AERODYNAMIC DESIGN OF THE STRAKE FOR THE ROCKET PLANE IN TAILLESS CONFIGURATION.

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Abstract

The paper presents results of the aerodynamic design of the Rocket Plane in a tailless configuration. It is part of a Modular Airplane System - MAS. The system is devoted to the space tourism and the Rocket Plane is the main component of the system. The main goal of the research was improving aerodynamic characteristic of the Rocket Plane. The paper presents the proposal of modification of the initial Rocket Plane geometry which is being results from the optimization process. The final geometry of the Rocket Plane is resulting of a number of optimization.

1 Introduction

Space tourism is a very promising and fast developing branch of an aerospace technology [1]. Especially the idea of suborbital tourist flights is a very promising concept. The main advantage of this type of flights is a lower price [1] compare to a tourist visit on the International Space Station. During a suborbital flight the boundary between the Earth's atmosphere and outer space is crossed, zero gravity condition appears due to parabolic trajectory. Moreover, the spherical shape of the Earth can be observed by the passengers in the vehicle.

At Warsaw University of Technology- WUT a concept of suborbital vehicle [3] has been developed. A Modular Airplane System (MAS) is inspired by Tier One [2], but the MAS concept (see Fig. 1) has a few quite interesting solutions compare to Tier One. For example a tailless configuration of both vehicles which connected together creates a conventional airplane where the Rocket Plane is used as a tail of the MAS. Moreover, the Rocket Plane is able to fly at high angles of attack. It is assumed that, it should be equipped with a strake.

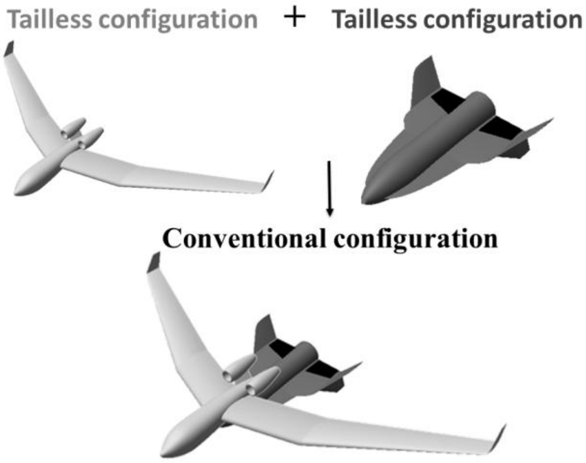

Fig. 1 Concept of the MAS

The mission profile of the MAS is presented in Fig. 2. The mission profile of the MAS consists of the following five main phases:

- Take-off
- Objects separation
- Climbing and ballistic flight
- Return
- Landing

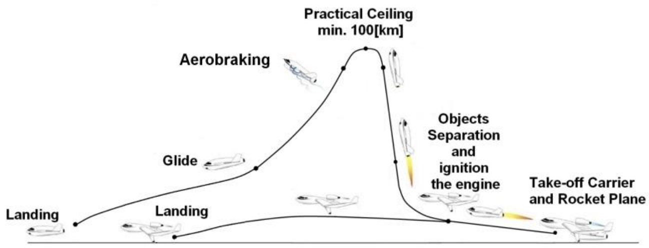

Fig. 2 MAS mission profile.

Success of MAS mission depends mainly on the Rocket Plane's performance. So, a lot of attention was focused on its aerodynamic design. The most important requirements of the Rocket Plane's aerodynamic configuration have been defined by the return flight. The mission profile assumes flight at high angles of attack during this phase and using the phenomenon of a vortex flow. The additional vortex lift [9] generated by the strake will be utilized to decrease a sink rate during the return phase (Fig. 2). This method of reducing a flight speed is called aerobraking and prevents acceleration and overheating of the structure. It was assumed that an additional lift caused by the vortex flow, will be the best solution due to a small initial re-entry speed of the Rocket Plane.

All presented in this paper analysis is focused on the Rocket Plane only.

2 Basic considerations

The vortex lift has been studied for many years [10],[11],[12] . This phenomenon allows increasing in maneuverability by augmentation of the lift force for high angles of attack. This effect is usually utilized by military airplanes. Many investigations of the vortex generation, development and breakdown for different configurations were carried out [13],[14],. The simplest configuration of a wing which is able to generate the vortex lift is a delta wing [15], but more effective method is using a strake or a LEX(Leading Edge Extension) [16]. Both configurations provide a (completely or partially) high swept leading edge which is responsible for generating additional vortices. Unfortunately, generating the extra lift force has negative consequences. The first one is increasing the drag force too. Second one is vortex breakdown [11] which causes rapid loss of the lift force and problems with the longitudinal and directional stability due to the asymmetry of the breakdown.

3 Preliminary design of the Rocket Plane

The vortex generation study by the Rocket Plane is not a new issue. The initial study on the concept of the MAS and the Rocket Plane were presented in [3], [4], [6],[7], [8].

Results of initial CFD calculation of the Rocket Plane is presented in Fig. 3. The comparison of the lift curve for with and without the strake is presented. The lift force benefit on high angles of attack is significant.

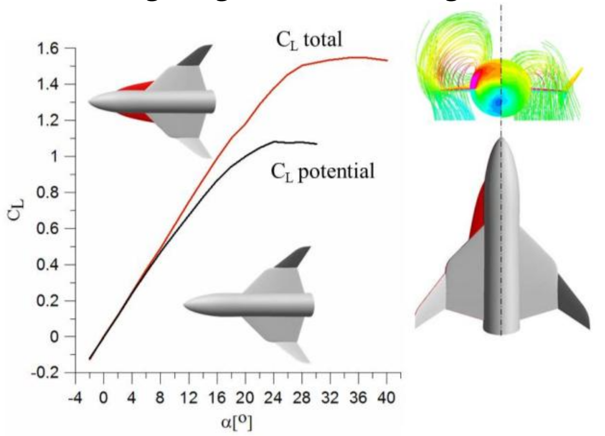

Fig. 3 Increase of lift coefficient caused by vortex flow on the Rocket Plane

Geometry of the Rocket Plane is a result of the design process. A lot of constrains had an influence on the final result. The shape of the fuselage depends on a cabin arrangement (see Fig. 4) and a strength condition of the fuselage structure. The cross section close to the passenger cabin is presented in Fig. 5. The circle cross section seems to be the optimal solution according to an aerodynamic and strength point of view.

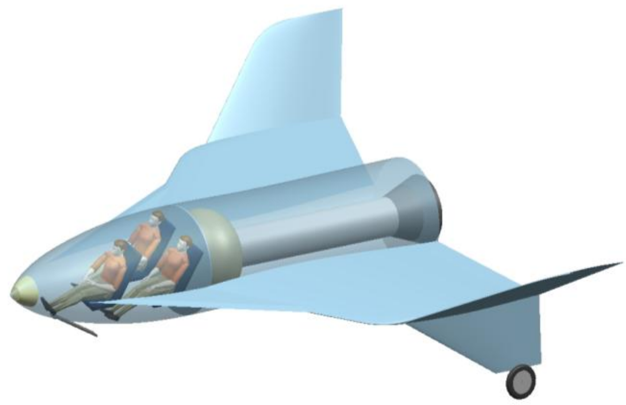

Fig. 4 Cutaway of the Rocket Plane

Fig. 5 The Rocket Plane's fuselage cross section close to passengers section

The configuration of a wing and tail was a result of wind tunnel tests. The shape and configuration of the all moving tail should satisfy directional stability and controllability for a wide range of Mach numbers. The flow visualization for one of considered cases of Rocket Plane's strake geometry [7] is presented in Fig. 6. The visualization was carried out during the wind tunnel test.

Fig. 6 Vortex flow visualization from wind tunnel test

The optimization the strake's shape was a one of the possible methods to improve the Rocket Plane performances. The main goal was to increase the lift by the vortex flow during the return flight. The additional lift allow to reducing the sink rate. To achieve the goal it was decided to optimize the strake's shape.

4 Problem definitions

4.1 Assumption

The paper is focused only on aerodynamic aspects of an aircraft design and optimization. The main goal was to obtain only the shape of the strake. The geometry of other components of the Rocket Plane like a main wing, tail was assumed to be unchanged. The initial geometry, called the base model, of the Rocket Plane is presented in Fig. 7

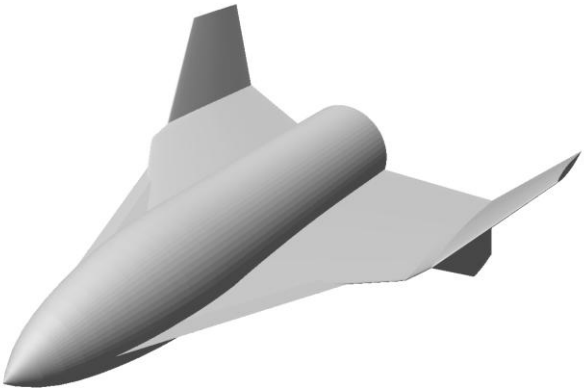

Fig. 7 The initial geometry of the Rocket

The all sets of computation were made for the one Mach number equal 0.1. This Mach number is corresponding to the WUT's wind tunnel parameters. All previous experimental tests were made for these conditions. Success of the presented calculation will be the motivation to research the geometry of the Rocket Plane for a greater Mach number.

4.2 Optimization method

Especially for this kind of study, the authoring program for the optimization process was created. The program was written in C++ and Fortran language.

The steepest descent method [17] has been chosen as an optimization method. It belongs to the group of gradient method. This method is the simplest method among directional methods. It does not need a lot of calculations and its numerical implementation is easy. On the other hand this method is less effective. A result which is obtained can be only a local minimum. The mathematical formula of the steepest descent method to calculation of new variables has been described by the equation (1).

$$x_{K+1} = x_K + \alpha_K p_K \qquad (1)$$

where :

K – number of iteration
x – design variable vector
p – direction vector
α – step's length

The method was enhanced by the Armijo [17] condition. This condition is checked in every step and help to assess the proper step's length. The direction vector was calculated by central or right-hand derivative.

The chart flow of the software is presented in Fig. 8.

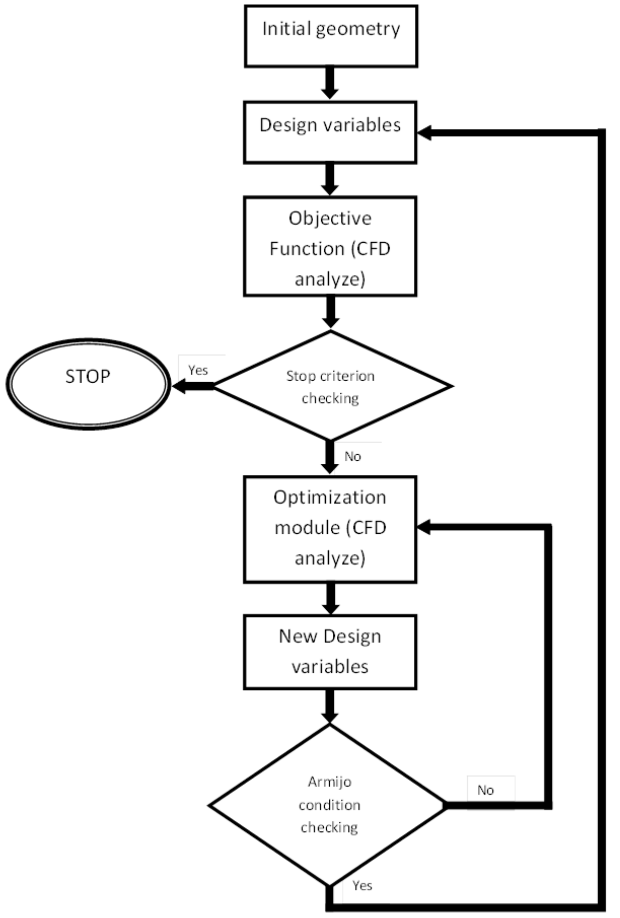

Fig. 8 The chart flow

The calculation starts from the initial geometry defined by design variables. An objective function is calculated with a usage of CFD analyses. Next the stop criterion is checked. If it is not fulfilled, the calculation goes further. New variables are calculated by the optimization module and it is checked whether they fulfill an Armijo condition or not. If no, the optimization module works until they satisfy the Armijo condition. Then the next iteration starts. The calculation ends when the stop criterion is fulfilled.

4.2.2 CFD method

Numerical calculations were conducted by MGAERO software [18], which is based on Euler equations and multi-grid scheme [19]. This software can be used to a vortex flow calculations. The method does not include the vortex breakdown. The CFD results of the initial strake optimization were verified in wind tunnel tests and compatibility of both numerical and experimental outcomes are satisfied.

The example of the surface grid of the numerical model has been presented in Fig. 9.

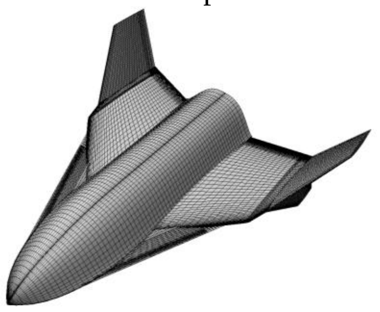

Fig. 9 Grid of numerical model

To prepare aerodynamic calculations multi grid should be created. Especially for the base model the special grid blocks were generated and a lot of attention was focused on the region near to the Rocket Plane's strake. The multi-grid generated for the optimization process is presented in Fig. 10.

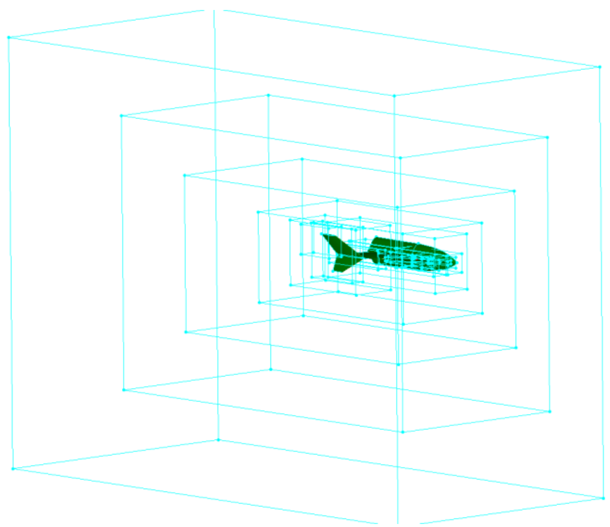

Fig. 10 Multi-grid blocks

4.3 Design variables

The proper choice of the type and the number of design variables allows to obtain a good solution. Too small number of design variables cause weak accuracy of the result. In the other hand excessive number of design variables cause that calculations time is very long. For the presented analysis the number of design variables was established about 10-33. In that case of optimization of the Rocket Plane strake the shape correction and smoothing will be need

Because of the problem definition all chosen design variables describe the geometry of the strake. For different sets of computation, different numbers of design variables were chosen. Fig. 11 presents definition of the length section which was used as a one of design variables.

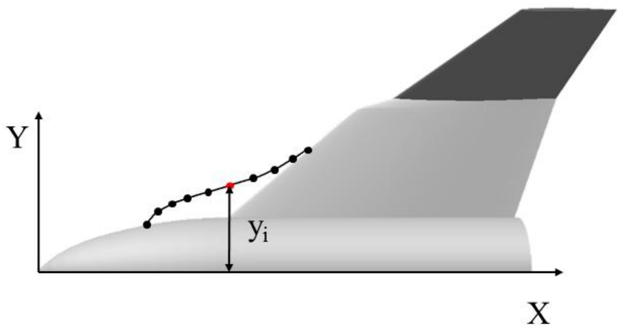

Fig. 11 Strake's geometry definition by the sections

4.4 Objective function

The objective function included only aerodynamic coefficients, the other aspect of aircraft design was not considered. For almost all computation cases the objective function which describes the search of the maximum lift coefficient was used. The equation (2) presents the objective function.

$$OF = 1/C_L \qquad (2)$$

For the selected cases the objective function was modified. The part of the pitching moment coefficient was added (see equation 3).

$$OF = 1/C_L+|C_{MY}| \qquad (3)$$

4.5 Design parameters

As a design parameter the angle of attack was chosen. For all computational cases a few values of the angle of attack were used. The range was established between 26 and 40 deg.

5 Results

As was mentioned in the paragraph 2, aerodynamic design of the strake was started form the base model of the Rocket Plane. The layout of the base model which always includes the triangular strake's shape is presented in Fig. 12

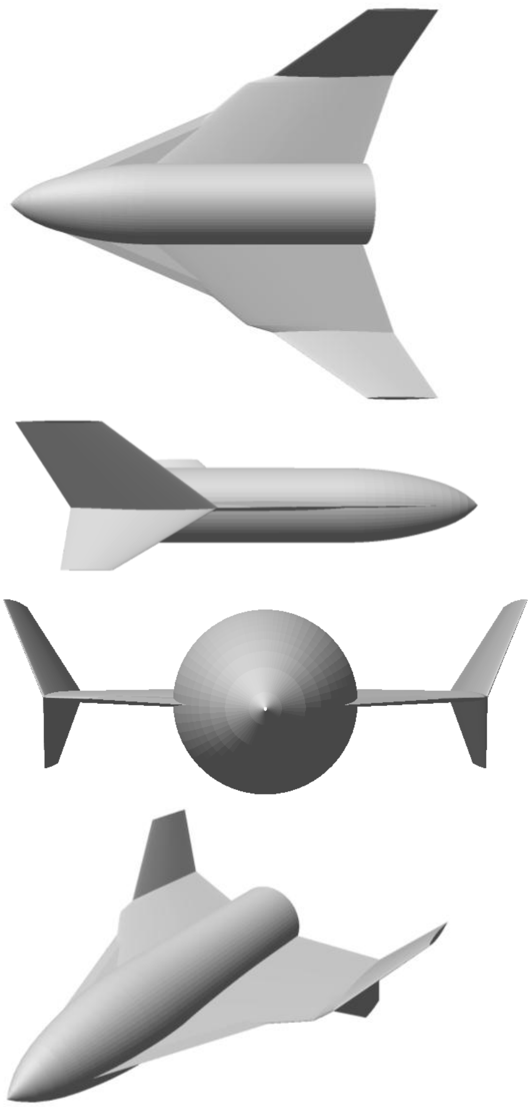

Fig. 13 The layout of the initial geometry of the Rocket Plane

A set of optimization process were made. They were made for different design parameters. As a result of the optimization process different shapes of the Rocket Plane's strake were obtained. The resulting geometries are presented in Fig. 15 to Fig. 14

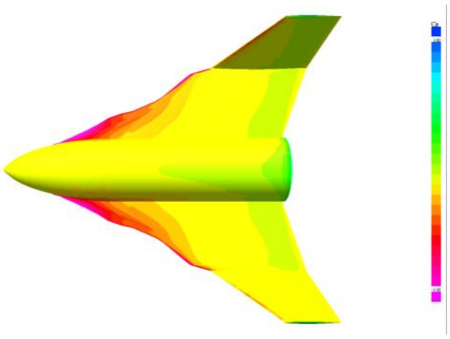

Fig. 15 Cp distribution for design parameter AoA=26[deg]

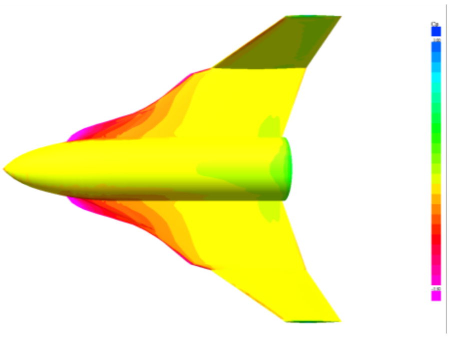

Fig. 16 Cp distribution for design parameter AoA=a30[deg] model6

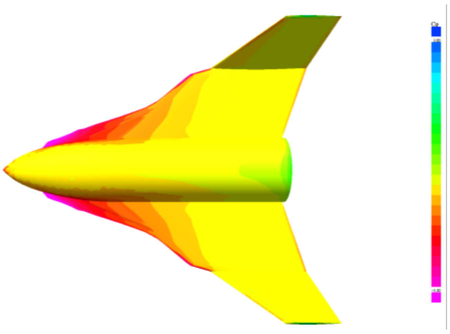

Fig. 17 Cp distribution for design parameter AoA=38[deg]

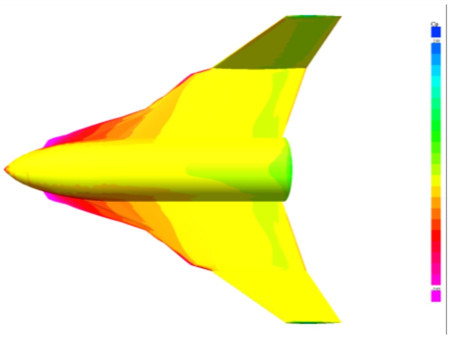

Fig. 18 Cp distribution for design parameter AoA=40[deg]

The Conclusions reveal:

- The optimization process were conducted for a few design parameters, the obtained shapes are different however the aerodynamic characteristics are similar.
- The lift coefficient increasing respect to the initial configuration is negligible. Also the change of other aerodynamic coefficients is insignificant.
- Probably the cause of not satisfying results is too short length of the strake's edge.

To analyze a relationship between models optimized for different design parameters the Average Sweep Angle -ASA was established. This parameter describes the average value of the sweep angle of the strake edge. Fig. 19 presents the course of analyzed parameter.

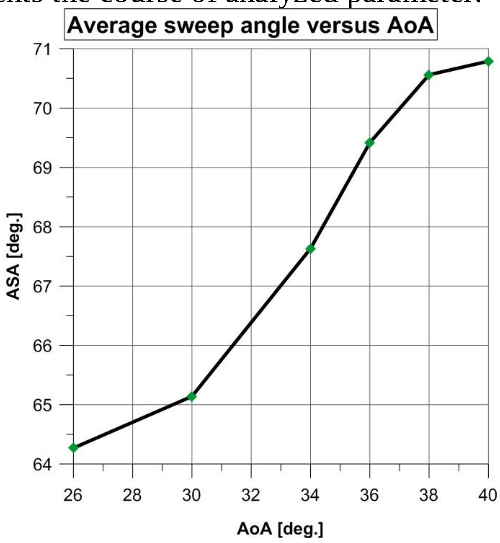

Fig. 19 ASA - Average Sweep Angle vs. design parameter

The change of the design parameter reveals increasing in the ASA parameter. The Fig. 20 presents the change of wetted area parameter versus design parameter. Increase in Sw/S means that the total wetted area of the Rocket Plane increased.

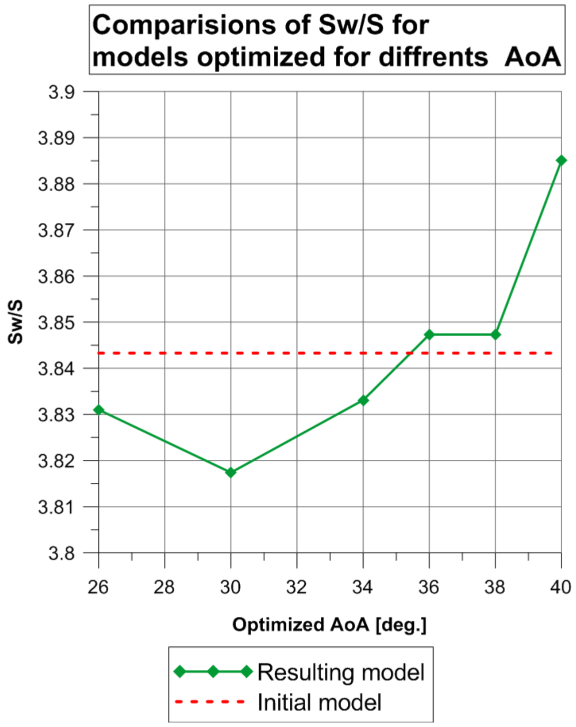

Fig. 20 Wetted area parameter vs. design parameter

To validate these results second software solving Navier-Stokes equations was used. Selected models were computed by ANSYS Fluent 14.0. The obtained results confirmed previous analysis. The vortex flow visualizations over the Rocket Plane and the pressure distribution for the Rocket Plane are presented in Fig. 21.

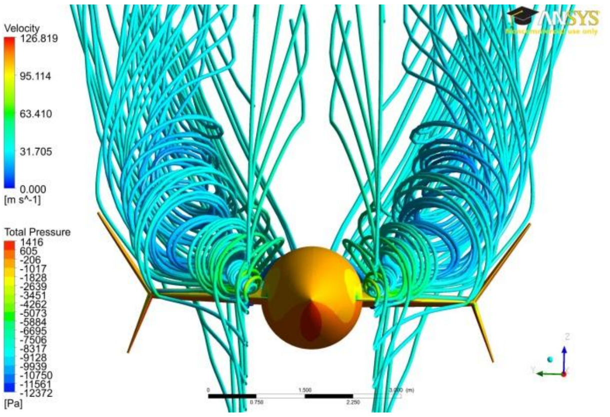

Fig. 21 Vortex flow visualization over the Rocket Plane model no 6 and pressure coefficient distribution on the Rocket Plane. Calculation conditions: Ma=0.1, Re=10.5M and AoA=30 degree

The results of the optimization process show the direction of next modification of the Rocket Plane strake. The strake's edge length increased was caused by the decreasing in the strake's sweep angle. It means that the strake was extended backward. The results of the modification are increasing in the total strake's area. Other components like the fuselage, wing etc. remained unchanged. The new base model (MODEL No 2) of the Rocket Plane is presented in Fig. 22.

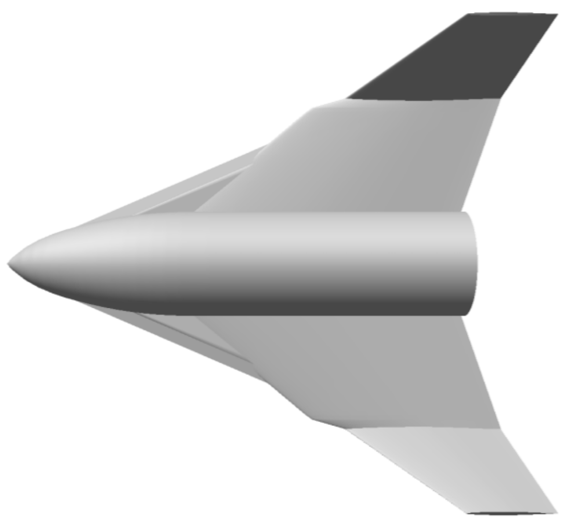

Fig. 23 Next generation of Rocket Plane model

The computation was conducted only for the one design parameter - the angle of attack equal 30 deg. As a result of computation the shape of the strake is presented in Fig. 24. The Cp distribution for the resulting geometry of the Model No 2 is presented in Fig. 25.

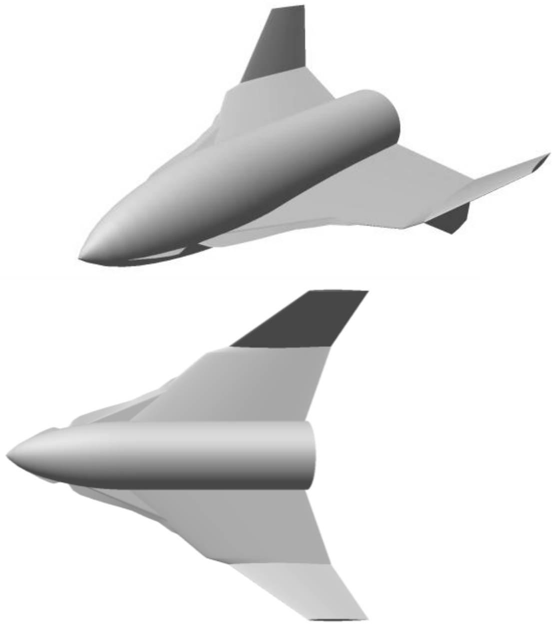

Fig. 24 Resulting geometry of next generations

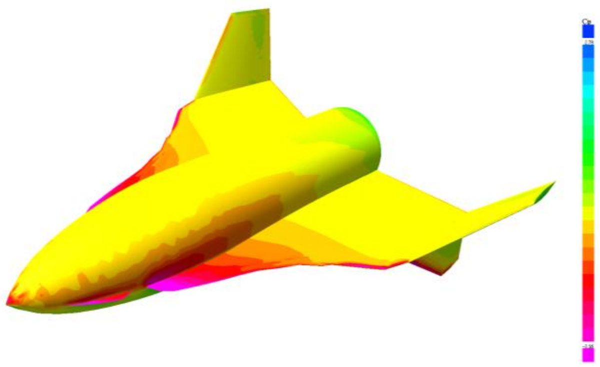

Fig. 25 Cp distribution for next generation model of Rocket Plane AoA=30[deg]

The analysis of results reveals that:

- The shape of resulting geometry is similar to the previous shape (see Fig. 16) but an additional part of the strake occurs on the front part of the fuselage.
- The change of the value of aerodynamic coefficient is negligible respect to the base model.

Analysis of previous computation reveals that there is no possibility for further modification of the strake's shape. This conception was fulfilled. It was caused by the limited length of fuselage. The length of fuselage impact on the pitching moment significantly.

One of the possible modifications is a change the fuselage's cross section. Fig. 26 presents a proposal of description of the fuselage's cross section. It was described by super-ellipse [20]. The super-ellipse is defined by the factors which were selected, in such a way, to satisfy the previous circle section. It means that the new cross section area is greater than the old one. This very important issue is caused by the passengers' cabin arrangement. The comparison of the cross section of the fuselage described by super-ellipse and the old one is presented in Fig. 26.

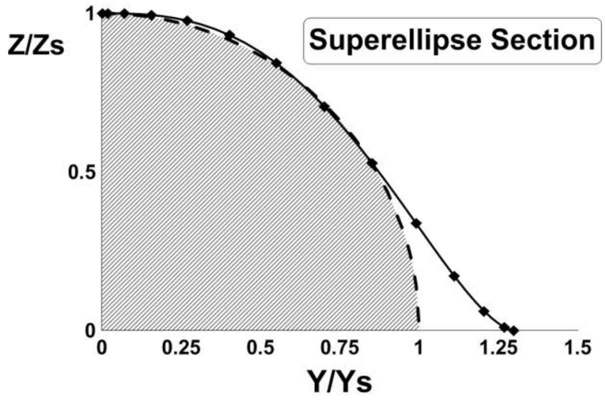

Fig. 26 Example of the fuselage shape defined by the super- ellipse.

The new geometry of the Rocket Plane (Model No 3) with the new concept of the fuselage is presented in Fig. 27 and Fig. 28.

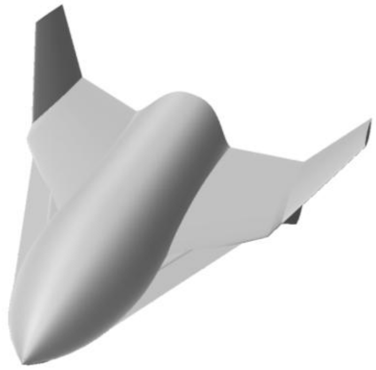

Fig. 27 The new geometry of the Rocket Plane's fuselage – Model No 3

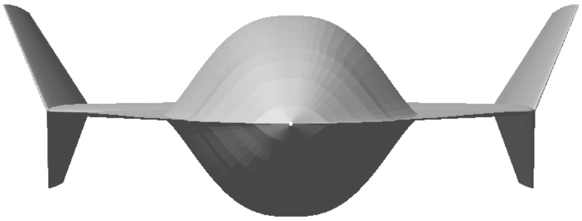

Fig. 28 Front view of the next generation of the Rocket Plane Model No 3

The computation was performed for the two angles of attack: AoA=30 deg and AoA=38 deg. The resulting geometry for design parameter AoA=30 deg. is presented in Fig. 29. During optimization process both the strake and the front part of the fuselage were optimized.

The resulting geometry for design parameters AoA=30 and the CP distribution for analyzed model are presented in Fig. 31 and Fig. 30.

Fig. 29 The resulting geometry of the Rocket Plane for AoA=30[deg]

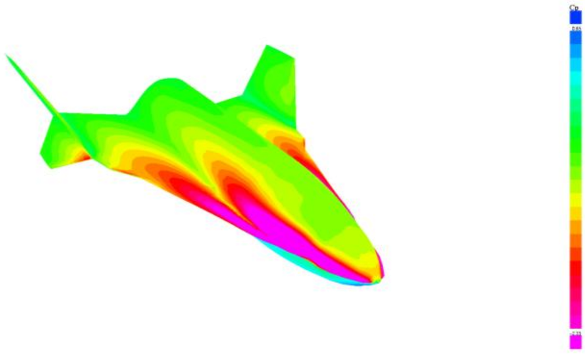

Fig. 30 Cp distribution for the Rocket Plane Model No 3 AoA=30deg

The resulting geometry and the Cp coefficient distribution for design parameters AoA=38 deg is presented in Fig. 31.

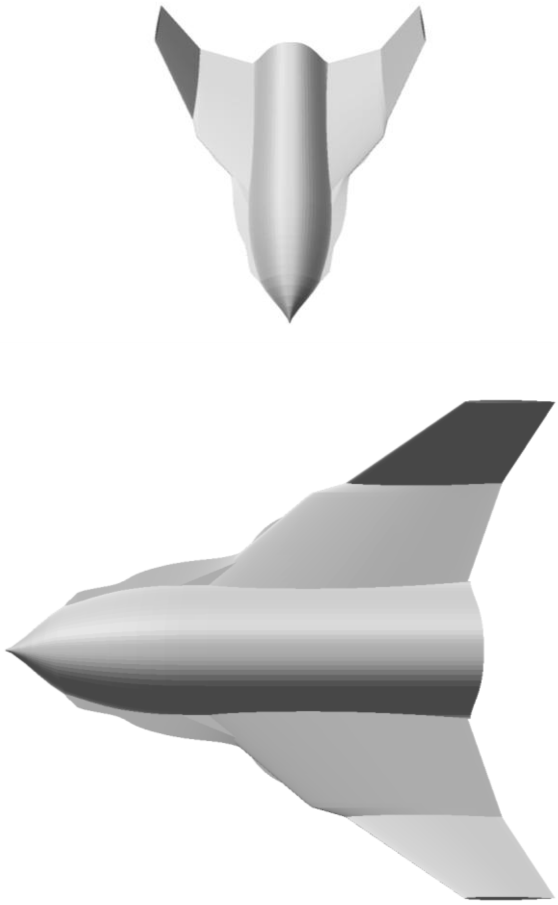

Fig. 31 The resulting geometry for Rocket Plane with smoothed shape of the strake for design parameter AoA=38deg

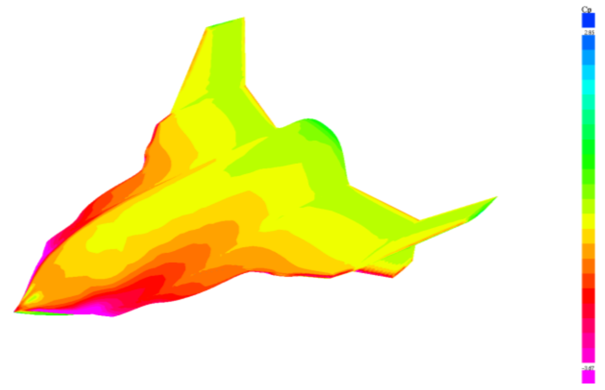

Fig. 32 Cp distribution for resulting geometry of the rocket plane

Fig. 33 to Fig. 35 present aerodynamic characteristic of the last modification of the Rocket Plane's geometry. Moreover, results were compared with the results of the previous models (with the circular cross section of the fuselage).

The significant difference of the aerodynamic coefficients was obtained. Especially, maximum lift coefficient's increase respect to the previous model was observed. However, the static margin decreased but it was caused by the fuselage geometry modification especially its front part (see Fig. 31).

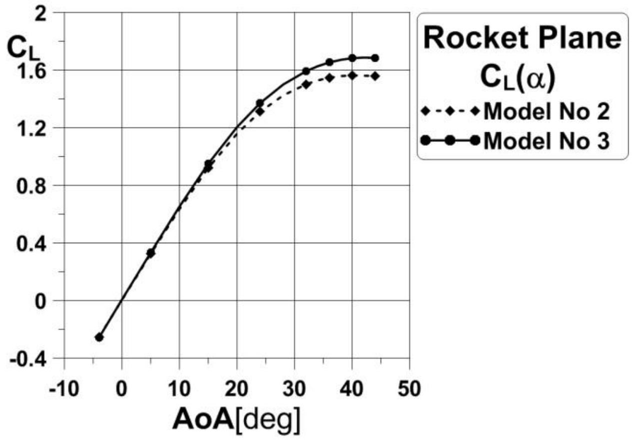

Fig. 33 Lift force coefficient versus angle of attack – comparison of Model No2 and Model No 3

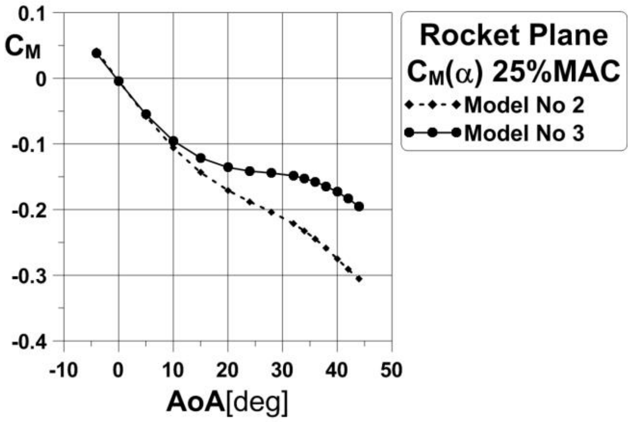

Fig. 34 Pitching moment vs. angle of attack for the Rocket Plane Model No 2 and Model No 3

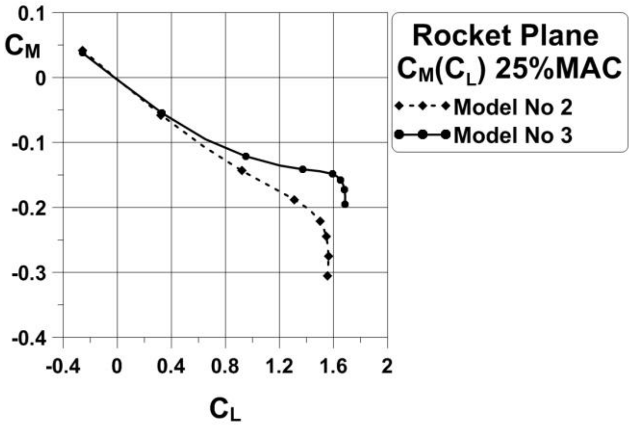

Fig. 35 Pitching moment vs. lift coefficient for The Rocket Plane Model No 2 and No 3

6 Conclusions

The optimization of the Rocket Plane was a challenge. A lot of constrains like geometry of the wing and the fuselage were settled. A lot of calculations were made to obtain presented results. The preliminary calculation (Model No 2) reviled not satisfying results. It was caused by negligible value of aerodynamic coefficients' increase. Only the knowledge about changing the geometry of the strake respect to the design parameters was obtained. Decision about the strake's and the fuselage's geometry modification was taken after analyzing results of the previous steps in the optimization process. The choice of the super-ellipse as a new definition of the fuselage's cross section (Model No 3) was a right. It improved the Rocket Plane's aerodynamic characteristic significantly what was the main goal of whole optimization process.

Nomenclature:

AoA –Angle of Attack
ASA – Average Sweep Angle
C_D – drag force coefficient
C_L – lift force coefficient
C_M – pitching moment coefficient
Cp – pressure coefficient
K – number of iteration
LEX – Leading Edge Extension
p – direction vector
S_w/S – wetted area to reference area ratio
x – design step vector
α – step's length

References

[1] Futron Corporation "Space Tourism Market Study orbital space travel & destinations with suborbital space travel", October 2002
[2] http://www.scaled.com/projects/tierone/
[3] Galiński C., Goetzendorf-Grabowski T., Mieszalski D., Stefanek Ł. A concept of two-staged spaceplane for suborbital tourism. *Transactions of the Institute of Aviation*, Vol.191, No. 4/2007, pp. 33-42.
[4] Figat M., Galiński C., Kwiek A. Modular Aeroplane System. A concept and initial investigation. *Proceedings of 28th ICAS*, Brisbane, paper number ICAS 2012-1.3.2, 2012
[5] Figat M., Galiński C., Kwiek A. Aeroplane Coupled
[6] System to Space Tourism. *Progress in Aeronautics Vol32 No. 1 pp 23-37 ,2011*
[7] Kwiek A. Initial optimization of the strake for the rocket plane. *AIAA Pegasus Student Conference*, Poitiers, 2012
[8] Kwiek A., Figat M. Study on influence of deflected strake on the rocket plane aerodynamic characteristics. *Proceedings of 4th CEAS 2013 Air & Space Conference in Linköping*, paper number 10, pp. 7-16, 2013
[9] Lamar J.E., Neal Frink N.T. Experimental and Analytical Study of the Longitudinal Aerodynamic Characteristics of Analytically and Empirically Designed Strake-Wing Configuration at Subcritical Speeds. *NASA Technical Paper 1803*
[10] Ahmad Z. Al.-Garni, Farooq Saeed, Abullah M. Al-Garni, Ayman Abdullah and Ayman Kassem, Experimental and Numerical Investigation of 65-deg delta and 65/40-deg Double Delta Wings. *44th AIAA Aerospace meeting & Exhibit, Reno*, AIAA Paper 2006-0063 January 2006,
[11] Frink N. T., Lamar J. E. Analysis of Strake Vortex Breakdown Characteristics in Relation of Design Features. *Journal of Aircraft* Vol. 18, No. 4, April 1981
[12] Lamar J. E., Frink N.T. Aerodynamic Features of Design Strake-Wing Configuration. *Journal of Aircraft* Vol. 19, No. 8, August 1982
[13] Mitchell A. M., Delery J. Research Into Vortex Breakdown Control, *Progress in Aerospace Sciences* 36 (2001) 385-418
[14] Rao Dhanvada M. Vortical Flow Management for Improved Configuration Aerodynamic
[15] Luckring J. M. Reynolds Number, Compressibility, and Leading-Edge Bluntness Effect on Delta Wing Aerodynamics, *24th International Congress of the Aeronautical Sciences*, 2004.
[16] Luckring J.M. Aerodynamics of Strake-Wing Interaction. *Journal of Aircraft* Vol. 16, No. 11, November 1979
[17] Nocedal J., Wright S.J. *Numerical optimization*, Springer 1999
[18] MGAERO user's manual Version 3.1.4
[19] Mavriplis D.J. Three-Dimensional Unstructured Multigrid for the Euler Equations, *Journal of Aircraft*, Vol. 30, No 7, July 1992
[20] Gundlach J. *Designing Unmanned Aircraft System: A Comprehensive Approach*, Chapter 4, AIAA Education Series American Institute of Aeronautics and Astronautics, 2012

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