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Influence of a slotted flap gap size on the aerodynamic characteristics of a light aircraft wing at taking off and landing

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Abstract— The purpose of the study is to examine the impact of the gap size of a slotted flap on the aerodynamic characteristics of a light aircraft wing at take-off and landing. All surveys in the paper are numerical, executed in Ansys Fluent, using transient analysis and dynamic mesh method. The models used are 2 dimensional. Statements are made for the aerodynamic efficiency of a wing with a slotted flap, depending on the slot size. Optimal gap size is defined, for a specific wing configuration. Comparisons between the different slotted flap configurations and a plain flap wing design are made. The main goal of this study is the evaluation of the gap size of a slotted flap wing design upon the aerodynamic efficiency and determination of an optimal gap size for the examined wing.

Keywords— *wing airfoil, slotted flap gap, high lift devices, CFD simulation, dynamic mesh, sliding mesh, Wing mechanization*

I. INTRODUCTION

Flaps are high-lift devices used to increase the lift force of an aircraft wing [1]. Flaps are usually mounted on the wing trailing edges of a fixed-wing aircraft and they are used for extra lift on take-off and landing stages. Extending the wing flaps increases the wing area, which aids the generation of the required lift force at low speeds of the aircraft.

$$L = \frac{1}{2} \rho V^2 S c_L, \quad (1)$$

This is the exact essence of the wing flap – required amount of lift force, generated at low speed, by increasing the area of the wing. The increase in the wing area also increases the wing drag.

$$D = \frac{1}{2} \rho V^2 S c_D \quad (2)$$

Extra drag can be beneficial during landing, because it slows the aircraft. During cruising flight, the drag force is undesirable and flaps are retracted.

Considering this brief introduction of wing flaps, one can conclude, that wing flaps are used during take-off and landing. The deflection angle of the flaps during take off is 20° estimated. The flaps deflect up to an angle of 40°, during landing, due to the required high drag [1].

The current paper focuses on slotted flap designs [2], [3] (Fig.1) and specifically on the influence of gap size

on the aerodynamic characteristics of the wing with a slotted flap.

SLOTTED FLAP

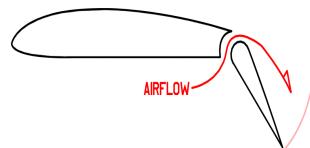


Fig. 1. Slotted flap

References [4], [5], [6] show that there is no unified method for defining an optimal gap size of the slotted flap. In the current study, surveys on the NACA2412 (Fig.2) [7] airfoil are executed. Wings for airplane such as Cessna 172 [8] are designed using NACA2412 airfoil.



Fig. 2. NACA 2412 Airfoil

In order to define an optimal gap size of a slotted flap design, a sequence of numerical simulations, performed in Fluent Ansys, are made. First several slotted flap wing configurations are designed in SolidWorks, differing in the gap size and angle of deflection - 20° for take-off stage and 40° for landing stage. Two main approaches are performed:

- A sequence of transient analysis is executed, using sliding mesh method, defining the aerodynamic characteristics, for a range of angles of attack, for different slotted flap configurations. The angle of attack is variable in time and the gap size is fixed.
- A sequence of transient analysis is executed, using dynamic mesh method, defining the aerodynamic characteristics for a range of gap sizes. The slotted flap gap size is variable in time and the angle of attack is fixed.

Relying on the described method, important wing design decisions could be made.

II. MODEL DESCRIPTION

A. Geometric model

In the current studies, a 2D plane model is chosen in order to reduce the computational time and to improve the result accuracy. No finite wing effects like wing tip vortices [1] or fuselage induced drag are considered. As mentioned several slotted flaps are designed, based on the NACA2412 airfoil (Fig.3).



Fig. 3 2D plane model of NACA 2412 a slotted flap with gap size 10% of the main chord and angle of deflection 40°

The length of the main chord of the 2D wing is 1m. The designs differ in 2 parameters: the gap size, which with respect to the main chord length of the wing is as follows: 0% (a plain flap), 4%, 10%, 18%, 26% and 32%. The second parameter is the deflection angle: 20° (lift-off) and 40° (landing). The dimensions of the computational domain are as follows: 26m height, 50m length and 2m diameter of the rotating sector. The models are simulated for relative velocity of 160 km/h (44.4 m/s).

B. Numerical Modeling

The described models are implemented in Ansys Fluent. The software solves numerically, the governing equations of fluid-dynamics: the Continuity equation (3), the Navier-Stokes' equations (4) and the Energy equation (5) [1], using Finite Volume Method (FVM) [9]. In the most general form, the equations are:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{V}) = 0 \quad (3)$$

$$\frac{\partial(\rho \vec{V})}{\partial t} + \nabla(\rho \vec{V} \cdot \vec{V}) = -\nabla p + \rho \vec{g} - \rho \vec{\omega} \times \vec{V} + g \rho \vec{T} + \nabla(\mu \nabla \cdot \vec{V}) \quad (4)$$

$$\begin{aligned} \frac{\partial}{\partial t} \left[\rho \left(e + \frac{V^2}{2} \right) V \right] + \nabla \cdot \left[\rho \left(e + \frac{V^2}{2} \right) V \right] = \\ \rho \vec{q} \cdot \nabla(p \vec{V}) + \rho \vec{f} \cdot \vec{V} + Q_{\text{viscous}} + W_{\text{viscous}} \end{aligned} \quad (5)$$

Depending on the assumptions of the real physical system, the equations are modified in a more specific form. For the current study, the following assumptions are made:

- the air is assumed to be incompressible - with a constant density;
- the fluid is considered to have isotropic viscosity ;
- Spalart-Allmaras turbulence model is used [10]. The turbulence model adds an additional equation to the system of Partial Differential Equations (PDE);
- No heat transfer is considered;

The assumptions made, result in the following system of PDE

$$\begin{aligned} \nabla \cdot \vec{V} &= 0 \\ \frac{\partial \vec{V}}{\partial t} + \vec{V} \cdot \nabla \vec{V} &= \vec{f} - \nabla \left(\frac{p}{\rho} \right) + \nu A \vec{V} \\ \frac{\partial \tilde{v}}{\partial t} + u_j \frac{\partial \tilde{v}}{\partial x_i} &= C_{b1} [I - f_{t2}] + \frac{1}{\sigma} \left[\nabla \cdot [(\nu + \tilde{v}) \nabla \tilde{v}] + C_{b2} |\nabla \tilde{v}|^2 \right] - \\ \left[C_{w1} f_1 - \frac{C_{b1}}{k^2} f_{t2} \right] \left(\frac{\tilde{v}}{d} \right)^2 + f_{t1} A U^2 \end{aligned} \quad (6)$$

Where $\sigma=2/3$, $C_{b1}=0.1355$, $C_{b2}=0.622$, $k=0.41$, $C_{w1}=C_{b1}/k^2+(1+C_{b2})/\sigma$, $C_{w1}=0.3$ are coefficients of Spalart-Allmaras turbulence model [10].

As mentioned two major sequences of surveys are executed. The 1st type of surveys is based on the sliding mesh method. The wing cross section is placed in a rotating domain (fig.2). This approach allows the calculation of the aerodynamic parameters for different angles of attack – particularly for a range of angles of attack $\alpha=0^\circ-18^\circ$. The rotating domain rotates relatively slowly in order to avoid disturbances in the flow, due to the rotation of the domain. The angular velocity of the domain is $\omega=0.017\text{rad/s}$. The finite element mesh is based on the principles published by Ansys [12] and is shown in (Fig.4)

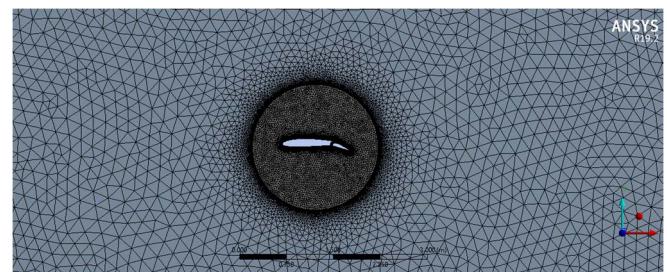


Fig. 4. Finite element mesh for 2D NACA 2412 wing-slotted flap model (gap size 40mm, $\delta_r = 20^\circ$).

The 2nd type of surveys executed in the current study is based on dynamic mesh method. In this approach the angle of attack is fixed - 11° and the wing flap itself moves – translates, expanding the gap size between the wing and the flap. This approach, allows the calculation of the aerodynamic parameters of the slotted flap wing design, for a wide – continuous range of gap sizes - from 0% to 30% of the main chord, for a fixed angle of attack. In order to avoid disturbances in the flow due to the motion of the wing flap, the translation velocity of the flap is set to be 0.01m/s. Transient analysis is executed for physical time of 30 seconds with a time step of 0.0025 seconds. A UDF is compiled from a source file, using Microsoft Visual Studio [11]. A sample of the dynamic remeshing, for different time steps, is shown in (Fig.5).

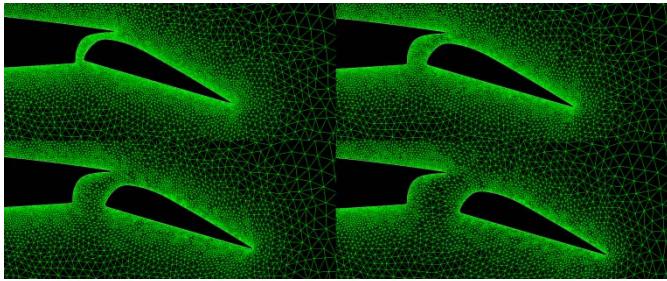


Fig. 5. Dynamic remeshing of a slotted flap, with angle of deflection $\delta_f = 20^\circ$, for fixed angle of attack for four different time steps.

III. RESULTS AND ANALYSIS

The coupling of the results from the first sequence of surveys, for all gap sizes - 0% (a plain flap), 4%, 10%, 18%, 26% and 32%, for angle of deflection 20° is shown in (Fig.6), (Fig.7) and (Fig.8).

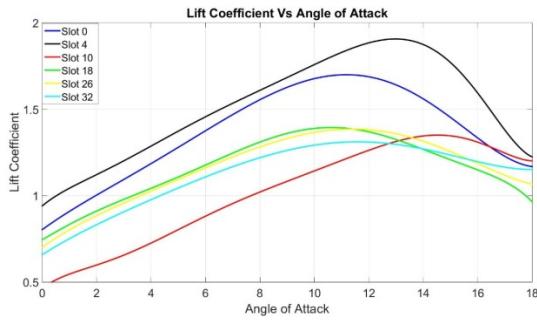


Fig. 6. Lift coefficient CL as a function of the angle of attack α , for deflection angle $\delta_f = 20^\circ$.

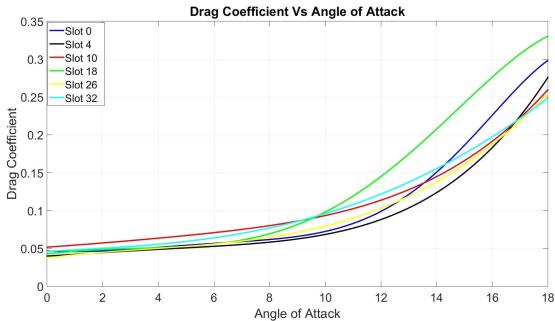


Fig. 7. Drag coefficient CD as a function of the angle of attack α , for deflection angle $\delta_f = 20^\circ$.

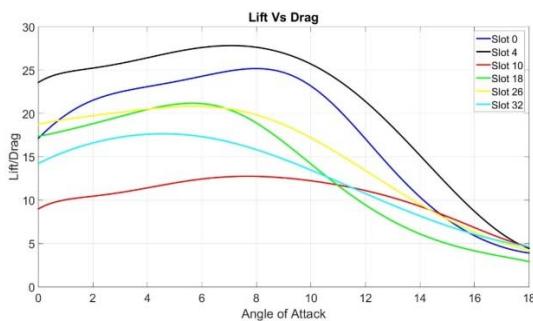


Fig. 8. Lift to Drag ratio as a function of the angle of attack α , for deflection angle $\delta_f = 20^\circ$.

The coupling of the results from the first sequence of surveys, for all gap sizes - 0% (a plain flap), 4%, 10%, 18%, 26% and 32%, for angle of deflection 40° is shown in (fig.9), (fig.10) and (fig.11).

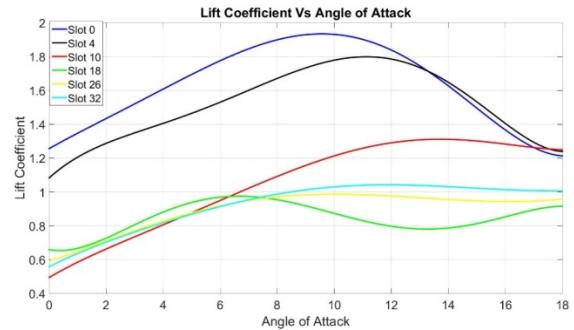


Fig. 9. Lift coefficient CL as a function of the angle of attack α , for deflection angle $\delta_f = 40^\circ$.

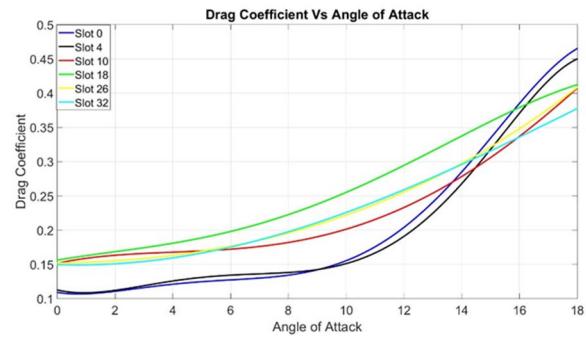


Fig. 10. Drag coefficient CL as a function of the angle of attack α , for deflection angle $\delta_f = 40^\circ$.

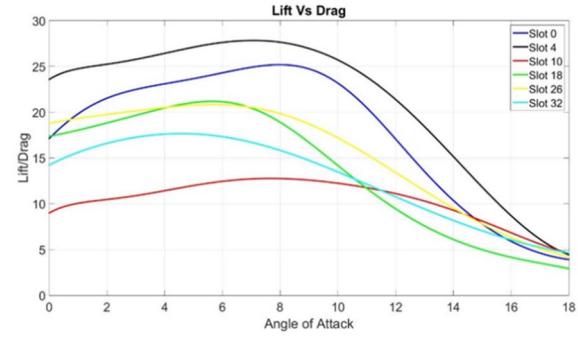


Fig. 11. Lift to Drag ratio as a function of the angle of attack α , for deflection angle $\delta_f = 40^\circ$.

One can clearly establish, that the slotted flap with gap size of 4% has optimal aerodynamic parameters, comparing to the other configurations. The plain flap shows second best characteristics. In the case of deflection angle 40° , the plain flap and slotted flap 4% have very similar aerodynamic characteristics. It is interesting to mention that the design with a gap size of 10% show worst aerodynamic characteristics. This phenomenon will be explained later in the publication.

The second type of calculations gave the following results. (fig.12) shows the variance in the lift coefficient for angle of deflection 20° (lift-off stage) and 40° (landing stage) as a function of the gap size.

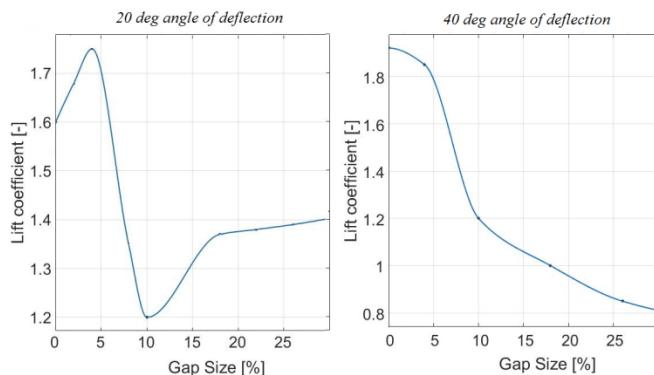


Fig. 12 a) Lift coefficient as a function of the gap size for an angle of deflection 20°; Fig. 12 b) Lift coefficient as a function of the gap size for an angle of deflection 40°

The increase in the lift force, for small gap sizes can be understood by analysing the pressure and velocity distribution around the wing airfoil. Looking at (fig.13) one can see that for very small range of gap sizes (1% - 5% of the main chord length), the flow passing through the slot, has relatively high speed and low pressure, keeping flow on the upper surface of the airfoil attached. When the gap size increases (6% - 12% of the main chord length) (fig. 14) the pressure of the passing through the gap flow increases, separating the flow on the upper surface of the wing, which results in a lift drop.

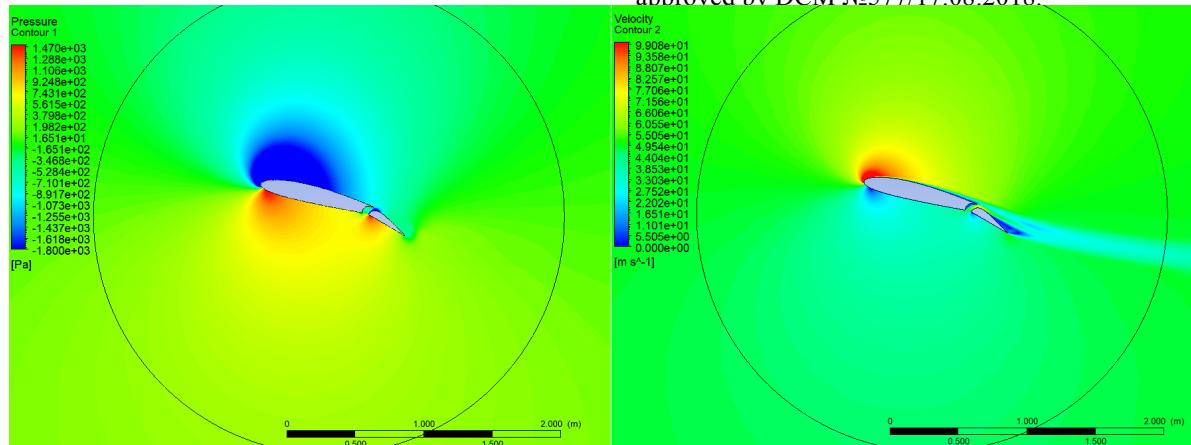


Fig. 13. Pressure and velocity fields for a gap size of 4% of the main chord length.

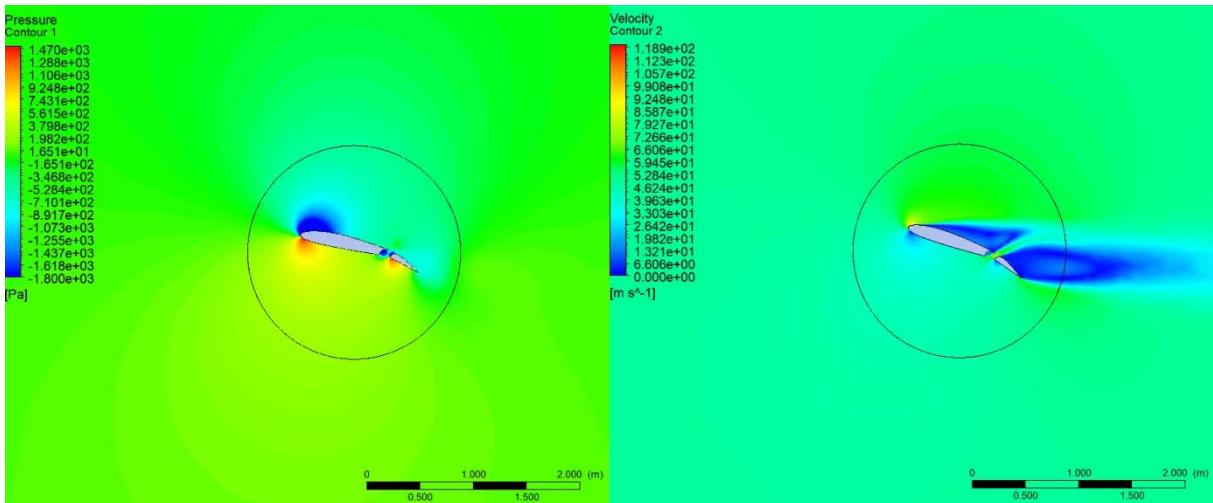


Fig. 14. Pressure and velocity fields for a gap size of 10% of the main chord length.

IV. CONCLUSION

The results from the described surveys, suggest that an optimal gap size for NACA2412 slotted flap wing design is close to 4% of the main chord length, for both flying stages – take-off (deflection angle of 20°) and landing (deflection angle of 40°). The results show lift drop for gap sizes close to 5-10% of the main chord length, due to pressure increase of the flow passing through the slot. The executed surveys are particular for NACA2412 airfoil and the established conclusions should not be accepted for all wing configurations. However the described sequence of surveys performed in Ansys Fluent, using sliding mesh method and dynamic mesh method, would be applicable for large range of aerospace engineering surveys and could be executed for various wing configurations and designs. Based on similar numerical results, important wing design decisions could be made.

ACKNOWLEDGMENT

This work was supported by the Bulgarian Ministry of Education and Science under the National Research Program E+ „Low carbon energy for transport and live”, approved by DCM №577/17.08.2018.

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