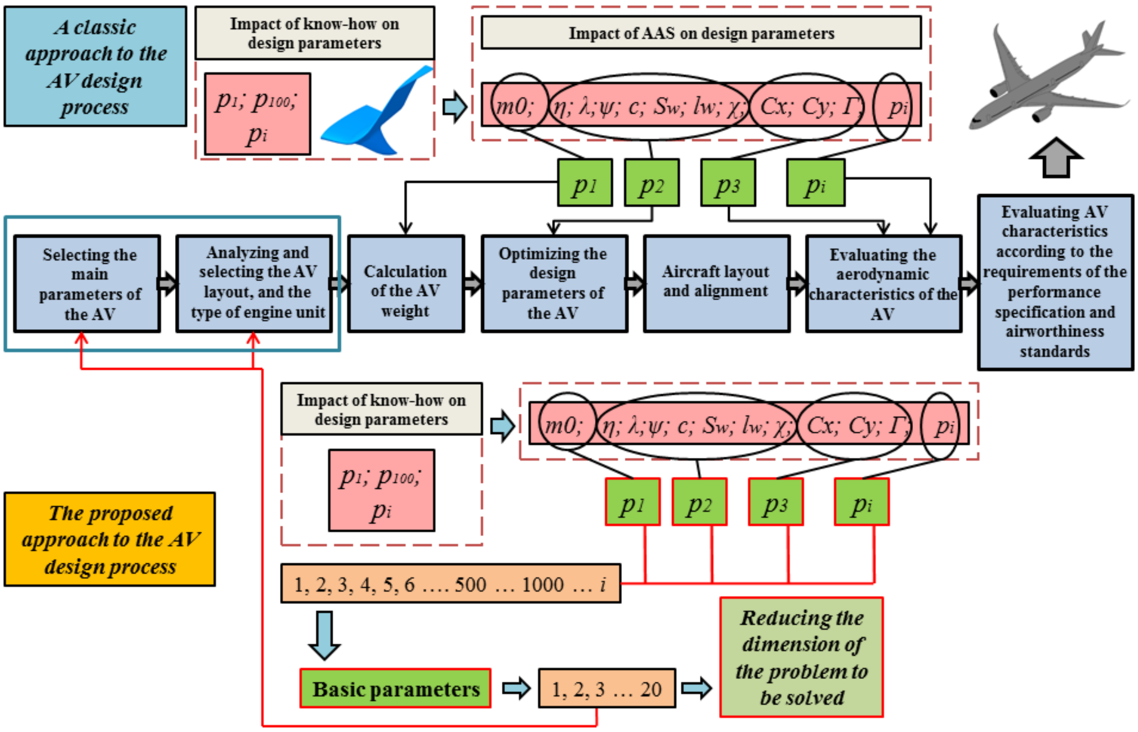

Fig. 3 The proposed approach to the process of forming the conceptual design of the mainline aircraft

III. RESULTS AND DISCUSSION

Based on the fact that the AV and its components are a complex multiparametric system, a certain designed AV and its elements can be represented as a functional dependency Z.

$$Z = F(X, Y) \qquad (6)$$

where F is the object function, being an unknown quantity which can be determined through numerical simulations (CFD) and physical experiments in wind tunnels;

X is the aircraft conceptual design (geometric, energy, and aerodynamic characteristics);

Y is the AV operation conditions (operating characteristics).

The object function *(F)* can be represented as a set of interrelated and interdependent parameters. Knowing a certain model *(M)*, it is possible to calculate the approximate value of an object that has comparable performance characteristics, but different conceptual design parameters, with a certain correlation value. Then the following relation is valid for the object function

$$F(X_i, Y_j) \approx F_M(X_i, Y_j) \qquad (7)$$

where *M* is the transition model; *i* is the variable (*1,2,3...p*); *j* is the observed quantity *(1,2,3...k).*

The function $F(X_i, Y_j)$ is an analog of the designed AV or its element consisting of a set of parameters, while $F_M(X_i, Y_j)$ is a newly designed element or AV considering a new technical solution, for example, AAS. Then, to compare or obtain a certain value that will allow finding certain aircraft conceptual design characteristics under the same operating conditions, it is necessary to have *M* (transition model, method, or function).

The physical meaning of applying AAS is to change the effective aspect ratio of the wing. The geometric interpretation of the change in the effective aspect ratio of the wing looks like an equivalent wing with a comparable area, but with a larger span, where *S1* = *S2*, a λef 2 > λef 1.

According to expression 7, two commensurate multitudes can be considered comparable if their functions are associated via the transition model *(M).*

Considering the fact that the AV and its elements are a statistical system, then in such a system, a change in one of the parameters should affect the other parameters of the system. Such a system should have a correlation relationship, where the relationship of two or more individual parameters correlates with each other with a certain degree of accuracy. In the case of a high degree of correlation for the multitude describing the projected AV or its component, it is possible to study the relationships between the variables through factor analysis. In factor analysis, the main assumption is equality for X_i, which is calculated by the formula

$$X_i = \sum_{r=1}^{k} a_{ir} \cdot F_{r+e_i} \qquad (8)$$

where *i* – (1,2,3...p); X_i is the variable; F_r is the *r*-th factor; a_{ir} is the factor load; *k* is the number of factors; e_i are the excesses that represent the sources of deviations acting only on X_i.

These p random variables e_i are assumed to be independent both with each other and with k variables F_r. Equation 8 cannot be checked directly, since the p variables X_i are expressed in them through *(p+k)* unobservable variables. But these equations contain a hypothesis about the covariances and variances X_i, which can be checked [6]-[9]. The classical model of factor analysis R is calculated by the formula

$$R = A \cdot C \cdot A' \tag{9}$$

where R is the correlation matrix; A is the matrix of factor loadings; C is the correlation matrix reflecting the relationships between factors; A' is the transposed matrix of factor loadings.

If imposing the condition of uncorrelated factors, i.e. $C = I$, where I is the unit matrix, maximize the function which is associated with a certain number of additional conditions using the Lagrange multiplier method, and apply the varimax method proposed by B. Kaiser to determine the position of the coordinate axes with normalized variables and equal weights, we obtain the calculated formula

$$M \sum_{s=1}^{r} \sum_{i=1}^{m} \left(\frac{b_{is}}{h_i}\right)^4 - \\ - \sum_{s=1}^{r} \left|\sum_{i=1}^{m} b_{is}^2 / h_i^2\right|^2 = max \tag{10}$$

To determine the coefficients of the regression equation of a linear normal equations system, the least-squares method is used, which consists in calculating the following expression

$$Y = a \cdot \prod f_s(X_s) \tag{11}$$

where $f_s(X_s)$ is any function of the X_s variable.

In the case of a nonlinear dependence, the form of the function $f_s(X_s)$ is determined using the correlation field, then the type of dependence is determined by the form and the coefficients are calculated using the least-squares method.

If the number of parameters is more than three and the order of the polynomials $f_s(X_s)$ is more than two, equation 11 becomes very cumbersome and inefficient for practical use. Therefore, a simplified method for describing multi-factor processes was developed, namely, sequential smoothing of the hypersurface response, which is calculated by the formula

$$Y = \sum_{j=1}^{M} \varphi_j(X_j) \tag{12}$$

where $\varphi_j(X_j)$ are polynomials of increasing powers of the variable X_j.

Before calculating the polynomials φ_j, it is necessary to perform a preliminary ranking of the variables according to the degree of their influence on the optimization parameter y, using the Chebyshev orthogonal polynomials. Then a set of polynomial models built on the basic parameters with a certain correlation value can be considered a transition model M. The software implementation of the automated selection methods of the composition of the design parameters of the AV is implemented in the package of scientific subroutines of the Fortran V and C++ algorithmic languages.

To consider the effect of the studied characteristics and their transfer to the calculations at the stage of the detailed design of the wing and AV elements, it is necessary to obtain a certain coefficient, a value that would allow changing the calculated parameters in one direction or another, considering the results of experimental studies. Because AV is a multiparametric system, it is impossible to consider the effects of all parameters in a single coefficient. Therefore, it is necessary to use a group (series) of interdependent parameters that have the greatest impact (the contribution of the quantitative conditionality of the dependent parameter).

Knowing the contributions of the basic parameters, we obtained a group of dimensionless quantities ranging from 0 to 1. The impact of the parameter on the dependent value k_{eq}, is calculated by the formula

$$k_{eq} = p_i - (p_i \cdot k_i) \tag{13}$$

where *keq* is the equivalent parameter, considering the contribution; p is the dependent parameter (wing aspect ratio, λ, sweep angle, χ ...); *ki* is the contribution value.

The proposed method for selecting the composition of rational design parameters allows providing the specified characteristics for its components at the early phases and stages of the mainline aircraft design. The results of the present work are accepted into the design and engineering activities of Military-Industrial Corporation Research and Industrial Association of Machine Building (MIC NPO Mashinostroyenia), a Branch of JSC Scientific and Production Association Orion, as well as in JSC State Corporation Rostec, and RT-Techpriemka.

IV. CONCLUSIONS

The presented research results formed the basis of a conceptual model, mathematical support, and applied software that implements the methodology for selecting the composition of rational design parameters, which allows giving a commonality from the standpoint of the complexity of the parameters taken into account in assessing the effectiveness of the AV under the same operating conditions, invariant to the type of AV and its components. Using the C++ programming language will allow integrating the developed software into the enterprises of the aviation and military-industrial cluster.

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