OPTIMISATION OF THE HELICOPTER FUSELAGE WITH SIMULATION OF MAIN AND TAIL ROTOR INFLUENCE

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Abstract

The paper presents the methodology of parametric design and optimisation, which was applied to a redesign of a helicopter fuselage. The purpose of the presented study was to design a new shape of the fuselage, in order to improve aerodynamic properties and overall performance of complete helicopter, especially during high-speed flight. The process of aerodynamic optimisation of the fuselage was carried out taking into account a strong influence of working the main and tail rotor as well as a number of geometric and structural constraints. Aerodynamic properties of designed variants of the helicopter were evaluated using RANS solver FLUENT, while effects of rotating rotors were simulated using the Virtual Blade Model. The design and optimisation process was carried out in three main stages: 1st - development of parametric model of the helicopter, 2nd - design of a few base modifications of the helicopter fuselage using interactive design approach, 3rd - design of the final version of the redesigned fuselage using a multi-objective optimisation method based on genetic algorithm and morphing technique.

Nomenclature

A	- area of the fuselage shell
B	- vector of base objects for morphing
C_E	- constraint function, see definition (8)
C_F	- skin friction coefficient
C_P	- pressure coefficient
C_D	- drag coefficient
C_L	- lift coefficient (down-force coefficient)
C_m	- pitching moment coefficient
P	- vector of design parameters
V_F	- capacity of the fuselage front part
V_T	- total capacity of the fuselage
V_∞	- speed of flight
W	- vector of morphing weights
α	- angle of attack

Subscripts

(0)	- referred to the baseline helicopter
(p)	- pressure component of aerodynamic force
(f)	- viscous component of aerodynamic force

1 Introduction

The mainstream of development of the rotorcraft technology is focused on designing new or improving existing solutions of the most crucial systems of a helicopter. This concerns especially the main rotor, however rising expectations about the performance of modern helicopters make it necessary to take also into account the increasingly sophisticated design of their fuselages. According to [1] "the fuselage can significantly affect the overall performance of the helicopter in all flight conditions". This is especially important when coping with requirements of greater range and greater flight speed of new helicopters. Hence, in recent years, more and more effort is spent on developing new design and optimisation techniques of rotorcraft fuselages. The example may be European R&D Project ADHERO [2] aimed at aerodynamic drag reduction of light-weight-class helicopters by optimisation of their fuselages and other components producing a large amount of aerodynamic drag.

A helicopter fuselage may be designed and optimised taking into account several criteria, such as: improvement of aerodynamic properties and performance of the helicopter, structural optimisation, weight reduction, vibrations and noise reduction, maximisation of usable space, etc. Usually most of these criteria should be taken into consideration so as to obtain really optimal fuselage.

This paper presents a developed methodology of parametric design and optimisation, which was used to redesign of the fuselage of the light-weight-class helicopter. Pre-designed fuselage of this helicopter had a number of disadvantages found based on CFD analyses. These disadvantages were particularly evident in high-speed cruise flight of the helicopter and presented as:

- relatively high drag force
- considerable down-force
- large negative pitching moment, pitching the helicopter nose downwards

All these factors were disadvantageous especially from the viewpoint of performance and controllability of the helicopter. Additionally, the designers of the helicopter had found the need to introduce some changes of the fuselage geometry. In particular, this concerned the need to increase the capacity of the front part of the fuselage. This requirement was partially motivated by preliminary flight dynamics analysis, which indicated the need to shift the centre of gravity of the helicopter forward. All these factors led to the decision to redesign and optimise the fuselage so as to correct the found disadvantages. The methodology developed and applied for this purpose as well as results of the design and optimisation process are presented in this paper.

2 Problem Definition

The main purpose of the study was to redesign and optimise the originally designed fuselage of a light-weight-class helicopter. The baseline version of the fuselage, named BAS-0, is shown in Fig. 1. It was assumed, that during the design and optimisation process, the allowable changes of geometry would be limited to the principal part of the fuselage, while keeping all other components of the helicopter in such form as in the baseline version. The objective of the optimisation process was to reduce as much as possible the drag force, the down-force (usually characterising helicopter fuselages in cruise flight) and negative pitching moment, acting on helicopter fuselage in high-speed flight. For the optimised light-weight helicopter, the design flight conditions were established as follows:

- flight speed: V_∞=180 km/h
- angle of attack: α= -9°

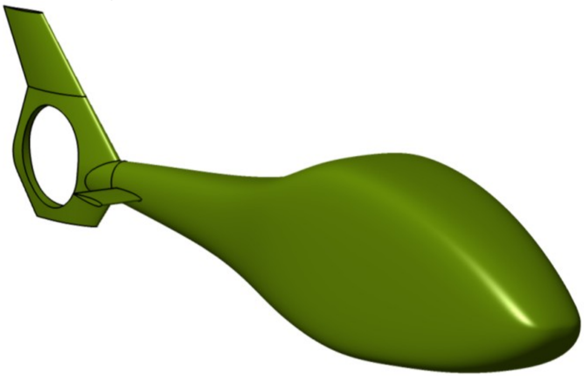

Fig. 1. Initial version of the fuselage BAS-0.

To achieve the required improvement of mass balance and increment of usable space of the helicopter, the following geometrical constraints were formulated:

- The redesigned fuselage must comply with other components of the baseline helicopter. In particular, the interior of the redesigned fuselage must contain the defined envelope of necessary structure and equipment of the helicopter. This envelope is shown in Fig. 2.
- The capacity of the front part of the redesigned fuselage (the part lying in front of the helicopter centre of gravity) should be greater by at least 5% compared with a baseline fuselage.
- The mass of the redesigned fuselage shell should not exceed the mass of the baseline shell, with tolerance 0.5%.

The formulated above task is a typical multi-objective-optimisation problem with design constraints. Initially, this problem has been solved using a simplified methodology [5] where only the symmetric flow around isolated fuselage (without the tail) was taken into consideration. In this approach the impact of the main rotor and tail rotor on fuselage aerodynamics was neglected. However further investigations showed that a disturbance induced by the operating rotors considerably changes the flow around the fuselage. In a real flight of a helicopter, besides the phenomenon of asymmetric flow caused by rotating main rotor and tail rotor, also significant changes in pressure field around the fuselage are observed. This phenomenon is shown in Fig. 3, where pressure-coefficient fields around the isolated fuselage and around the helicopter with operating main and tail rotor are compared.

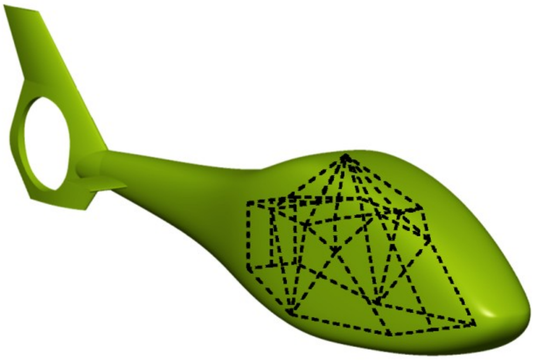

Fig. 2. The baseline fuselage with the envelope of necessary equipment and structure which must be contained inside the fuselage.

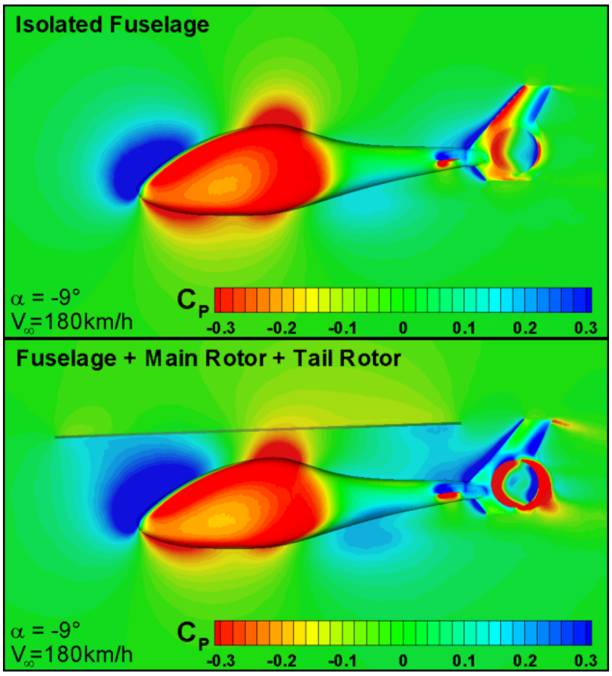

Fig. 3. Comparison of pressure-coefficient fields around the isolated fuselage and the helicopter with operating main rotor and tail rotor. Results of CFD computations. α=-9°, V_∞=180km/h.

The comparison concerns the results of CFD computations performed for design flight conditions (α=-9°, V_∞=180km/h). Fig. 3 shows that operating main rotor enhances the effect of overpressure on the front-upper surface of the fuselage causing a significant increase of pressure drag. In presented CFD calculations the effect of operating main rotor caused the 57% increase of the pressure drag while the total drag rose by 44% (the friction drag was similar in both compared cases). Similar significant differences in pitching moment reached 46%. Above results led to the conclusion, that during the design and optimisation of the helicopter fuselage, the influence of operating main rotor and tail rotor should have been appropriately simulated.

3 Methodology

The defined above problem was solved using the parametric-design methodology developed in Institute of Aviation [8],[9],[10],[11]. The general scheme of this methodology is presented in Fig. 4. The design process is managed by the *Designer*, who may be both the human and the computer code. In the former case the experienced engineer designs interactively sequential variants of the product and manages the optimisation cycles including executing CFD computations. In automatic mode the *Designer* is an optimisation code. In presented methodology, for this purpose, the Genetic Algorithm (multi-objective, taking into account design constraints) is used.

When solving a real engineering-design problem, both approaches - the interactive and automatic are useful. The interactively designed product may be used as initial variant for the *Numerical Optimisation*. On the other hand, the *Interactive Design* can also be useful to perform the final corrections of results of the automatic design. The *Numerical Optimisation* approach is commonly recognised as a powerful tool aiding a designing of modern products of aeronautical engineering.

Fig. 4 shows, that the *Designer* uses the parametric-modelling software to create different variants of optimised product. In the presented methodology the parametric model was build using the in-house software ParaDes™ [5]. The Graphical User Interface of this software, used in the Interactive Design mode, is shown in Fig. 5.

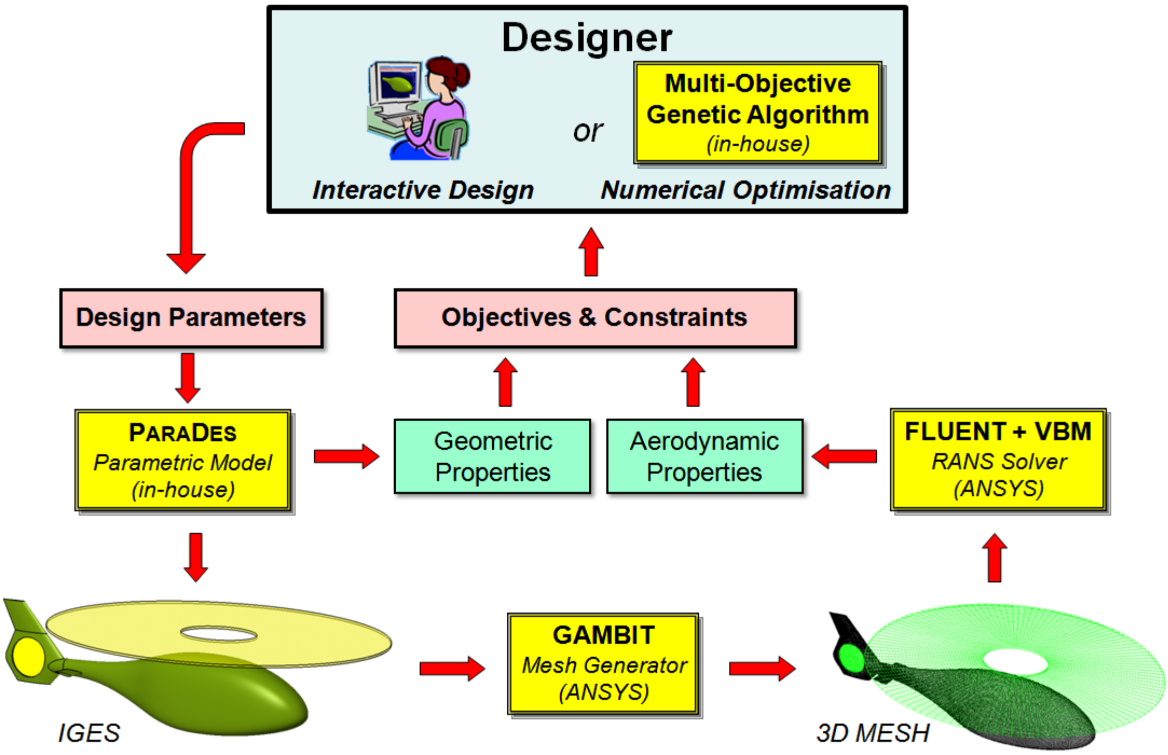

Fig. 4. The general scheme of parametric-design-and-optimisation methodology applied to redesign of the helicopter fuselage.

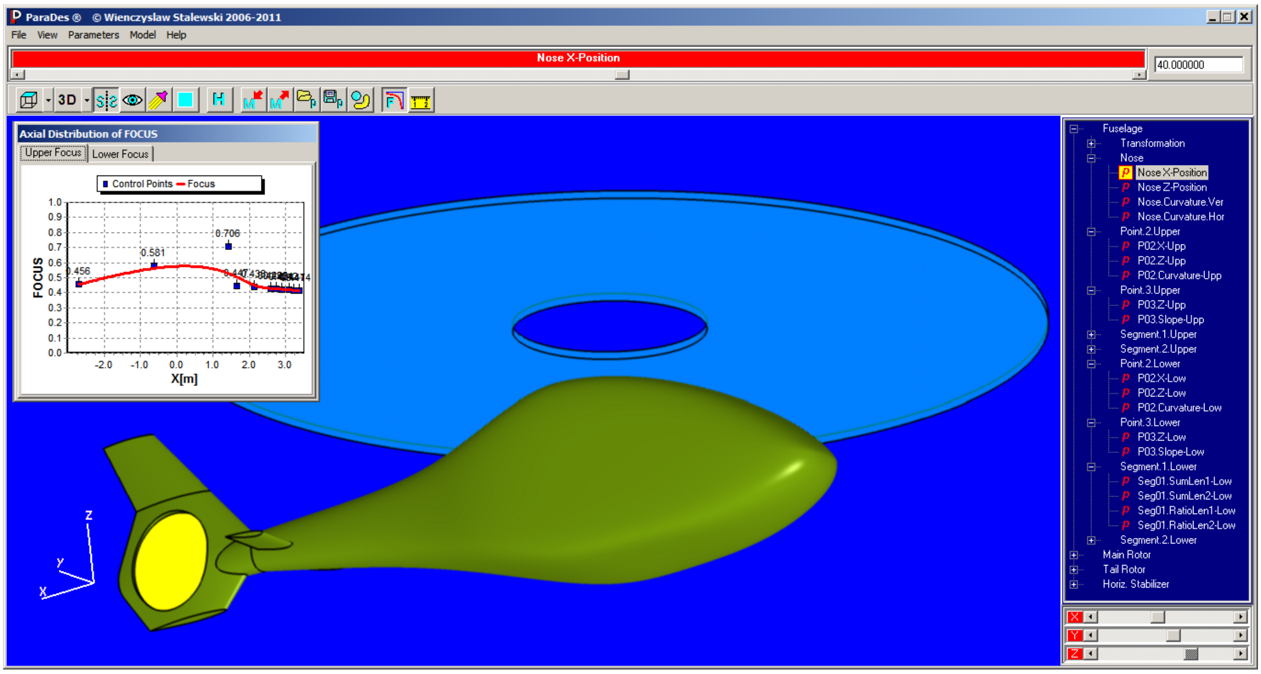

Fig. 5. The GUI environment of the PARADES software.

The PARADES uses NURBS (Non-Uniform Rational B-Splines) representation of parameterised objects. This concerns not only geometry but also any functions describing physical properties of these objects. It is assumed that a designed product is uniquely described by a set of *Design Components*: scalars, vectors and NURBS curves, surfaces and solids. The *Design Parameters* describe modifications of the *Design Components*, this way influence the final form of the product. As it is shown in Fig. 4, the PARADES software creates given variant of the product based on a set of *Design Parameters* – i.e. a set of numbers uniquely describing a certain subclass of all possible forms of the product. The extent of this subclass depends on the specifics of given parametric model and largely on the number of assumed *Design Parameters*.

In a design-and-optimisation practice, the ParaDes may be applied in two alternative modes of parametric modelling, as it is shown in Fig. 6. In the *standard mode* the set of *Design Parameters* defines directly given variant of designed product. An alternative is an application of *morphing mode*, which consists in creating a given variant of product as an affine combination of certain number of base variants. In such a case it is assumed that the base for morphing was prepared in earlier stage of the design, usually using the *Interactive Design* approach. The affine combination of base variants is realised in the space of *Design Parameters*, giving as a result the set of *Design Parameters* defining a morphed variant of the designed product. In this case, the weights corresponding to different base variants may be considered as alternative, higher-order *Design Parameters*. The example of the morphing technique implemented in the ParaDes software is shown at the bottom of Fig. 6. The base geometries for the morphing were: cone (B_1), sphere (B_2) and cube (B_3). All these three different solids were modelled by the same parametric model. By defining appropriate morphing weights it was possible to generate a two-parametric subclass of solids, examples of which are shown in Fig. 6.

The application of the morphing technique in parametric modelling has several advantages. First of all, it allows to reduce considerably the number of design parameters, which is usually the key factor determining the success of *Numerical Optimisation*. Secondly, the morphing technique helps to control a quality of automatically generated geometries because such features as feasibility, smoothness, etc. are usually inherited from the base geometries.

The ParaDes may be used both in interactive mode and in fully automatic mode (batch mode). In the *Interactive Design* mode the set of *Design Parameters* is defined by a human *Designer* while in the *Numerical Optimisation* mode this set is created by optimisation software.

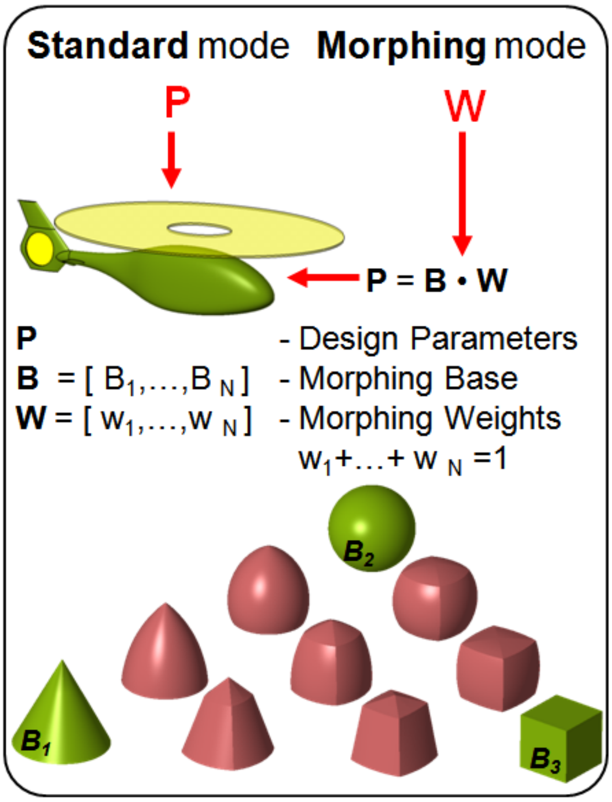

Fig. 6. Two modes of parametric modelling
in the PARADES software.

The output data from the ParaDes software is the geometry of designed product written in IGES format. Besides creating geometry, the ParaDes software also performs specialised analyses of this geometry. In presented design process, these analyses concerned:

- calculation of the fuselage shell area (approximate assessment of weight of the fuselage shell)
- calculation of the total capacity of the fuselage and the capacity of its front part
- checking whether the envelope of the necessary equipment and internal structure (Fig. 2) is completely contained inside the helicopter fuselage.

The next very important component of the methodology presented in Fig. 4 is the CFD package applied for evaluation of aerodynamic objectives and constraints. The principal component of this package is the FLUENT™ code [3], which is the RANS solver based on the Finite Volume Method. For the simulation of flow effects caused by rotating main rotor and tail rotor, the Virtual Blade Model (VBM) [7] was applied. In this approach real rotors are replaced by volume-discs (see Fig. 7) influencing the flow field similarly as rotating rotors. Time-averaged aerodynamic effects of rotating blades are modelled using momentum source terms placed inside rotor-disk fluid zones. The source terms are computed based on the Blade Element Theory. The blade geometry is represented by radial distributions of twist, chord and type of airfoil. A local blade aerodynamics is not resolved but its effects are simulated based on local flow parameters (angle of attack, Mach and Reynolds numbers) associated with databases of 2D-aerodynamic characteristics of blade sections.

The VBM takes into consideration the following kinematic data:

- rotational speed of the rotor
- collective and cyclic pitch of blades
- coning and flapping of blades

The collective and cyclic components of the blade pitch may be also obtained as results of trimming procedure performed in order to obtain the assumed thrust and/or pitching and rolling moments acting on the rotor.

The input data for the FLUENT code – the computational mesh, was generated using the GAMBIT™ software [4]. The input for this software was a mathematical model of given variant of the helicopter, created by the PARADES software and written in IGES format. Both codes: the FLUENT (together with the VBM module) and GAMBIT were executed in batch mode in both the *Interactive Design* and the *Numerical Optimisation* mode.

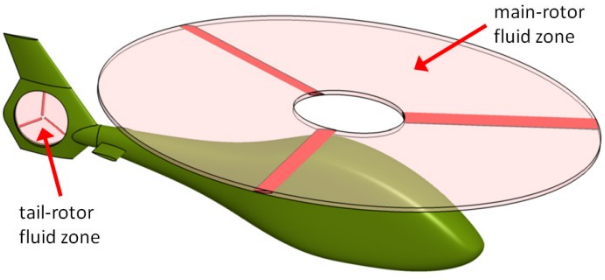

Fig. 7. Fluid zones modelling real rotors in the Virtual Blade Model.

The CFD calculations were conducted using following computational model:

- flow model: steady, compressible, viscous
- turbulence model: Spalart-Allmaras
- mesh quality: $y+ \approx 1$

For all designed variants of the helicopter the same input data for the VBM were taken into consideration. In particular this concerned the kinematic parameters of rotors and blades. To establish the collective and cyclic components of pitch of the main-rotor blades, the trimming procedure was conducted for the baseline helicopter BAS-0 so as to obtain the balance of vertical forces and to neutralize the total pitching and rolling moments acting on the helicopter. The collective pitch of tail-rotor blades was matched so as to neutralize the total yawing moment acting on the helicopter.

4 Design and Optimisation

The goal of the design process was to minimise following quantities characterising the fuselage in high-speed flight of the helicopter:

$$C_D / C_{D(0)} \qquad (1)$$

$$C_L / C_{L(0)} \qquad (2)$$

$$C_m / C_{m(0)} \qquad (3)$$

taking into account the following geometrical constraints:

$$V_T / V_{T(0)} > 1 \qquad (4)$$

$$V_F / V_{F(0)} > 1.05 \qquad (5)$$

$$A / A_{(0)} < 1.005 \qquad (6)$$

$$C_E < 0 \qquad (7)$$

where C_D is a drag coefficient, C_L is a lift coefficient (actually: down-force coefficient), C_m is a pitching moment coefficient, V_T is a total capacity of the fuselage, V_F is a capacity of front part of the fuselage (a part lying in front of the helicopter centre of gravity), A is a total area of the fuselage shell. Subscript $_{(0)}$ refers to the baseline helicopter (BAS-0). The constraint (7) utilises the function C_E, which checks whether the envelope of necessary equipment and internal structure of the helicopter (Fig. 2) entirely lies inside the fuselage. This function is defined as follows:

If the envelope entirely lies
inside the fuselage:
C_E = - *{ minimal distance between*
fuselage shell and points
of the envelope } (8)
Otherwise:
C_E = *{ maximal distance between*
fuselage shell and points
of the envelope lying
outside the shell }

Summarising, the goal of the fuselage redesign was minimisation of:

- relative drag force (1)
- relative down-force (2)
- relative pitching moment (3)

acting on the complete fuselage (together with the vertical tail and horizontal stabilizer) in conditions of high-speed flight of the helicopter (α=-9°, V_∞=180km/h). The redesigned fuselage should have fulfilled the constraints (4)-(7).

The redesign of the fuselage was conducted in the following three stages:

1) Development of the helicopter parametric model using the PARADES software.
2) Design of a few base variants of redesigned fuselage using the *Interactive Design* approach.
3) Design of the final version of redesigned fuselage using the *Numerical Optimisation* method based on the Genetic Algorithm and the morphing technique.

4.1 Parametric Model of the Helicopter

The parametric model of the helicopter was developed using the PARADES software. Generally, this model concerned all principal components of the helicopter: fuselage, horizontal stabilizer, vertical tail, main rotor and tail rotor. Taking into account the assumed simplified modelling of the effects of rotating lifting surfaces, geometries of main rotor and tail rotor were modelled in accordance with the requirements of the VBM. Although all principal components of the helicopter were parameterised, only *Design Parameters* describing a geometry of the fuselage were taken into consideration within the optimisation process.

The shell of the fuselage was modelled as a NURBS-surface. The idea of parameterisation of this surface is shown in Fig. 8. The surface was created by a family of *section curves* swept along *guiding curves*. Shapes of these base curves could have been changed by modifying their control points, this way influencing a change of the fuselage shape. The smooth changes of control points of the *section* and *guiding curves* were defined by appropriate *Design Parameters*.

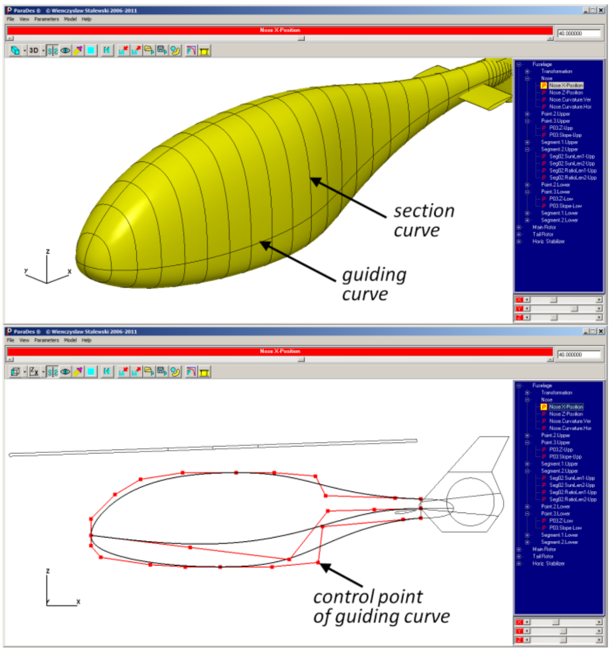

Fig. 8. The parametric model of the helicopter fuselage developed using the PARADES software.

4.2 Interactive Design

The *Interactive Design* stage of the fuselage redesign was conducted by an experienced aeronautical engineer, who was working in the cycles presented in Fig. 4. The *Designer* was using the PARADES software for geometry designing and the FLUENT & VBM software for CFD analyses. The parametric model of the helicopter was used in standard mode, i.e. the *Designer* was changing directly values of *Design Parameters*, this way creating new variants of the fuselage. Within this task, the *Designer* tried to design a few redesigned fuselages so as to minimise as much as possible the objectives (1) - (3). At this stage of the design it was assumed that some of design constraints (4) - (7) could have been neglected if it had helped to minimise the objectives. As the result of the *Interactive Design* process, three new versions of the helicopter fuselage were designed. They were named: BAS-1, BAS-2 and BAS-3. Their properties are presented and compared with the baseline fuselage BAS-0 in Tab. 1 and Tab. 2.

Fuselage	Geometry			
	$\frac{V_T}{V_{T(0)}}$	$\frac{V_F}{V_{F(0)}}$	$\frac{A}{A_{(0)}}$	$C_E<0$
BAS-0	1.000	1.000	1.000	true
BAS-1	1.026	1.064	1.000	true
BAS-2	0.974	1.048	0.999	false
BAS-3	0.980	1.061	1.000	false

Tab. 1. Geometrical properties of the redesigned fuselages BAS-1, BAS-2, BAS-3 referenced to the analogous properties of the baseline fuselage BAS-0.

Fuselage	Aerodynamics		
	V_∞=180km/h α=-9.0°		
	$\frac{C_D}{C_{D(0)}}$	$\frac{C_L}{C_L/C_{L(0)}}$	$\frac{C_m}{C_{m(0)}}$
BAS-0	1.000	1.000	1.000
BAS-1	0.946	0.870	-0.184
BAS-2	0.939	0.817	-0.272
BAS-3	0.935	0.802	-0.392

Tab. 2. Aerodynamic properties of the redesigned fuselages BAS-1, BAS-2, BAS-3 referenced to the analogous properties of the baseline fuselage BAS-0.

The fuselage BAS-1 besides having good aerodynamic properties fulfils all geometrical constraints. The fuselages BAS-2 and BAS-3 have even better than BAS-1 aerodynamic properties, but the BAS-2 does not fulfil constraints (4),(5),(7) and BAS-3 does not fulfil constraints (4),(7).

4.3 Numerical Optimisation

The main goal of the *Numerical Optimisation* was to improve the aerodynamic properties of the fuselage BAS-1, while meeting all constraints (4) - (7). To solve the optimisation problem, the Multi-Objective Genetic Algorithm was applied. In this case, the parametric model was based on the morphing methodology. The base for morphing consisted of four variants of the fuselage: the baseline BAS-0 and the fuselages BAS-1, BAS-2 and BAS-3 designed in the *Interactive Design* process.

In total, 150 optimisation cycles were performed by the Genetic Algorithm. The final result of the optimisation was the *Pareto Set* – the set of non-dominated genotypes, fulfilling all constraints. The values of objectives evaluated for base variants and Pareto-optimal variants are compared in Fig. 9 and Fig. 10, where the variants marked in yellow meet all constraints while the marked in red do not fulfil some constraints.

From the *Pareto Set* the one solution PAR-1 was chosen. The choice was motivated by the highest priority established for a drag minimisation and very good geometrical properties of the variant PAR-1. Geometric and aerodynamic properties of selected variant are presented and compared with the baseline variant BAS-0 in Tab. 3 and Tab. 4. The values of objectives calculated for the variant PAR-1 are also presented in Fig. 9 and Fig. 10.

Fuselage	Geometry			
	$\frac{V_T}{V_{T(0)}}$	$\frac{V_F}{V_{F(0)}}$	$\frac{A}{A_{(0)}}$	$C_E<0$
BAS-0	1.000	1.000	1.000	true
PAR-1	**1.013**	**1.056**	**1.000**	**true**

Tab. 3. Geometrical properties of finally redesigned fuselage PAR-1 referenced to the analogous properties of the baseline fuselage BAS-0.

Fuselage	Aerodynamics				
	V_∞=180km/h α=-9.0°				
	$\frac{C_D}{C_{D(0)}}$	$\frac{C_{D(p)}}{C_{D(p)(0)}}$	$\frac{C_{D(f)}}{C_{D(f)(0)}}$	$\frac{C_L}{C_{L(0)}}$	$\frac{C_m}{C_{m(0)}}$
BAS-0	1.000	1.000	1.000	1.000	1.000
PAR-1	**0.927**	**0.922**	**0.996**	**0.803**	**-0.027**

Tab. 4. Aerodynamic properties of finally redesigned fuselage PAR-1 referenced to the analogous properties of the baseline fuselage BAS-0.

In Fig. 11 the geometry of helicopter PAR-1 is shown together with the base helicopters BAS-0, BAS-1, BAS-2, BAS-3 and associated with them weights giving as a result of morphing the helicopter PAR-1.

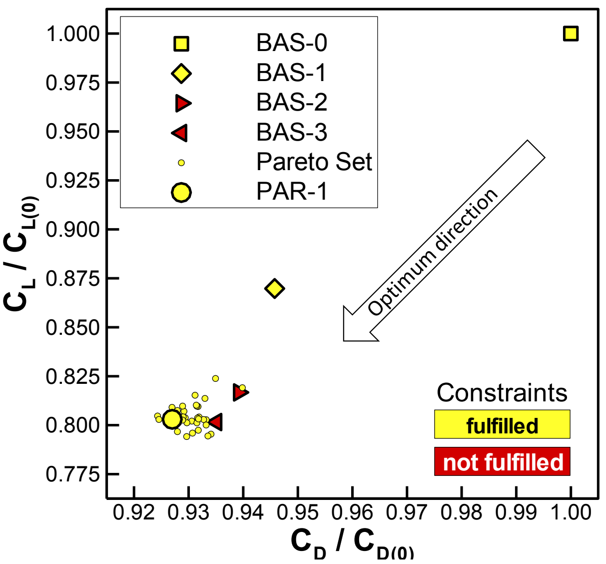

Fig. 9. Comparison of objectives $C_D/C_{D(0)}$ and $C_L/C_{L(0)}$ evaluated for base variants and Pareto-optimal variants of fuselage during *Numerical Optimisation* process.

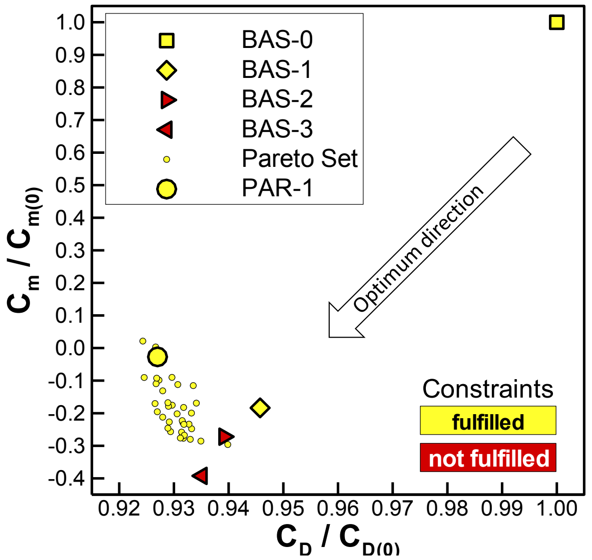

Fig. 10. Comparison of objectives $C_D/C_{D(0)}$ and $C_m/C_{m(0)}$ evaluated for base variants and Pareto-optimal variants of fuselage during *Numerical Optimisation* process.

Based on the presented results it may be concluded that the helicopter PAR-1, chosen as a final solution, fulfils all constraints (4)-(7) and it has aerodynamic properties considerably better than baseline helicopter BAS-0. In comparison with the baseline, the variant PAR-1 is characterised by 7% reduction of drag, 20% reduction of down-force and considerable reduction of negative pitching moment which even became positive. Additionally, the fuselage PAR-1 has of 5.6% larger the capacity of its front part, while the total area (and weight) of the fuselage shell remains the same as for the baseline fuselage BAS-0.

In comparison with the helicopter BAS-1 the selected helicopter PAR-1 is also characterised by improved aerodynamic properties except the relative pitching moment. However this objective had the lowest priority in the process of selection of the final solution from the Pareto Set. Saying precisely, the fulfilment of the condition:

$$C_m / C_{m(0)} < 0 \tag{9}$$

was entirely satisfactory when choosing the final solution. The fulfilment of the condition (9) means, that given variant of the fuselage is characterised by positive pitching moment in high-speed cruise flight conditions. The selected variant PAR-1 satisfies this requirement.

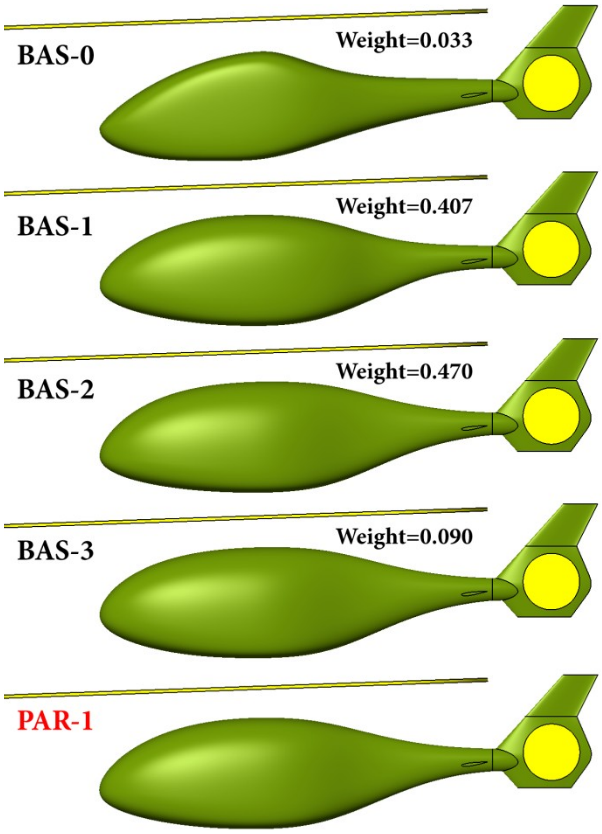

Fig. 11. The helicopter PAR-1 as a result of morphing of base helicopters: BAS-0, BAS-1, BAS-2 and BAS-3.

The more detailed analysis of the results presented in Tab. 4, shows that reduction of drag coefficient mainly concerns its pressure part $C_{D(p)}$ while the frictional part $C_{D(f)}$ is reduced to a lesser extent. Considerable reduction of the pressure drag is explained in Fig. 12 and Fig. 13, where the comparison of pressure-coefficient fields (C_P) around the helicopters BAS-0 and PAR-1 is presented. The C_P-field around the helicopter PAR-1 is much more favourable from the point of view of pressure drag reduction.

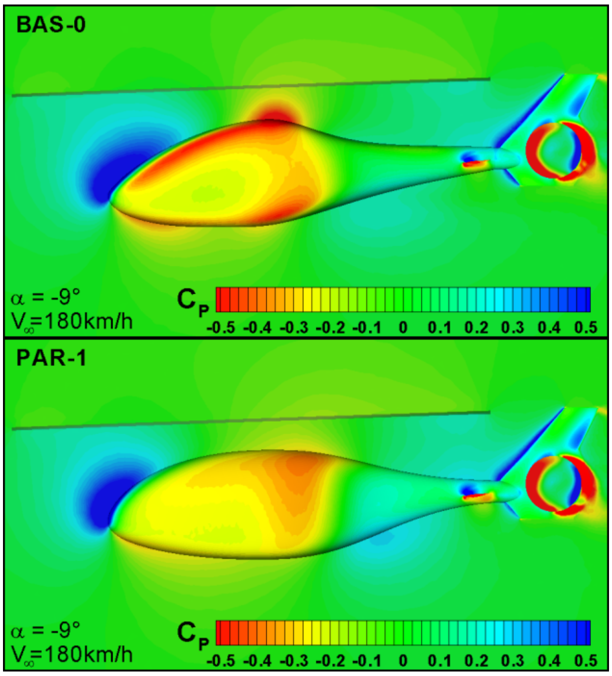

Fig. 12. Comparison of pressure-coefficient fields around the helicopters BAS-0 and PAR-1. $\alpha=-9^{o}$, $V_{\infty}=180$km/h. Left view.

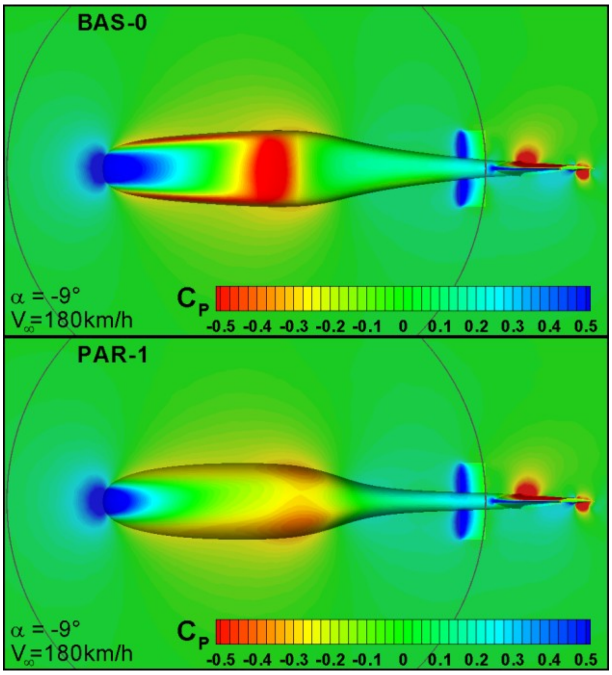

Fig. 13. Comparison of pressure-coefficient fields around the helicopters BAS-0 and PAR-1. $\alpha=-9^{o}$, $V_{\infty}=180$km/h. Top view.

Fig. 14 shows that the helicopter PAR-1 is also characterised by more favourable distribution of friction coefficient C_F on the fuselage shell, which favours reduction of friction drag of the fuselage.

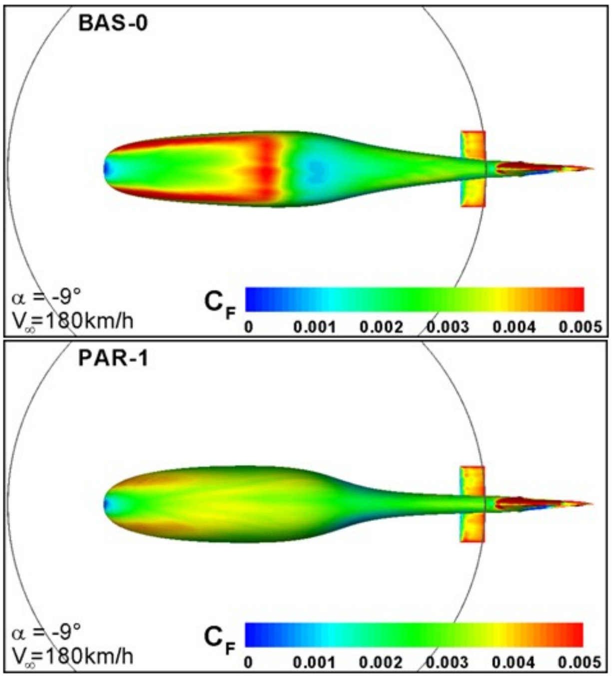

Fig. 14. Comparison of friction-coefficient distributions on the fuselages BAS-0 and PAR-1. $\alpha=-9^{o}$, $V_{\infty}=180$km/h. Top view.

5 Conclusions

In this paper, the methodology of parametric design and optimisation has been presented. The methodology is focused particularly on aeronautical-engineering applications. The purpose of the work was to redesign the helicopter fuselage so as to improve its aerodynamic and geometrical properties. The work was carried out using both the *Interactive Design* and the *Numerical Optimisation* based on the Multi-Objective Genetic Algorithm and the morphing technique. CDF calculations took into account effects of rotating main rotor and tail rotor modelled using the Virtual Blade Model.

The optimisation was conducted in conditions of high-speed cruise flight of the helicopter. In such conditions the redesigned helicopter in comparison with its initial version was characterised by 7% reduction of drag, 20% reduction of down-force and considerable reduction of negative pitching moment, which even became positive. Although the introduced modifications concerned only the principal part of the fuselage, the above improvements apply to the whole helicopter and finally should give an improvement in its overall performance and controllability.

The carried out research had two main goals. The first one was to develop an efficient methodology supporting a design of fuselages of modern helicopters. The second goal was to prove that the developed methodology is useful in the aeronautical engineering practice. Based on the presented results of conducted design and optimisation of helicopter fuselage it may be concluded, that both these goals were achieved.

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