Analysis of the impact of trailing-edge wing flaps on the aerodynamic characteristics and performance of the Diamond DA-20 aircraft

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Abstract. One of the factors affecting the aerodynamics and performance of aircraft profiles are flaps. The work presents the influence of selected types of flaps on Diamond DA-20 properties. The aircraft aerodynamics is described in detail. Furthermore, the three types of steady flight are presented and the ways of calculating the basic performance of the airplane are taken into consideration. The techniques used to carry out the research are discussed, the conclusions are drawn and the final results are presented. The aim of this article was to analyse the influence of trailing-edge wing flaps on the aerodynamic characteristics and performance of the Diamond DA-20 aircraft. The research focused on the aircraft in smooth configuration and with four types of trailing-edge wing flaps: pop-up, split flap, single-slotted flap and double-slotted flap in 15° and 45° positions.

1. Introduction
The dynamic development of new technologies made the design and testing of the aerodynamic properties of new types of aircraft much more efficient and less costly than in the past. Thanks to more and more advanced engineering tools, it is possible to precisely design and conduct thorough research, and improve designs to achieve the desired results. In many works, the aerodynamic characteristics of aircraft were studied using the CFD method. The study [1] presents tests of aerodynamic forces and moments generated on individual autogyro elements. The effect of a sideslip angle on the load of the gyrocopter stabilizer with an inverted twin tail is examined in the work [2] and aerodynamic forces acting on vertical and horizontal stabilizers as well as pressure distribution on their surfaces are obtained. Gyroplane longitudinal static stability for the selected stabilizer angles was also studied [3]. A CFD method was also applied to evaluate how the main rotor, its configuration and flight conditions influence gyrocopter aerodynamic characteristics and stability [4]. It was found that the airflow generated by the main rotor changes the most important aerodynamic coefficients and stability derivatives of the gyroplane body. The work [5] presents the methodology of designing and optimising gyroplane rotors with a CFD method. The authors in [6] used a CFD technique to create a dynamic model of the designed unmanned gyrocopter. Such an approach shortens the design process so the aircraft can be produced faster, and thus faster complete its assigned tasks, e.g. cargo transport or agro tasks[7-8].

In this work, the impact of four types of trailing-edge wing flaps on the aerodynamic characteristics and performance of the Diamond DA 20, a light performance aircraft for private use and basic flight training, has been investigated [9].
The aerodynamic tests of the aircraft are performed in wind tunnels. They consist in measuring absolute values of aerodynamic forces or moments acting on the tested object depending on the angle of attack. The obtained values are converted into coefficients (lift force, drag force, etc.), and on their basis tables and diagrams - the so-called aerodynamic characteristics - are drawn up [10]. An example of such research is the work [9] that presents an experimental gyroplane study including aerodynamic characteristics, the pitch moment coefficient in relation to an angle of attack for various gyroplane configurations (with and without a tail). Another example of the wind tunnel research are works [12-14] in which the Particle Image Velocimetry (PIV) method is used to visualise the velocity field around the gyroplane. This method can also be used to analyse the aerodynamics of the wing [15-16]. The basic aerodynamic characteristics should include:

- dependence of the lift force coefficient on the angle of attack, \( c_l = f(\alpha) \),
- dependence of the drag force coefficient on the angle of attack, \( c_d = f(\alpha) \),
- lift-to-drag ratio \( K = f(\alpha) \),
- polar curve \( c_z = f(c_l) \).

The main factor that influences the aerodynamic characteristics is the shape of the aircraft. Lift-to-drag ratio \( K \) as in equation (1) is expressed by the ratio of lift force to drag force, or the ratios of \( c_l \) and \( c_z \) [17]. The shape of curve \( K = f(\alpha) \) is similar to curve \( c_z = f(\alpha) \). The lift-to-drag ratio changes as the angle of attack changes [18]. The highest value is taken for the optimal angle of attack of \( \alpha_{opt} \).

\[
K = \frac{p_z}{p_x} = \frac{c_z}{c_x}
\]  

(1)

The polar curve of the aircraft, also called the Lilienthal curve, is the diagram of the dependence of the lift force coefficient to the drag force coefficient. This curve is plotted from the characteristics of \( c_z = f(\alpha) \) and \( c_x = f(\alpha) \).

The polar curve is very important for calculating the performance of an aircraft [17]. Each of its points corresponds to a specific angle of attack. On the Lilienthal curve several characteristic points can be distinguished:

- \( \alpha_0 \) – zero-lift angle - for this angle the aircraft can only rise almost vertically or dive almost vertically,
- \( \alpha_{c, \text{min}} \) – the angle of attack at which coefficient \( c_z \) reaches its lowest value - the plane reaches its maximum speed for this angle in horizontal flight,
- \( \alpha_{opt} \) – the optimum angle of attack - the angle of attack for which lift-to-drag ratio \( K \) reaches its highest value; this point is the point of contact between the curve and the straight line passing through the beginning of the coordinate system,
- \( \alpha_{cr} \) – the critical angle of attack - the angle of attack for which coefficient \( c_z \) reaches its maximum value.

The lift force generated by aircraft wings depends on the shape of an airfoil, the area of the lifting surface and the speed of the aircraft in relation to the air. During take-off and landing, the speed of the aircraft is relatively low, so to obtain the required value of lift force, devices are used to change airfoil shapes, the area of the lifting surface and circulation – so-called wing mechanisation elements. Such devices include trailing-edge wing flaps. These are narrow elements located at the edge of wings. Their main task is to increase the lift force on the wing [19]. As a result of flap deflection, the \( c_{z, \text{max}} \) value is increased and the angle of attack for a given value of the lift force coefficient is decreased. An increase in the \( c_{z, \text{max}} \) value results in a decrease in stall speed. The deflection of flaps is also accompanied by an increase in the drag force coefficient, and as a result, despite the increase in the \( c_{z, \text{max}} \) value, lift-to-drag ratio \( K \) decreases.

The increase in the load factor value, \( \Delta c_{z, \text{max}} \), is dependent on the swing angle of trailing-edge wing flaps and reaches a maximum of approximately 60° [20]. Different types of trailing-edge wing flaps are used in aviation. They differ for their design and influence on changes in the aerodynamic force coefficient [21]. Trailing-edge wing flaps were well researched [22-26]. Such solutions can also be used in wind turbine blades [27]. An example of a flap located on a trailing edge of wings is the Gurney flap.
The issue of aerodynamics of airfoils with the Gurney flap was investigated in the works [29-31]. The combination of the Gurney flap with the trailing-edge flap was investigated in the papers [32-33]. There are also flaps at the end of the wing [34]. The wingtip can also be modified by using winglets, i.e. non-movable elements that change the geometry and thus aerodynamic performance [35-36].

2. Research object
The research object is the Diamond DA20-C1 aircraft (Figure 1). It is a two-seat lightweight semi-aircraft with the T-type impact, designed for basic aviation training, manufactured by Diamond Aircraft Industries.

The fuselage and wings are made of composite reinforced with glass fibre and polymer cover [38]. The Wortmann FX 63-137/20 laminar airfoil with the following parameters was used to construct the wings:

- maximum thickness of 13.7% at 30.9% chord,
- maximum arrow 6% at 53.3% chord [39].

Single-slotted flaps are mounted on the wings, swivelling by 15° in the "take-off" and 45° in "landing" position [38][40]. The DA20-C1 three-support undercarriage is made up of two undercarriage wheels fixed to an aluminium frame and a front-wheel fixed to an elastomer spring [38]. The drive unit consists of a Continental IO-240 boxer piston engine with a capacity of 3.9 litres and a maximum output of 93.2 kW at 2800 rpm, powered by AVGAS 100/100LL aviation gasoline, and a Sensenich twin-blade fixed-pitch propeller driven directly from the engine shaft [38].

For research purposes, a 1:1 scale 3D model of the aircraft in the SolidWorks software was created (Figure 2).
Due to the lack of detailed technical documentation, it was not possible to accurately reproduce the plane. The model was simplified, among others, by omitting the propeller and elements of the construction which are of little importance for the analysis of the airflow (e.g. the antenna). The basic performance of the Diamond DA20-C1 aircraft was calculated by theoretical formulas. The following values of individual parameters were assumed for the calculations:

- Air pressure $p$ at sea level in a standard atmosphere of 1.225 kg/m$^3$,
- Aeroplane weight $G$ equal to the product of maximum aeroplane weight $m$ of 800 kg and mean ground acceleration $g$ of 9.81 m/s$^2$,
- Area of wings $S$ specified by the manufacturer, equal to 11.6 m$^2$,
- Maximum engine power of the Continental IO-240, equal to 93.2 kW,
- Propeller efficiency $\eta$ equal to a standard maximum efficiency of 0.85 [40].

The calculations were made for five different flap solutions. The first configuration is called "smooth configuration". It is a configuration without trailing-edge wing flaps. The next tested solutions of flaps, i.e. vaulting flaps (a), split flaps (b), single-slotted flaps (c), double-slotted flaps (d), are shown in Figure 3.

3. Results of the calculation

3.1. Aircraft in smooth configuration

The load factor takes positive values over the entire range of tested angles of attack (Figure 4). The linear trend of the characteristics can be observed in the range of the angles of attack from -5° to approximately 8°. The critical angle at which the aircraft is stalled is equal to 15° and the corresponding value of the lift force coefficient is 1.443. The stall characteristics are relatively smooth. The aerodynamic drag force coefficient reaches its lowest value for an angle of attack of -3° and is 0.06.
Based on the calculations performed, the lift-to-drag ratio as a function of the angle of attack was also determined. The lift-to-drag ratio increases rapidly in the range of angles of attack from -5° to 3°, reaching the highest value of 10.212 and then decreases rapidly. For the smooth $c_z$ and $c_x$ configurations, corresponding maximum $K_s$ are respectively 0.934 and 0.091.

3.2. Aircraft with vaulting flaps
The lift force coefficient values for both flap deflections are greater over the entire range of tested angles of attack than for the smooth configuration (Figure 5). The critical angle of attack is slightly smaller than the angle for retracted flaps and is 13°. The maximum value of the $c_z$ coefficient is 1.533 for flaps inclined by 15° and 1.634 for 45°, respectively. The stall characteristics is smoother for both flap positions than for the smooth configuration. The swinging of the flaps is accompanied by an increase in the aerodynamic drag force coefficient. The angle of attack for the smallest $c_z$ does not change with the flap deflection and lift -3°. Coefficient $c_{x, \text{min}}$ is equal to 0.077 for a flap deflection of 15° and 0.133 for 45°, respectively.

![Figure 5. Characteristics of $c_z = f(\alpha)$ (left) and $c_x = f(\alpha)$ (right) for configurations with retracted and released flaps at angles of 15° and 45°.](image)

Based on the calculations performed, the lift-to-drag ratio as a function of the angle of attack was also determined. Lift-to-drag ratio $K$ for flaps inclined by 15° takes greater values than for retracted flaps in the range from -5° to -1°. The highest value of the lift-to-drag ratio in this configuration is 9.206. With flaps inclined by 45°, the lift-to-drag ratio is greater than with retracted flaps only for angles smaller than -4°. The maximum value in this configuration is only 6.773. The optimum angle of attack after tilting the flaps remains the same and is equal to 3°.

3.3. Aircraft with split flaps
Lift force coefficient $c_z$ for swinging flaps is significantly greater than for retracted flaps (Figure 6). The maximum value of the $c_z$ coefficient is 1.551 for flaps which are inclined by 15° and 1.651 for 45° respectively and the stall in both cases occurs at an angle of attack of 13°.

As the flaps are tilted, the aerodynamic drag force coefficient increases, as shown in Figure 6. $c_z$ takes the smallest value for an angle of attack of -3° and is equal to 0.080 for 15° and 0.127 for 45°. Based on the calculations performed, the lift-to-drag ratio as a function of the angle of attack was also determined. The lift-to-drag ratio $K$ with ejected flaps is lower over almost the entire range of angles of attack. Exceptions are in the range from -5° to 0° for flaps inclined by 15° and the range from -5° to -4°.
for flaps inclined by 45°. The highest value of the lift-to-drag ratio for 15° flaps is 9.280 and for 45° flaps 7.087. The optimum angle of attack for ejected flaps is 3°.

Figure 6. Characteristics of $c_z = f(\alpha)$ (left) and $c_x = f(\alpha)$ (right) for configurations with retracted and released flaps at angles of 15° and 45°.

3.4. Aircraft with single-slotted flaps
The values of the lift force coefficient are significantly greater for single-slotted flaps than for retracted flaps (Figure 7). With an inclination of 15°, the maximum value of $c_z$ is 1.580, while with an inclination of 45°, it is 1.672. In both cases, the critical angle of attack is 13°. The stall characteristics are very smooth for both flap positions. The drag force coefficient of $c_x$ reaches its lowest value of 0.082 and 0.124 for flaps that are tilted by 15° and 45°, respectively. Lift-to-drag ratio $K$ changes very dynamically as the angle changes. A very sharp increase is observed in the range of attack angles from -5° to around -2°. Further growth, however much slower, occurs until the angle of attack reaches the optimal value of 3°. The maximum value is then 9.187 with the flaps in the 15° position and 7.365 with the flaps in the 45° position.

Figure 7. Characteristics of $c_z = f(\alpha)$ (left) and $c_x = f(\alpha)$ (right) for configurations with retracted and released flaps at angles of 15° and 45°.
3.5. Aircraft with double-slotted flaps
The lift force coefficient of $c_z$ reaches much greater values with the double-slotted flap inclined than in the smooth configuration, as can be seen in Figure 8. The maximum values of $c_z$ are 1.586 at 15° inclination and 1.729 at 45° inclination. In both cases, the critical angle of attack is 13°. As in the case of single-slotted flaps, the stall characteristics are very smooth for both positions of double-slotted flaps. The drag force coefficient of $c_x$ reaches its lowest values of 0.081 and 0.132 for flaps which are inclined by 15° and 45°, respectively. Lift-to-drag ratio $K$ with flaps inclined by 15° takes greater values than for flaps retracted in the range from 5° to 0°. The highest value of the lift-to-drag ratio in this configuration is 9.252 for an optimal angle of attack of 3°. With flaps that are tilted by 45°, the lift-to-drag ratio is greater than with flaps that are retracted only for angles less than -3°. The maximum value in this configuration is 7.324 for an angle of attack of 3°.

![Figure 8. Characteristics of $c_z = f(\alpha)$ (left) and $c_x = f(\alpha)$ (right).](image)

3.6. Performance comparison
The performances of the DA20-C1 aircraft in the smooth configuration and with flaps released are shown in Table 1 and Table 2 where:
- $v_{\text{max}}$ – maximum speed,
- $v_{\text{opt}}$ – optimum speed,
- $v_{\text{min}}$ – minimum speed,
- $v_{v_{\text{max}}}$ – speed of greatest climb angle,
- $v_{\text{BG}}$ – glide speed for the greatest range,
- $K_{\text{max}}$ – maximum lift-to-drag ratio,
- $\theta_{\text{min}}$ – minimum glide angle.

The release of trailing-edge wing flaps is accompanied by a deterioration in aircraft performance - characteristic speeds and maximum lift-to-drag ratio decrease, while the smallest gliding angle increases. With flaps inclined by 15°, the smallest drop in speed was observed for vaulting flaps, while the largest drop was observed for single- and double-slotted flaps (Table 1). The maximum lift-to-drag ratio in all cases decreased by approximately 1, which resulted in the value of the minimum gliding angle increasing by 0.5° for split and double-slotted flaps, and by 0.6° for vaulting and single-slotted flap. Since the permitted speed with flaps in the 15° position is limited to 51.4 m/s (100 kt), the maximum speed can only be achieved in the configuration with single- and double-slotted flaps.
There are several reasons for these differences: the aircraft model was not accurately reproduced due to the

| Table 1. Performance of the DA20-C1 aircraft in the smooth configuration with flaps in the 15° position [own study]. |
|---------------------------------------------------------------|
| Smooth configuration | Vaulting flaps | Split flaps | Single-slotted flaps | Double-slotted flaps |
|----------------------|----------------|------------|----------------------|----------------------|
| $v_{\text{max}}$  | 57.10 m/s | 52.47 m/s | 51.96 m/s | 51.44 m/s | 51.44 m/s |
| $v_{\text{opt}}$  | 34.47 m/s | 31.90 m/s | 30.87 m/s | 30.35 m/s | 30.35 m/s |
| $v_{\text{min}}$  | 27.78 m/s | 26.75 m/s | 26.24 m/s | 26.24 m/s | 26.24 m/s |
| $v_x$            | 34.47 m/s | 31.90 m/s | 30.87 m/s | 30.35 m/s | 30.35 m/s |
| $v_{BG}$          | 34.47 m/s | 31.90 m/s | 30.87 m/s | 30.35 m/s | 30.35 m/s |
| $K_{\text{max}}$ | 10.212 | 9.206 | 9.280 | 9.187 | 9.252 |
| $\theta_{\text{min}}$ | 5.6° | 6.2° | 6.1° | 6.2° | 6.1° |

| Table 2. Performance of the DA20-C1 aircraft in the smooth configuration with flaps in the 45° position [own study]. |
|---------------------------------------------------------------|
| Smooth configuration | Vaulting flaps | Split flaps | Single-slotted flaps | Double-slotted flaps |
|----------------------|----------------|------------|----------------------|----------------------|
| $v_{\text{max}}$  | 57.10 m/s | 44.76 m/s | 44.24 m/s | 43.73 m/s | 43.73 m/s |
| $v_{\text{opt}}$  | 34.47 m/s | 30.35 m/s | 29.84 m/s | 29.32 m/s | 28.81 m/s |
| $v_{\text{min}}$  | 27.78 m/s | 25.72 m/s | 25.72 m/s | 25.72 m/s | 25.21 m/s |
| $v_x$            | 34.47 m/s | 30.35 m/s | 29.84 m/s | 29.32 m/s | 28.81 m/s |
| $v_{BG}$          | 34.47 m/s | 30.35 m/s | 29.84 m/s | 29.32 m/s | 28.81 m/s |
| $K_{\text{max}}$ | 10.212 | 6.773 | 7.087 | 7.365 | 7.324 |
| $\theta_{\text{min}}$ | 5.6° | 8.4° | 8° | 7.7° | 7.8° |

With flaps inclined by 45°, the smallest drop in the characteristic speed is for vaulting flaps, and the largest one for double-slotted flaps, as shown in Table 8. The maximum lift-to-drag ratio and minimum gliding angle differ significantly from those for the smooth configuration. The permitted speed with flaps in the 45° position is 40.1 m/s (78 kt), so maximum speed cannot be achieved for any configuration.

4. Conclusion

The aim of this article was to analyse the influence of trailing-edge wing flaps on aerodynamic characteristics and performance of the Diamond DA-20 aircraft. The research focused on the aircraft in the smooth configuration and with four types of trailing-edge wing flaps: vaulting flaps, split flaps, single-slotted flaps and double-slotted flaps in 15° and 45° positions. The design of aircraft models for the research and simulations were possible thanks to an advanced engineering tool which was the SolidWorks software. Based on the results of the simulation and the formulas formulated in the available literature, the basic performance of the aircraft in the defined configuration and for the analysed types of flaps was calculated.

The research showed that the performance of the DA-20 aircraft is mainly influenced by the position of the flaps. The type of flap used plays a secondary role, and the differences between the performances of individual flap types are small. Thanks to the analyses carried out in a virtual environment, aerodynamic properties and performance of the aircraft can be pre-determined and its airframe structure can be adjusted to meet the required conditions. This work has shown the significant impact of trailing-edge wing flaps on aircraft performance.

Wing flaps reduce characteristic speeds in the least way, however, the range of speeds at which flight is possible is the narrowest. The opposite situation accompanies the double-slotted flap. Thanks to the lowest speeds, an aircraft with such flaps can operate at the widest speed range. The differences in performance between the different types of flaps are small; it follows that for small light aircraft, the type of flaps used has little impact on performance.

Despite the small differences between the test results and the actual performance of the DA20-C1 aircraft reported by the manufacturer, it can be assumed that the results obtained are reliable. There are several reasons for these differences: the aircraft model was not accurately reproduced due to the
lack of detailed documentation from the manufacturer and some simplifications like omitting the impact of a working propeller were adopted.

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