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A Retrospective of High-Lift Device Technology

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Abstract—The present paper deals with the most adopted technical solutions for the enhancement of the lift force of a wing. In fact, during several flight conditions (such as take off and landing), the lift force needs to be dramatically enhanced. Both trailing edge devices (such as flaps) and leading edge ones (such as slats) are described. Finally, the most advanced aerodynamic solutions to avoid the separation of the boundary layer from aircraft wings at high angles of attack are reviewed.

Keywords—High lift devices, Trailing Edge devices, Leading Edge devices, Boundary Layer Control devices.

I. Introduction

Aircraft technology has experienced a great evolution during the whole 20^{th} century. Several innovations aimed at the improvement of the lift force. In fact, as shown from Fig. 1, lift is a fundamental aerodynamic component of action for an aircraft, since it is intended to contrast its weight force. In order to increase the lift, several aerodynamic devices, depending on the size, speed and complexity of the aircraft, have been studied and developed.

The present work analyzes the most important technical solutions adopted to enhance the lift force. The most common trailing edge devices, such as flaps, are first analyzed; afterwards, some examples of leading edge devices are reported. Finally, more complex boundary layer control systems are investigated.

II. Increasing the Lift Force

The lift force of a wing is determined by the following equation:

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

where L is the amount of produced lift, ρ is the air density, V is the velocity of the airplane, S is the surface area of the wing and C_L is the lift coefficient. The C_L is determined by the camber of the airfoil, the chord of the profile and the angle of attack. In order to generate a sufficient amount of lift even for low airspeeds, both the area (S) and the lift coefficient (C_L) should be increased. The increase of the lift force is obtained by means of two main factors: the increment of the curvature of the aerodynamic profile or the accretion of its chord length (the possible coeval growth of the drag force represents a secondary effect).

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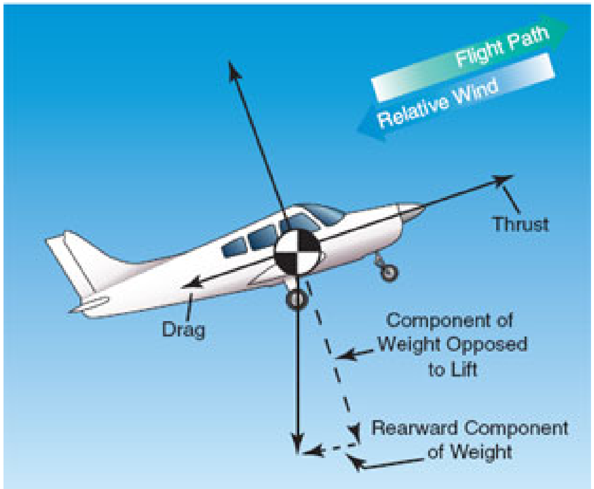

Fig. 1. Schematic representation of the aerodynamic forces acting on an aircraft during flight.

III. Trailing Edge Devices

Trailing edge devices, commonly known as flaps, represent the most used high-lift systems. A flap is a movable portion of the wing, it can be rotated around several hinges and be bent into the airflow in order to produce extra lift. The lift enhancement effect is mainly due to the increase of the profile chamber and the lift improvement occurs for the entire range of angles of incidence. Moreover, a peculiarity of trailing edge devices is their capability of generating high lift even for low angles of incidence, as can be seen in Fig. 2. Several flap configurations have been realized and tested, as shown in Figs. 3 and 4. The purpose of the present chapter is to define and discuss the existing flap architectures. Roskam and Edward Lan [1] presented a comparison of lift coefficients for the most common trailing edge devices, as shown in Fig. 6.

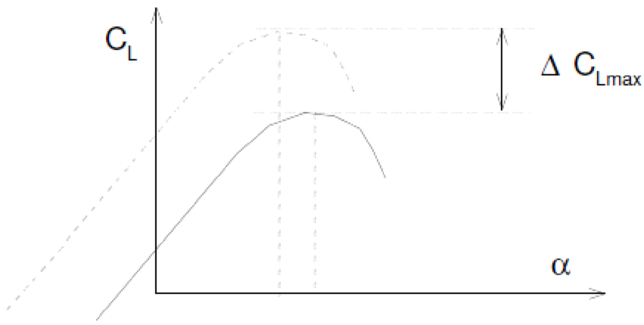

Fig. 2. Comparison between the lift curves for a wing with (dashed line) and without (consinuous line) plain flaps.

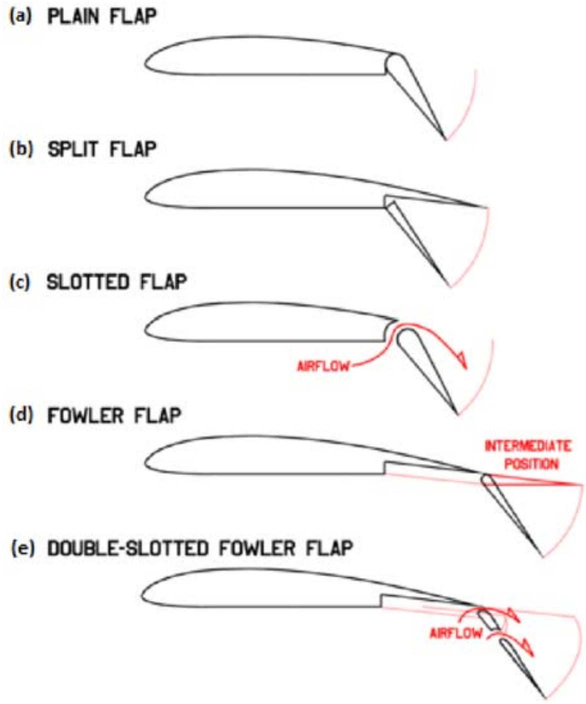

Fig. 3. A schematic representation of some trailing edge devices

A. Plain Flap

As can be observed from Fig. 3a, a Plain Flap can be obtained by bending the rear part of a wing section through the rotation around a simple hinge. The main effect of the deflection is the increment of the effective airfoil camber. Fig. 2 compares the evolution of the lift coefficient as a function of the angle of attack between a classical wing and a flapped one. As can be drawn, the introduction of the flaps determines a reduction in the stall angle of attack; no significant change in the slope of the curve is registered. Although the drag coefficient is increased, the lift to drag ratio results to be reduced. The flap deflection can usually be set to about 15 degrees without determining flow separation. The C_{Lmax} of the section will increase up to a deflection of 60 or 70 degrees for a flap to chord ratio of up to 0.3, with a great increase of the drag force. The Plain Flap provides a great efficiency and normally is the only one used, due to its simplicity. It was first utilized during World War I in the "Breguet Bre 14" aircraft. Several studies dwell on Plain Flaps, focusing on the improvement of their performances.

The Engineering Sciences Data Unit [2] provides a method to compute the increment in lift coefficient at zero angle of attack, due to the deployment of full-span or part-span Plain Flaps on the wings at low speeds.

B. Split Flap

Despite its low aerodynamic efficiency, the Split Flap is largely used due to its simplicity: the device operating mode consists in bending the rear portion of the lower surface of the airfoil through a hinge; in the meanwhile the upper surface remains blocked (the operating scheme is illustrated in Fig. 3b). One of the main consequences is the generation of a great increase in chamber, but the separation effects on the upper surface result to be less marked than those on a Plain Flap, because of the less camber of the surface.

The flap performance at high angles of attack is improved. The lift curve slope of the Split Flap appears to be higher than that of the Plain Flap: a larger increment in C_{Lmax} is registered and the angle of attack results to be lower. However, the drag force acting on a Split Flap is quite higher, because of the resulting large wake. The high benefits in C_L can be obtained using $20 - 25\%$ chord Split Flaps with a deflection angle of $60 - 70°$. A full deflection allows the Split Flap to be used as a spoiler, producing a great amount of drag force. It was design in the 1920s by James M. H. Jacobs and used in the "Douglas DC-3" and "C-47".

Chow et al. [3] performed several experiments on a wing model provided with Split Flaps, in order to study the main features of the resulting flow field, also investigating its noise impact.

The Engineering Sciences Data Unit [4] analyzed the lift increment for low speeds due to the adoption of a trailing edge Split Flap and also due to its combination with a leading edge high lift device.

C. Slotted Flap

The presence of some slots between the main portion of the wing and the bent flap represents the chief peculiarity of a Slotted Flap, as can be seen from Fig. 3c. In order to avoid flow separation over the flap, high pressure air is forced through the slots from the lower surface to the upper one. A high lift is generated by the accretion of the camber and the increment in C_{Lmax} is much higher than that associated to plain or Spit Flaps, while the registered drag is much lower. The pitching moment tends to be high and negative, thus inducing a depressive effect on the trimmed maximum lift coefficient of an airplane. The Slotted Flap usually ranges from the 25% up to the 30% of the chord. The first Slotted Flap dates back to the 1920s as a result of a research work performed at the "Handley-Page Limited" factory. The Engineering Sciences Data Unit investigated both lift [5] and drag [6] coefficient increments due to the introduction of a Slotted Flap. Such devices are also employed in several different technical applications, as the aero-trains: Dong-Hee et al. [7] demonstrated how the aerodynamic performances of the aero-trains can be improved by the presence of a single-Slotted Flap on the wing.

D. Fowler Flap

Fig. 3d illustrates a Fowler Flap. As far as the working principle is concerned, it is similar to the Slotted Flap; however, it can also be moved backwards while deflecting downwards. This motion allows the increment of the effective wing area, chord and camber. The Fowler Flap was invented by Harlan D. Fowler in 1924 and first used on "Martin Model 146" and "Lockheed L-10 Electra" in 1935. A further development is represented by the Double-Slotted Fowler Flap displayed in Fig. 3e. Some mechanisms fix and link a number of small tabs in order to increase the total surface and direct part of the flow to the upper wing surface through slots. Nowadays this version is still used in the modern jet transports, as in ”Boeing 727”, ”737” and ”747”.

Kozlov [8] reported the design process of Fowler Flaps with adaptive elements, using a FEM model including both passive flaps and active elements which were modeled using shape memory alloy actuators (SMA). The work succeeded in increasing the aerodynamic efficiency through the optimization of the geometry of the gap between the wing and the extended flap.

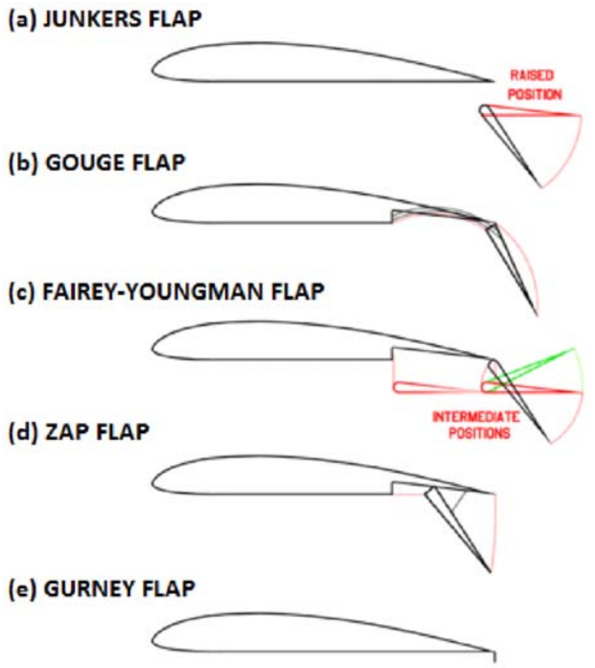

Fig. 4. A schematic representation of some trailing edge devices.

E. Junkers Flap

The Junkers Flap shown in Fig. 4a is similar to the above mentioned Slotted Flap; the flap is fixed below the trailing edge and can flip about its forward edge. This device generates much more lift than the other systems, although it produces more drag, also when not in use. A description of the Junkers Flap can be found in [9]. Created in the 1920s, it was used in the ”Junkers Ju 52” and is employed nowadays in many modern ultralights.

F. Gouge Flap

As defined in [10], a Gouge Flap is comparable to a Split Flap, but it can be moved backwards, in order to increase chord and camber without affecting trim or requiring additional mechanisms. Fig. 4b shows the described device. Invented by Arthur Gouge in 1936, it was used in both the ”Short Empire” and the ”Short Sunderland” aircrafts.

G. Fairey-Youngman Flap

As displayed in Fig. 4c, the Fairey-Youngman Flap can be related to the Junkers Flap: first of all it slides and then rotates up or down. It can be found in the ”Fairey Firefly” and ”Fairey Barracuda” as shown in Fig. 5. A negative angle of incidence can be assumed in the extended position and the aircraft could be dived vertically without needing excessive trim changes.

Fig. 5. The British carrier-borne torpedo and dive bomber ”Fairey Barracuda” was largely used during the Second World War and was the first of its type used by the Royal Navy’s Fleet Air Arm to be made entirely of metal.

H. Zap Flap

The Zap Flap consists of a quite simple mechanism. The leading edge of the flap is mounted on a track and a point at mid chord of the flap is connected to a pivot above the track through a mechanical arm. As shown in Fig. 4d, the sliding movement of the flap creates a triangle formed by the track itself, the shaft and the surface of the flap that forces the flap down. Invented by Edward F. Zaparka, it was used on the ”Northrop P-61 Black Widow”.

I. Gurney Flap

The Gurney Flap (see Fig. 4e) consists of a small flat tab attached on the high pressure side of the wing trailing edge. The tab length is usually 1-2% of the wing chord and can improve the performances of a simple airfoil, allowing it to reach the performance of a complex aerodynamic design. The lift is enhanced by increasing the resulting pressure in the airfoil pressure side and, in the meanwhile, decreasing the pressure in the suction side. The mechanism allows the boundary layer flow to stay attached to the trailing edge on the suction side. Gurney Flap was theorized in the 1930s but has never been used until 1971. It was named after the racing car driver Dan Gurney and it has been applied on some helicopters such as the ”Sikorsky S-76B”, in order to correct control problems. The aerodynamic performances of Gurney Flaps have been investigated by several researchers; worthy of mention are the rotorcraft applications [11], target drones [12] and horizontal axis wind turbines [13].

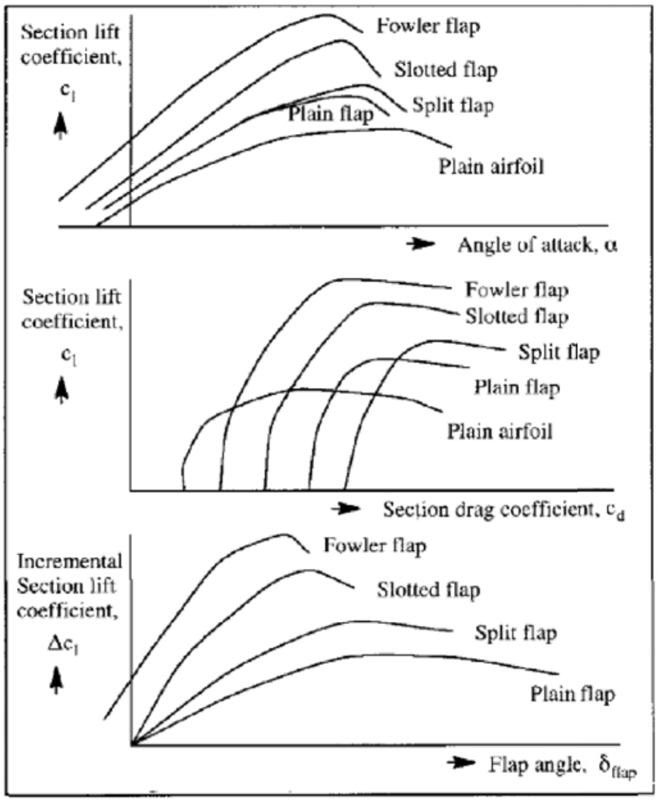

Fig. 6. Comparison of the lift coefficients for the main adopted trailing edge devices (from: [1]).

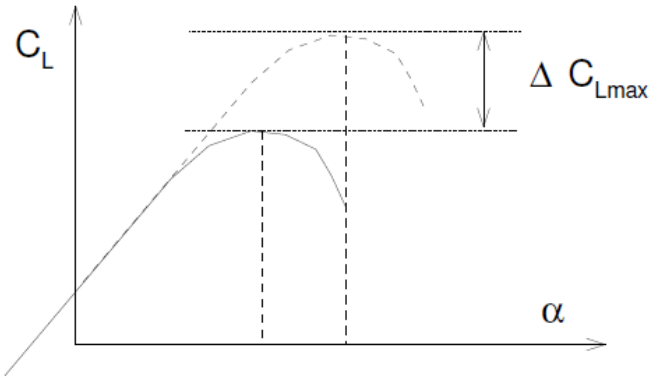

Fig. 7. Comparison between the lift curves for a wing with (dashed line) and without (consinuous line) leading edge devices.

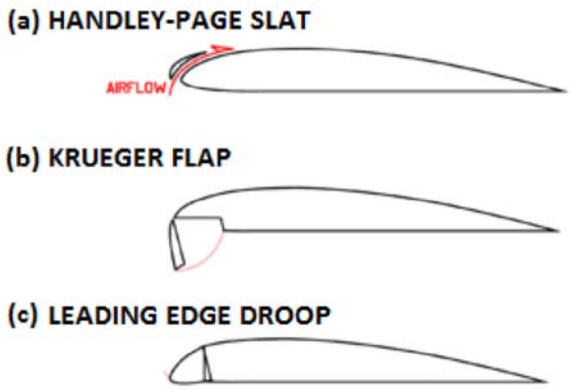

Fig. 8. A schematic representation of some leading edge devices.

IV. Leading Edge Devices

Even though leading edge mechanisms are not as powerful as the above mentioned trailing edge devices, they result mechanically simpler and prove to be very effective in combination with the latters. The pressure peak on the wing can be reduced, helping to maintain the flow attached to the surface. Leading edge devices work in conditions close to the optimal angle of incidence and they extend the linear trend of the lift curve beyond the critical angle of incidence of a normal wing without high-lift systems, as Fig. 7 shows. The main employed leading edge solutions are described in the following paragraphs and displayed in Fig. 8.

A. Handley-Page Slat

The Handley-Page Slat, shown in Fig. 8a, represents the most popular leading edge device; it consists of an airfoil, fixed or retractable, mounted on the top of the leading edge of the wing. The slat device helps the flow stream, especially at high angles of attack, and also avoids the leading edge stalling. The Handley-Page Slat increases the C_{Lmax} by as much as 50% and can be equipped with one or more slots in order to improve its effectiveness. It has been adopted since World War I. The Handley-Page Slat has been considered as the basis for the development of several alternative devices, as reported in [14].

B. Krueger Flap

The Krueger Flap can be extended downwards and forward from the leading edge, as displayed in Fig. 8b. Differently from the other leading edge devices, the upper wing surface and its nose are not being changed by this solution. The presence of a Krueger Flap increases the camber and the thickness of the wing and, at the same time, generates an accretion of lift and drag forces. Created by Werner Krueger in 1943, it is nowadays used on many modern swept wing airliners.

A structural optimization study on a Krueger Flap has been presented by Bayandor et al. [15]: in order to improve the flap performances, the multi-layer composite shell of the device has been optimized through a parametric analysis.

C. Leading Edge Droop

This category of high lift devices, represented in Figure 8c, includes several technical solutions: in the more common leading edge droops the entire leading edge of the wing rotates downwards, in order to increase the camber and slightly decrease the wing chord. Similar devices bend down the forward portion of the wing to form a droop.

V. Boundary Layer Control Devices

The Boundary Layer Control Devices (BCL) have been classified as active systems, in contrast to the passive systems analyzed in the previous paragraphs. The acronym BCL includes some solutions whose aim is to control the boundary flow separation caused by the adverse pressure gradient of the velocities around the wings. These systems use airflow from the engines to shape the flow air over the wing, in order to reach a higher maximum lift coefficient.

A. Blown Flap

In a Blown Flap the velocity of the airflow is increased by a small amount of compressed air produced by the jet engines. The mechanism exploits the tendency of a fluid jet to be attracted from a nearby surface, known as the Coanda effect [16], that delays the boundary layer separation [17]. The maximum lift coefficient C_{Lmax} and the stalling angle of attack are increased by injecting high energy air into the boundary layer. Indeed, the added air re-energizes the boundary flow and also provides additional energy to the retarded fluid particles. A large amount of air and energy, in particular at low speeds, is required by the Blown Flap system: the resulting effect is the reduction of the overall benefits of the solution. The French "Breguet Br 941" represents one of the first examples of applied blown wing. The transport airplane displayed four over-sized turboprops, opportunely placed, in order to allow the produced flow to invest the wings. After that, the USB (Upper Surface Bowling) configuration has been experimented in various models provided with turbofan engines as the "Boing YC-14" and the "Antonov An-72". Several modern transport airplanes, as the "McDonnell Douglas C-17" and the "Airbus A380" use the exhaust of the jet engines placed below the wings: the flow invests the flaps only when they are extended. It can be concluded that Blown Flaps improve the lift of a wing by about two to three times.

B. Circulation Control Wing (CCW)

The Circulation Control Wing (CCW) is the result of the development of the Blown Flaps and succeeded in increasing the velocity of the airflow ejecting high pressure air through a series of blowing slots [18]. As shown in Fig. 9, the trailing edge of the wing profile is modeled in a rounded form, in order to tangentially eject the air and take advantage of the Coanda effect [16]. The lift produced by CCW adds up to the conventional airfoil lift force without the production of any additional extra drag. The system is employed in many modern airplanes and could increase the lift of a Boeing 747 of about 200%, reducing in the meanwhile the approach speeds and the landing distances. Other benefits of the CCW are represented by the improvements to the maneuverability at low speed and the reduction of the noise pollution of modern aircrafts.

The CCW technique has been discussed in several studies. McGowan et al. [19] investigated the flow field over CCWs, focusing on the three-dimensional effects.

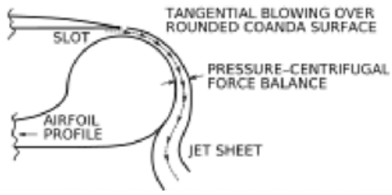

Fig. 9. A schematic representation of the CCW concept.

C. Suction Flap

The suction of the boundary layer can be provided using a suction pump, in order to suck the shear layers of the flow, thus subtracting the slowest layer from the flow, delaying the separation point. The suction effect can be obtained through a porous airfoil skin or through micro slots sited crosswise against the flow direction. The development of Suction Flap devices slowed down during World War II, due to the difficulty to maintain a perfect wing configuration. In fact, the impact of insects on the wing caused organic excrescences that, together with snow, ice or dust, could obstruct the micro cavities.

A first example of a complete system of Suction Flaps is represented by the "Northrop X-21" airplane [20], developed during the 1960s: its wings presented about 800000 micro cavities arranged along their whole length. The project demonstrated the possibility of obtaining a laminar boundary layer up to the 75% of the wing surface. Nevertheless the program was interrupted due to the excessive maintenance needed to preserve the cavities. In the 1990s, the NASA tested the F-16XL, a civil transport aircraft with about 12 millions micro holes on the left wing, obtained using a laser technology on a titanium sheet and linked to a turbo compressor through a complex valve and pipe system [21] and [22].

D. Jet Flap

In order to control the boundary layer, compressed air can be drawn from the engines and piped to the wings. The Jet Flap solution consists of a system of jets and pipes distributing a thick layer of air on the entire surface of the wing, especially on the trailing edge. The air distribution generates an asymmetric flow and an added circulation on the wing: the result is comparable to a high dimension flap. The air is blown from a number of cavities before the trailing edge of the wing and the direction of the flow can be regulated using a small flap. An example of Jet Flap can be found in the British experimental aircraft "Hunting H.126" and in the "Lockheed F-104 Starfighter". The device requests pipes inside the wings and hence is also known as "Internal Flow System" [23].

VI. Conclusion

The most adopted high lift systems used to enhance the lift of an aircraft have been summarized. The analyzed devices cause some modification to the airflow around a wing and are fundamental in order to simplify operations such as take off and landing. High lift devices can be classified into three main categories: (1) common trailing edge devices, that can be found in the wings of every airplane; (2) leading edge devices, which are often used in order to complement the trailing edge systems; (3) boundary control devices, which modify the air flow around a wing by blowing or sucking a certain amount of air.

REFERENCES

[1] J. Roskam and C. T. Edward Lan, *Aeroplane Aerodynamics and Performance*, DARcorporation (U.S.A.), 1997.

[2] Engineering Sciences Data Unit, *Wing lift coefficient increment at zero angle of attack due to deployment of plain trailing-edge flaps at low speeds*, ESDU 97011, ISBN: 978 1 86246 011 9.

[3] D. Angland, X. Zhang, N. Molin and L. C. Chow, *Measurements of flow around a split flap configuration*, Collection of Technical Papers - 45th AIAA Aerospace Sciences Meeting, Vol. 4, pp. 2657-2674, 2007.

[4] Engineering Sciences Data Unit, *Increments in aerofoil lift coefficient at zero angle of attack and in maximum lift coefficient due to deployment of a trailing-edge split flap, with or without a leading-edge high-lift device, at low speeds*, ESDU 94029, ISBN: 978 0 85679 916 7.

[5] Engineering Sciences Data Unit, *Lift coefficient increment due to full-span slotted flaps*, ESDU Aero F.01.01.08, ISBN: 978 1 86246 424 7.

[6] Engineering Sciences Data Unit, *Increment in aerofoil profile drag coefficient due to the deployment of a single-slotted flap*, ESDU 87005, ISBN: 978 0 85679 598 5.

[7] Y. Dong-Hee, K. Yasuaki, K. satoshi and K. Takuma, *Improvement of Aerodynamic Performance of the Aero-Train by Controlling Wing-Wing Interaction Using Single-Slotted Flap*, JSME International Journal, Series B: Fluids and Thermal Engineering, Vol. 49 - No. 4, pp. 1118-1124, 2006.

[8] O. Kozlov, *Design and Modeling of the Fowler Flap With Adaptive Elements*, ASME 2006 International Mechanical Engineering Congress and Exposition (IMECE2006), November 5 10, 2006 , Chicago, Illinois (USA).

[9] B. Gunston, *The Cambridge Aerospace Dictionary*, Cambridge, Cambridge University Press 2004, p. 331.

[10] B. Gunston, *The Cambridge Aerospace Dictionary*, Cambridge, Cambridge University Press 2004, p. 270.

[11] K. Yee, W. Joo and D. Lee, *Aerodynamic Performance Analysis of a Gurney Flap for Rotorcraft Application*, Journal of Aircraft, Vol 44 - No. 3, pp. 1003-1014, May/June 2007.

[12] Y. Zhao, J. Wang, L. Zuo and D. Yu, *Application of Gurney flap on certain target drone*, Journal of Beijing University of Aeronautics and Astronautics, Vol. 35 - No. 8, pp. 913-916, August 2009.

[13] Z. Shen and G. Yu, *Experimental investigation of effect of gurney flap on performance of horizontal-axis wind turbine*, Acta Energiae Solaris Sinica, Vol. 28 - No. 2, pp. 196-199, February 2007.

[14] A. L. Williams, *New and less complex alternatives to the Handley Page slat*, Journal of Aircraft, Vol 23 No. 3 (1986), pp. 200-206.

[15] J. Bayandor, M. L. Scott and R. S. Thomson, *Parametric optimisation of composite shell structures for an aircraft Krueger flap*, Composite Structures, Vol. 57, Issues 1-4, pp. 415-423, July 2002.

[16] S. Chavez and C. Richard, *Numerical Study of the Coanda effect*, Fluidics Quart, Vol. No. 4, pp. 40-48, 1970.

[17] B. E. Wake, J. S. Kearney, G. Tillman and S. S. Ochs, *Control of High-Reynolds-Number Turbulent Boundary Layer Separation Using Counter-Flow Fluid Injection*, Collection of Technical Papers - 3rd AIAA Flow Control Conference, 5-8 June, San Francisco, CA.

[18] T. Troia and M. Waters,*A Propulsion Concept for Circulation Control Wing Technology*, SAE Technical Paper 2005-01-3192, 2005, doi:10.4271/2005-01-3192.

[19] G. McGowan, C. Rumsey, H. Hassan and R. C. Swanson, *A three-dimensional computational study of a circulation control wing*, 3rd AIAA Flow Control Conference, 5-8 June 2006, San Francisco, CA.

[20] D. R. Jenkins, T. Landis and J. Miller, *AMERICAN X-VEHICLES An Inventory X-1 to X-50*, NASA, Monographs in Aerospace History, No. 31 SP-2003-4531, June 2003.

[21] L. A. Marshall, *Boundary-Layer Transition Results From the F-16XL-2 Supersonic Laminar Flow. Control Experiment*, NASA technical memorandum 209013, 1999.

[22] B. A. Smith, *Laminar flow data evaluated*, Aviation Week & Space Technology 145, October 1996.

[23] J. Williams, S. F. J. Butler and M. N. Wood, *The Aerodynamics of Jet Flaps*, Aeronautical Research Council Reports and Memoranda N. 3304, 1963.