

Parametric Modelling of Aerodynamic Objects - The Key to Successful Design and Optimisation *

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Abstract

In the paper, the methodology of parametric modelling of complex objects has been presented. The methodology is especially directed towards aerospace engineering applications, including numerical optimisation of flying objects and their components. Based on the presented methodology the PARADES software has been developed. This software differs significantly from conventional CAD systems. Its main features are:

- high level of compliance with professional grid generators and CAD systems
- high quality of generated geometries
- implementation of both the classical parametric modelling based on the set of design parameters and alternative parametric modelling based on the morphing technique, allowing to considerably reduce the number of design parameters
- possibility of work both in interactive and in fully automatic mode
- easy adaptation to any numerical optimisation system, operating system and hardware

The PARADES software has been applied in many commercial and non-commercial projects and research. Examples of application of the software have been presented in the paper.

1. Introduction

Within the aerospace engineering domain many typical problems concern an optimal designing of aerodynamic objects or their components. Usually such problems are solved using the parametric optimisation approach. General scheme of such approach is shown in Figure 1. The optimisation process is managed by the designer who may be both a human and a computer code. In the former case the experienced engineer designs the product in Interactive Design mode. In the latter case the Numerical Optimisation process is conducted in fully automatic mode. The designer, the human or the software, uses parametric model of designed product to generate various variants of this product. To do this, the designer generates appropriate set of numbers - Design Parameters. Based on this set, the parametric-modelling software creates appropriate variant of the product. Next, physical properties of this variant are evaluated usually using specialised codes. Based on this evaluation, the designer decides which variant is the best from point of view of assumed objectives and constraints.

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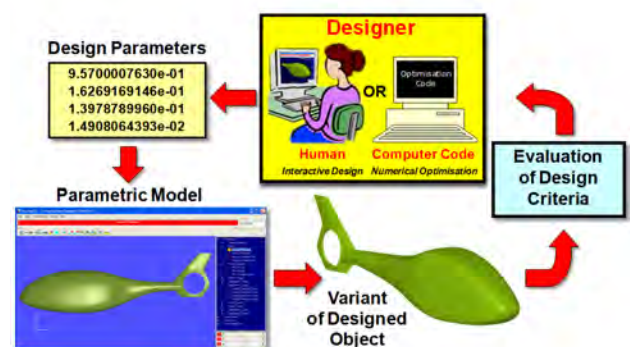


Figure 1. General scheme of process of parametric design and optimisation

In the optimisation system described above, a very important component is the parametric-modelling software, which is responsible for generation of sequen-

tial variants of designed product. In fully parametric approach, the complete geometry is unambiguously defined by certain set of Design Parameters. As a result, the optimisation problem comes down to search of the set of Design Parameters defining the optimal geometry. Application of parametric model enables to introduce orderliness and automation into optimisation process, which may be clearly formulated and solved using mathematical tools.

2. Methodology

For the parametric modelling of complex objects, the methodology worked out formerly in Institute of Aviation (Warsaw, Poland) was adapted, developed, and finally implemented as the PARADES software. Generally it was assumed, that the main area of applications of the methodology would be its usage as a parametric generator of geometry within the Numerical Optimization process. This assumption was the main factor determining the whole process of development of the presented below methodology and the software.

2.1. Fundamentals of methodology

The main idea of the methodology of parametric modelling of complex objects is shown in Figure 2. Usually the parametric model describes a geometry of

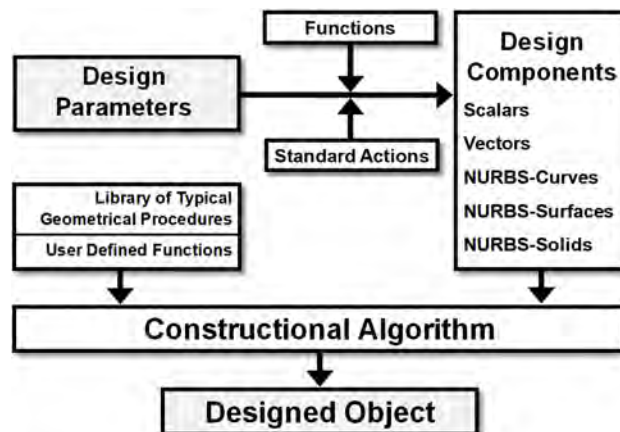


Figure 2. Functional diagram of the presented methodology of parametric modelling of complex objects

designed product. In mathematical terms a geometry may be treated as a system of functions describing curves, surfaces or solids. The presented methodology generally can be applied for parametric modelling of any functions, not necessarily describing the geometry. For example, it may be multi-dimensional func-

tion defining kinematics of given body or function describing distribution of certain physical quantities such as temperature, pressure, etc.

In the presented approach the parameterised object is modelled using a set of NURBS curves, surfaces or solids. The NURBS (Non Uniform Rational B-Splines) [2] are very flexible and powerful mathematical representation of three-dimensional geometry, that can accurately describe any shape. Such representation is commonly used in professional CAD systems. A general idea of the NURBS is shown in Figure 3. The NURBS object is defined by its order (or orders), a set of weighted control points, and knot vector (or vectors). The best way to change the shape of a NURBS object is to change positions or weights of its control points.

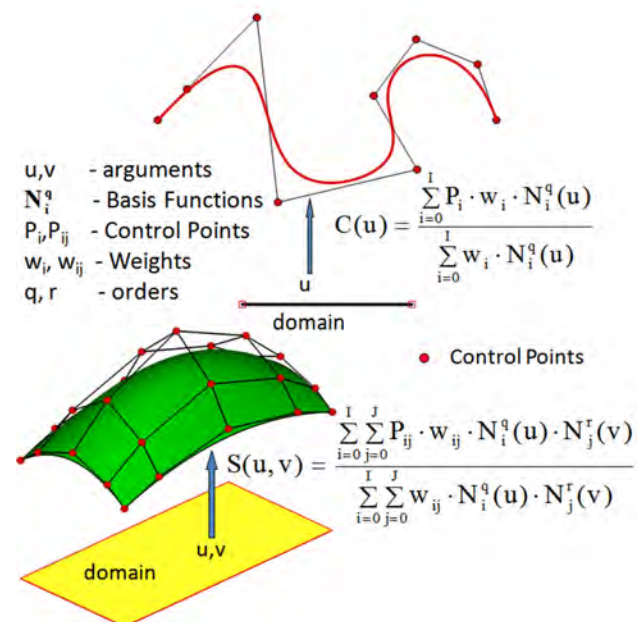


Figure 3. Modelling of curves and surfaces based on the NURBS representation

In the presented methodology, the NURBS representation of the parameterised object is created based on a set of Design Components: scalars, vectors and NURBS objects. These Design Components are the complete input data necessary to create parameterised object. In particular they may define dimensions, shape, topology, internal structure, kinematics, etc.

The Constructional Algorithm describes how to create the parameterised objects using the Design Components. The designer of given parametric model creates the Constructional Algorithm using three types of procedures:

- Standard Actions (procedures modifying the Design Components)
- Library of Typical Geometrical Procedures
- User Defined Procedures

The Design Parameters describe modifications of the Design Components. These modifications may be performed using Standard Actions and Functions defined by the designer. Generally, one Design Parameter can modify several Design Components, each according to another Function describing a speed and direction of the modification. The Standard Actions are elementary modifications of Design Components, like:

- change of value
- affine transformations
- modifications of NURBS Control Points
- global deformations of NURBS objects

In many cases the whole Constructional Algorithm may be written using only the Standard Actions. In more complex cases, part of Constructional Algorithm is attached as a set of User Defined Procedures. The designer writes them in C++ programming language having full access to the Design Components and data defining final geometry of parameterised object. Additionally, he may utilise Library of Typical Geometrical Procedures such as: interpolation, multi-section surface, generalised surface of revolution, trimming, etc.

In the presented methodology the Design Parameters do not directly influence the principal part of Constructional Algorithm. It means that the parameterised object may be built even without any defined Design Parameters. Such approach gives high level of freedom when given parametric model is finally defined. Depending on requirements, the number and the form of Design Parameters may be easily changed without significant changes in the Constructional Algorithm.

2.2. Reduction of number of Design Parameters

From the point of view of successful design and optimisation process, the number of Design Parameters should be strongly limited. This way, the dimension of search space could be limited, which would give higher probability of finding optimal solution in limited period of time.

Let us assume that the set of Design Components consists of N_s scalars, N_v vectors, N_n NURBS objects and that n -th NURBS object is modelled by C_n control points. Then, in presented methodology, the number of degrees of freedom (D_F) in modelling of given parameterised object equals:

$$D_F = N_S + 3N_V + 4 \sum_{n=1}^{N_n} C_n \quad (1)$$

In practice, in most design problems this is a huge number. Therefore the Design Parameters very rarely modify all Design Components separately. In properly defined parametric model either the Design Parameters modify only limited number of Design Components or the single Design Parameter modifies large subsets of Design Components. In practise, the number of Design Parameters should be well-balanced taking into account specific requirements of given optimisation problem. In Interactive Design mode it is allowed to define relatively large number of Design Parameters. In such a case, an experienced designer is able usually to create reasonable geometries (i.e. smooth and feasible) of high degree of freedom. However when Numerical Optimisation is performed it is strongly recommended to limit significantly the number of Design Parameters. It may be achieved by use of several different techniques like a global deformation or morphing.

2.2.1. Global deformation

In global-deformation approach, various shapes of NURBS objects are obtained by smooth movement of their control points. These deformations usually imitate behaviour of elastic materials. Each deformation is defined using usually only a few Design Parameters. In presented methodology the following global deformations are implemented:

- bending (see Figure 4)
- stretching
- skewing
- deformation of NURBS surface forced by deformation of its edge (see Figure 5)
- deformation of NURBS surface defined by a two-argument function (special-kind another NURBS surface)

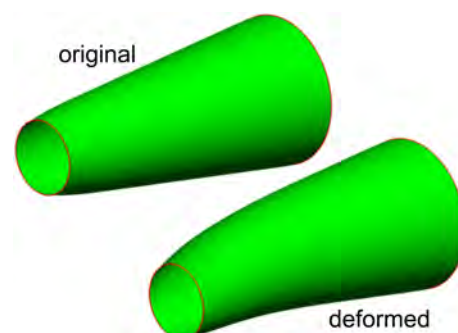


Figure 4. Bending of the NURBS surface

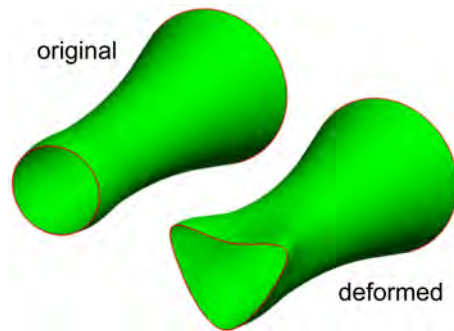


Figure 5. Deformation of the NURBS surface forced by deformation of its edge

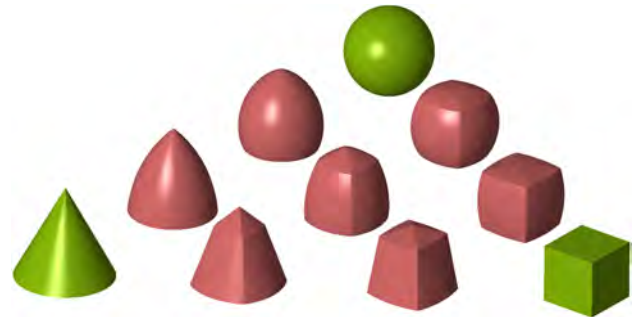


Figure 6. Application of the morphing technique for parametric modelling of a family of solids

2.2.2. Morphing

The parametric design based on the morphing technique consists in creating the new geometry as a convex combination of certain basic geometries. It is assumed that a set of basic geometries was prepared in earlier stage of the design process, usually using the Interactive Design approach. In this case the number of Design Parameters does not matter. In practice, the morphing is realised in the space of Design Parameters. The Design Parameters, that describe the morphed geometry, are obtained as convex combinations of Design Parameters defining basic geometries. In such a case, the weights defining the convex combination and corresponding to different basic geometries may be considered as alternative, higher-order Design Parameters.

The idea of parametric modelling based on the morphing technique is illustrated in Figure 6. In this case the basic geometries for morphing procedure were: the cube, the sphere and the cone. All these three different solids were modelled using the same parametric model and they have the same topology. By defining appropriate weights it was possible to generate a family of solids. Examples of these solids are shown in Figure 6.

The application of the morphing technique in parametric modelling has several advantages. The first one is a small number of Design Parameters, because usually the morphing is realised based on only a few basic geometries. The next advantage is that the geometries generated by the morphing technique usually inherit properties of their parents – the basic geometries. This helps to develop effective parametric models for optimisation problems with constraints. For example, if all basic geometries are smooth and feasible, it is likely (but not certain), that geometries obtained as results of morphing will have similar properties.

3. PARADES software

Based on the methodology described above, the software PARADES has been developed. The PARADES is the highly specialised tool supporting parametric modelling of complex objects, especially within the aerospace engineering domain. This software differs significantly from traditional CAD systems and the current version does not support the classical, not parametric design. By using the PARADES software, the experience is only required when creating a new parametric model, while the use of properly prepared parametric model is possible even in the case of the user inexperienced in the CAD domain.

The PARADES may be utilised in two modes: interactive and automatic. The Graphical User Interface (GUI) of the software, used in Interactive Design mode, is shown in Figure 7. The main elements of the GUI are:

- Main Window, where parameterised objects are visualised
- Tree of Design Parameters, where all the Design Parameters are displayed and may be selected
- Design Parameter Panel, where current value of selected Design Parameter is displayed and may be modified
- Tool Buttons collected in three groups: visualisation, parameters and properties
- Main Menu

In automatic mode the PARADES software is usually executed by the other software managing the process of the Numerical Optimisation. In such a case, the PARADES for given input – a set of values of Design Parameters, generates automatically the geometry. In case when the parametric model utilises the morphing technique, the input data are the morphing weights. Apart from generating the geometry of

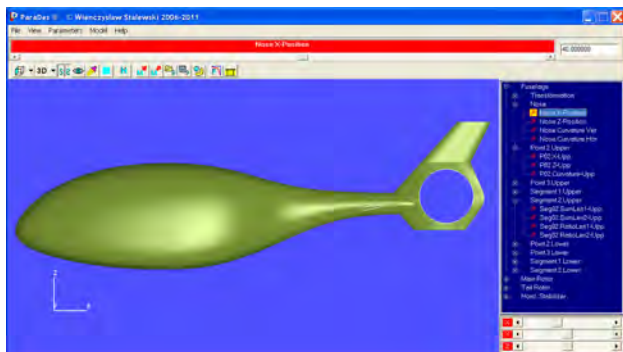


Figure 7. The GUI of the PARADES software used in Interactive Design mode

parameterised objects, the PARADES software may also perform some analyses concerning these objects. Typically, these analyses relate to geometric properties such as a surface area, a cross-sectional area, a solid volume, etc., but they may be customised taking into account specifics of given problem. If needed, it is also possible to perform additional analyses by executing external, specialised codes. In optimisation process, results of all these analyses may be used for evaluation of objectives and constraints.

4. Examples of applications

The PARADES software has been applied in many commercial and non-commercial projects and research. Area of applications of the software covers a wide range of problems concerning the design and optimisation mainly in the field of aeronautical engineering. Among other things these problems concerned design and optimisation of:

- airfoils [1], [7]
- aircraft wings [3], [5], [6]
- high lift devices [5], [6]
- air intake system for turboprop engine [4]
- nozzles of turbojet engines
- helicopter main rotor
- helicopter fuselage [8], [9]
- stratospheric aeroplane
- propellers
- wind tunnel

Selected examples of application of the PARADES software are presented below.

4.1. Multidisciplinary optimisation of aircraft wing

Within the EU Projects NACRE and CESAR the PARADES software was used in the multidisciplinary optimisation of aircraft wings [3], [5], [6]. In these studies usually the whole aircraft was modelled using the PARADES software but only wing and optionally its high lift system were optimised. The optimisations were performed taking into account the aerodynamic and structural properties of the wing. In parametric model both the aircraft external shell and the wing structure were taken into consideration. The parametric model of the aircraft shell was used to generate input data for CFD calculations, which results were global and local aerodynamic characteristics (see Figure 8). The parametric model of the wing box was used to generate data for CSM analysis concerning the assessment of minimal weight of the wing structure being able to withstand the aerodynamic loads evaluated by CFD analysis (see Figure 9). In described studies the parametric models of the wing were built usually in the same manner. The Design Parameters concerned:

- wing planform (surface area, span, base chords, sweep angle, taper ratio, wing segmentation)
- spanwise distribution of relative thickness and type of airfoil
- spanwise distribution of twist
- spanwise distribution of camber of airfoil mean line

This way, by using relatively small number of Design Parameters both the wing planform and wing cross-sections were parameterised. In project CESAR the wing high lift systems were also parameterised (see Figure 10). The high lift systems were optimised with regard of optimal position of Fowler flap during take-off and landing. In Figure 11 the results of Multidisciplinary Numerical Optimisation of low-speed, small aircraft have been presented. In this case only the wing planform was changed and two objectives were taken into consideration: minimal drag and minimal wing weight. Figure 11 presents obtained Pareto Set and shapes of selected, Pareto-optimal aircrafts.

4.2. Parametric model of exhaust system of turbojet engine

Within the EU Project HISAC the CFD studies of the exhaust system for Variable Cycle Turbofan of a small supersonic business jet were performed. The PARADES software was applied to create the parametric model of the investigated object. By using this model, shown in Figure 12, several alternative geometries were generated. CFD study of flow through the various variants of the exhaust system (Figure 13) allowed to perform the sensitivity analysis and to select the optimal solution.

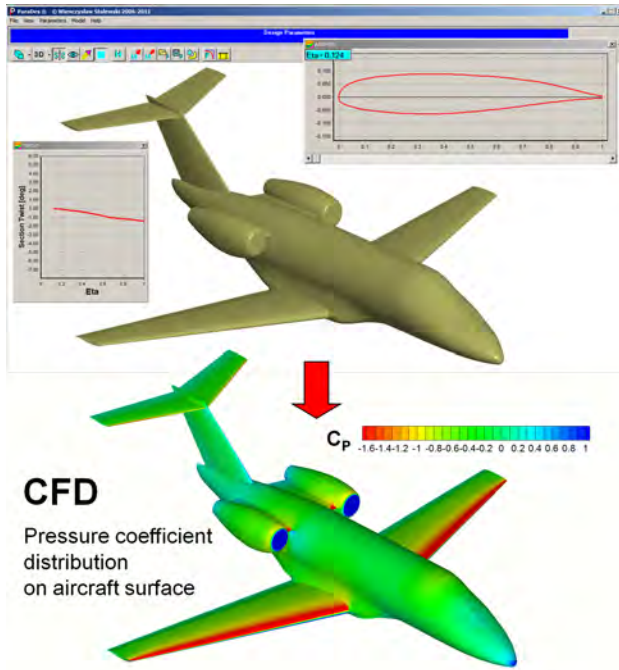


Figure 8. Parametric model of the aircraft external shell – the input for CFD calculations

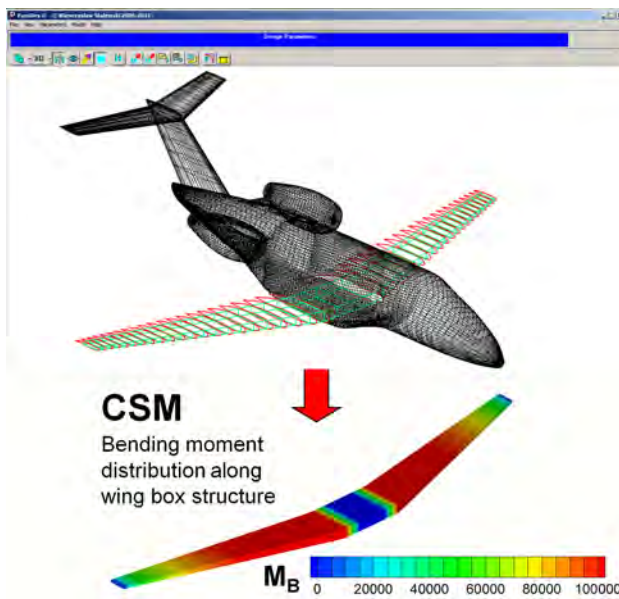


Figure 9. Parametric model of the wing spar – the input for CSM calculations

4.3. Optimisation of air intake system for turboprop engine

The PARADES software was applied in the Interactive Design process of air intake system for turboprop

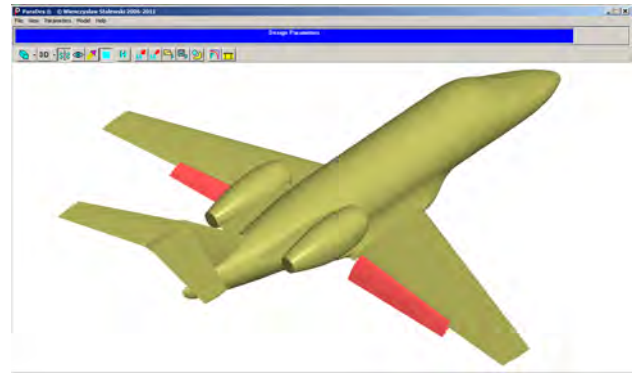


Figure 10. Parametric model of aircraft wing and its high lift system

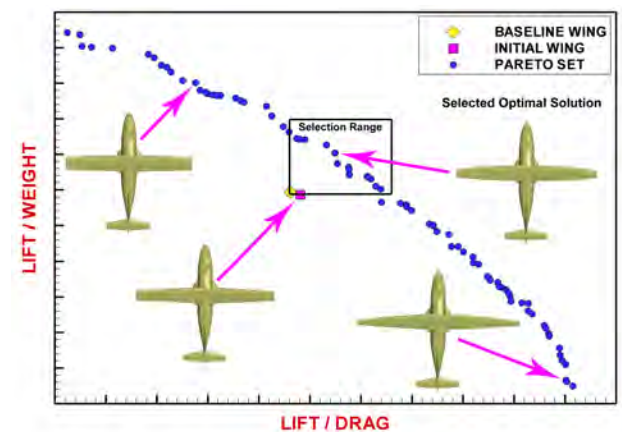


Figure 11. Parametric optimisation of low-speed, small aircraft based on two objectives: minimal drag and minimal wing weight

engine [4]. Both the air intake duct and the bypass (the foreign particles separator) were parameterised as it is shown in Figure 14. In preliminary stage of design process a simple, two-parameter model of isolated air intake was investigated. In the final phase, the complete air intake system was optimised. During the process of design and optimisation, for every configuration created by PARADES software, the thorough CFD analyses were performed. As an example of such analysis, the total-pressure distributions in cross-sections of air intake are shown in Figure 15.

4.4. Optimisation of helicopter fuselage

By using the PARADES software the parametric model of the helicopter has been worked out [8], [9]. The purpose of the work was to redesign the helicopter fuselage so as to improve aerodynamic properties and

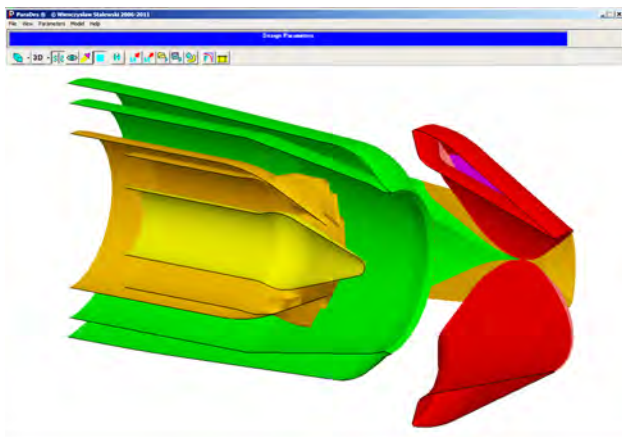


Figure 12. Parametric model of exhaust system of Variable Cycle Turbofan

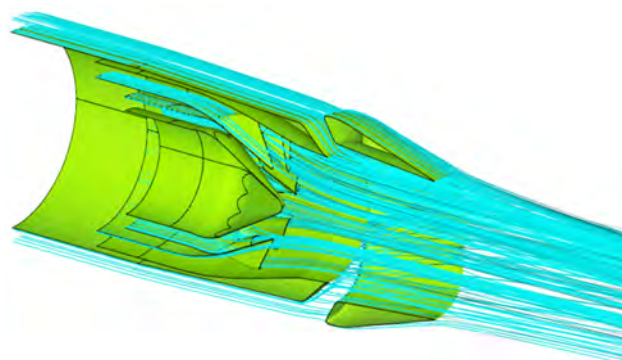


Figure 13. CFD study of flow through the exhaust system of Variable Cycle Turbofan

mass balance of the whole helicopter. It was assumed that within the optimisation process the effect of operating main and tail rotor should be taken into consideration. The work was carried out in three stages:

1. Development of parametric model of the helicopter
2. Design of few basic modifications of the helicopter using the Interactive Design approach
3. Design of the final version of the helicopter using the Numerical Optimisation method based on the Genetic Algorithm and morphing technique

The parametric model of the helicopter is shown in Figure 16. Although assumed modifications of geometry concerned only main part of the fuselage, other



Figure 14. Parametric model of air intake system for turboprop engine

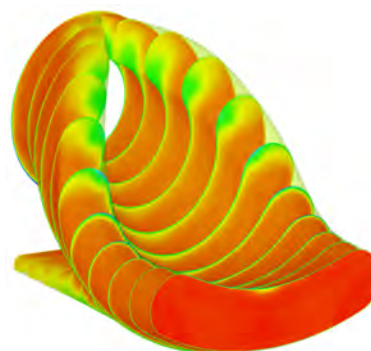


Figure 15. CFD study of parameterised air intake system for turboprop engine. Total pressure distributions in intake cross-sections. *Courtesy of EADS-CASA.*

components of the helicopter were also parameterised because of planned further research. In particular it concerned both the vertical and horizontal stabilizer. In presented approach, the effect of main and tail rotor was modelled in simplified way by application of Virtual Blade Model (VBM), which consists in the introduction of artificial sources of momentum in the fluid zones designated by the rotating rotor. As a result, in the parametric model the rotor blades were not physically modelled. Instead of this, the boundaries of fluid zones modelling the rotor were parameterised as well as geometric data of rotor blades (e.g. twist, thickness, planform, airfoils, etc.). All these data were the input for VBM. Within the presented parametric model, the main part of the fuselage was modelled as a multi-section surface, defined by the family of sections curves swept along the family of guiding curves. A part of Design Parameters defined the transformations of control points of guiding curves (see Figure 17). Addi-

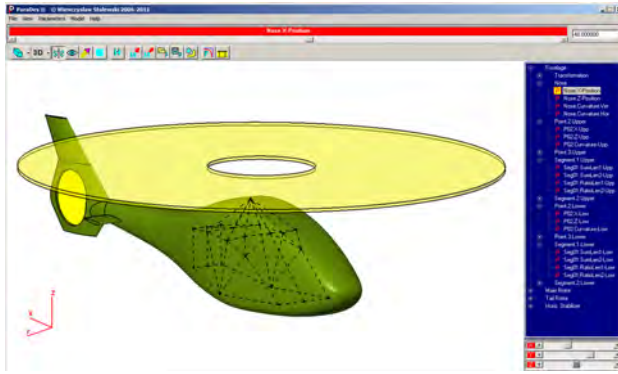


Figure 16. Parametric model of the helicopter

tionally, some Design Parameters defined smooth longitudinal changes of weights of control points of section curves, this way influencing the shape of fuselage cross-sections. Within the optimisation process only the Design Parameters defining main part of the fuselage were taken into consideration.

As a result of the Interactive Design process, three new variants of helicopter fuselage were designed. These variants: BAS-1, BAS-2 and BAS-3 together with the baseline BAS-0 were chosen as the base for morphing procedure. The Numerical Optimisation based on the Genetic Algorithm and the morphing technique led to the final solution, marked PAR-1. This helicopter has aerodynamic properties considerably better than initial version BAS-0. In Figure 18 the geometry of helicopter PAR-1 is shown together with the basic geometries and their weights giving as the result of morphing the final geometry.

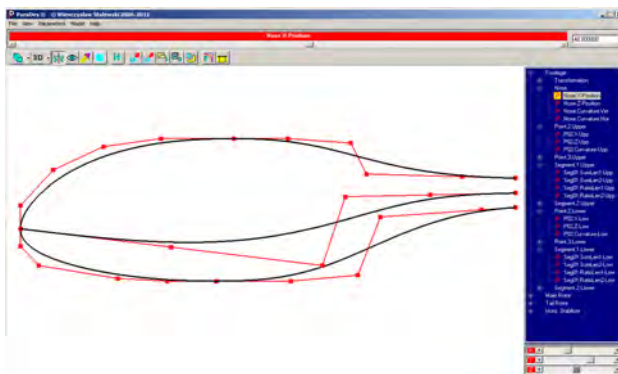


Figure 17. Parametric model of the helicopter fuselage surface based on a system of constructional NURBS curves

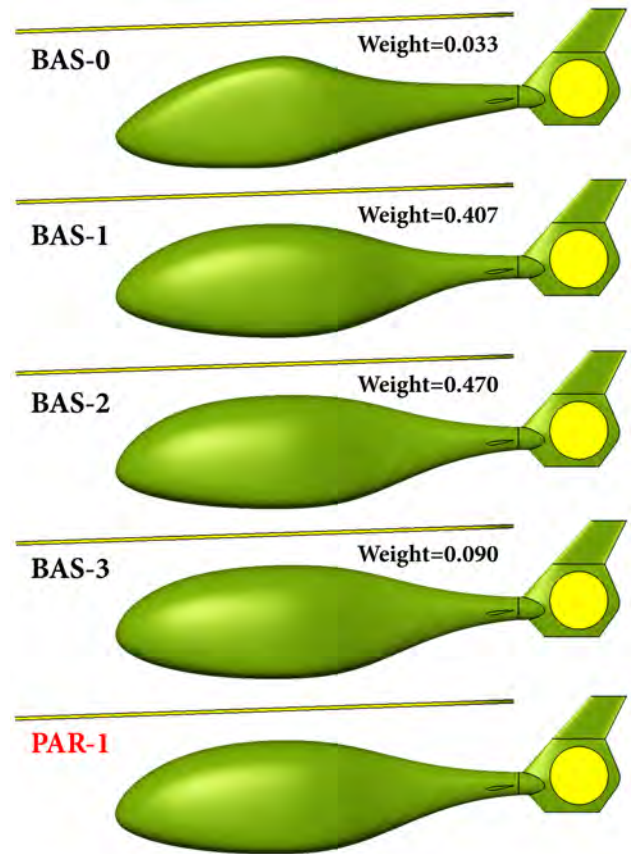


Figure 18. The optimised helicopter PAR-1 as a result of morphing of four basic helicopters

5. Conclusions

The PARADES is the software supporting parametric modelling of complex objects. The software is especially directed towards aerospace engineering applications. The PARADES was developed based on the methodology, which main idea was to create a tool capable to generate automatically a great number of different variants of complex geometries, smooth and feasible, properly read by the grid generators during a Numerical Optimisation process. The second idea was to create a tool supporting interactive parametric modelling, which could be used even by less-experienced CAD user for fast generation of several variants of designed product, using a friendly interface.

Previous experiences in practical applications of the software seem to confirm that the PARADES copes quite well to meet above challenges. The PARADES is still developed and improved to become the successful tool supporting design and optimisation of aerospace-engineering products.

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