Effect of flap deflection angle on flow characteristics of aerofoil

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Abstract. A wing is used in aircraft to employ lift based on the fundamental principle of aerodynamics. The cross-section of a wing gives the aerofoil shape, and thus investigation of flow characteristics of aerofoil is important to understand the lift and drag mechanisms in wing. Flaps are the components using in the wings to generate additional lift and drag when required. While aircraft take-off, flaps help in generating addition lift, and while in landing, they do aerodynamic braking. Therefore, flaps play an important role in aircraft. The present paper investigates the angle of flaps on flow characteristics in NACA 4415 aerofoil using XFOil software. The variations obtained showed notable variations in the coefficient of pressure (Cp) plots. The various aerodynamic coefficients such as lift and drag coefficients, and viscous pressure distribution were obtained corresponding to the flap deflection angle. From the results, for flap angles above 0°, the aerofoil can generate a “sudden” lift which is useful in take-off conditions. While the flap angles are made below zero degrees, the lift is observed to decrease contributing to more drag. Polar plots are made to summarize and visualize the above results graphically.

Keywords: aerodynamics, aerofoil shape, wings, flaps, flap angles, XFOil software.

1. Introduction

Aerofoil is a streamlined shape or surface or profile that provides an aerodynamic force when it interacts with the moving stream of air [1]. Generally, the high pressure or low velocity air flow section is generated beneath the aerofoil and the low pressure or high velocity air flow section is generated above the aerofoil [2]. Therefore, aerofoil plays an active and a crucial role in the aircraft motion. The aerofoils sometimes need to perform a sudden lift or drag. Thus, to achieve these requirements, the flaps are introduced in an aerofoil section of an aircraft. Flaps are the surfaces or profiles which are used to increase or decrease the lift of an aerofoil or to introduce the drag whenever required suddenly. They are usually mounted at the trailing edge of the wing [3]. The drag or lift is introduced by the flap in an aerofoil, is achieved by increasing the camber of an aerofoil. It is observed that the curvature of the wing increases as the camber of an aerofoil increases. The curvature which is achieved can be controlled by the deflection angle (αD) produced by the flaps [4]. Thus, various combinations or cases may be studied about the lift and drag according to the requirements. Another way to achieve the curvature control is by introducing flap to the specified location from the leading edge of an aerofoil. In this report, NACA 4415 is employed with plain type of flap [4].
2. Methodology
In this paper, a NACA 4415 aerofoil is used [5]. It is an asymmetric aerofoil which has the lower surface asymmetric with respect to the maximum chord length drawn from the leading edge to the trailing edge of an aerofoil [6]. NACA is the abbreviation for “National Advisory Committee for Aeronautics” and 4415 is the aerofoil section designation, of which first digit “4” describes 4% maximum camber with respect to chord length, second digit “4” describes the location of camber at 40% of the chord length and last two digits “15” describes 15% thickness with respect to the chord length [5]. The 2D analysis in the viscous mode was carried out on the given NACA 4415 aerofoil with Reynolds number, Re = 4 x 10^6, and the angle of attack (α) from -10° to 30°. A detailed viscous analysis on NACA 4415 was carried out successfully by using the Xfoil software. From the analysis, various polar plots like lift coefficient (C_L) variation with angle of attack (α), and C_L/C_D variation with α. All angles are measured in degrees. Furthermore, the plain flaps were introduced in the NACA 4415 aerofoil at the location 80% from the chord length measured from the leading edge and 50% of the maximum camber [4, 5]. In such a modified aerofoil, the front portion of a flap is rotated about the hinge near the trailing edge of an aerofoil [4]. The viscous analysis (Re = 4 x 10^6) on the modified NACA 4415 was carried out at α = 7°, 0° and -4° of an aerofoil explicitly, along with deflection angle (αD) from -90° (up) to +90° (down). The plain flap at α = -90°, -45°, +45°, +90° can be determined and studied using the figure 1 given below. From the analysis, various polar plots like lift coefficient (C_L) variation with angle of attack, and C_L/C_D variation with angle of attack.

![Figure 1](image-url)
3. Results and discussions
3.1. Lift and drag coefficients variation with angle of attack
The theoretical variation of the coefficient of lift \((C_L)\) with angle of attack \((\alpha)\) for NACA 4415 aerofoil is calculated using the Eq. (1), and is plotted in figure 2.

\[
C_L = 2\alpha + C_{L0}
\]  

where, \(C_{L0}\) is the lift coefficient at \(\alpha = 0^\circ\). For NACA 4415 aerofoil, \(C_{L0} = 0.456\) at \(\alpha = 0^\circ\), and \(C_L = 0\) at \(\alpha = 4^\circ\) [7, 8]. From the figure 2, we can say \(C_L\) is directly proportional to \(\alpha\) depicting a straight line. Figure 2 can be used to summarize the theoretical approach. When viscosity is considered in the analysis, the variation of \(C_L\) with \(\alpha\) is shown in figure 3. From the figure 3, it is observed that \(C_L\) increases when \(\alpha\) increases till \(17^\circ\), and when \(\alpha > 17^\circ\), the \(C_L\) decreases. This phenomenon is called as stalling and has a remarkable significance in the flight of an aircraft.

![Figure 2. CL variation with \(\alpha\) (a) theoretical (b) considering the viscosity effects.](image)

Figure 3 shows the \(C_L/C_D\) variation for an aerofoil at different angles of attacks. It is observed that the \(C_L/C_D\) ratio increases to the maximum when \(\alpha\) reaches \(7^\circ\). For \(\alpha > 7^\circ\), the \(C_L/C_D\) ratio decreases. This analysis depicts the stability of an aerofoil with respect to the variation in \(\alpha\). Thus, the optimum value of \(\alpha\) is between \(0^\circ\) to \(7^\circ\) above which the drag is observed to be contributing such that the \(C_L/C_D\) is seen to be decreasing.

![Figure 3. Variation of \(C_L/C_D\) with angle of attack, \(\alpha\).](image)

3.2. Lift coefficient variation with flap deflection angle \((\alpha_D)\)
Figure 4 shows the variation of coefficient of lift with the flap deflection angle and different angles of attack of \(\alpha = -4^\circ\), \(0^\circ\), and \(7^\circ\). It is observed that when \(\alpha_D\) is positive and is less than \(70^\circ\) (flaps down), \(C_L\) increases, and thus lift increases. This sudden lift generation is employed for short run lift generation in an aerofoil of an aircraft. Similarly, when \(\alpha_D\) is negative and is greater than \(-70^\circ\) (flaps up), \(C_L\) decreases, thus lift decreases. This condition is observed as if an aerofoil is under braking
condition and this condition is thus called as “aerodynamic braking”. For the considered angles of attack cases in figure 4, there is an upward shift in the values of $C_L$ with increasing $\alpha$ values.

![Figure 4. $C_L$ variation with flap deflection angle at different angles of attack.](image)

Figure 5 shows the $C_L/C_D$ variation with flap deflection angles at the angles of attack values of $\alpha = 7^\circ$, $0^\circ$, $-4^\circ$. It is observed that $C_L/C_D$ ratio increases appreciably till $\alpha_D = +12^\circ$, and thereafter decreases slowly due to the contribution of drag component in the motion of the aerofoil. As $\alpha$ increases, this plot tends from asymmetric nature to symmetric nature.

4. Conclusions
A detailed viscous analysis on NACA 4415 was carried out successfully by using the Xfoil software. By the analysis, it was observed that, the flaps can either increase or decrease the lift according to its orientation and geometry. It was observed and concluded that the down deflection angle (positive $\alpha_D$) is used to introduce the lift of an aerofoil and up deflection angle (negative $\alpha_D$) is used to introduce the drag in the aerofoil. The drag introduction to the aerofoil is termed as “aerodynamic braking” and it was studied in detail using the results obtained by the analysis.

5. References
[1] Rubel R I, Uddin M K, Islam M Z, and Rokunuzzaman M (2017). Comparison of aerodynamics characteristics of NACA 0015 & NACA 4415 aerofoil blade. International Journal of Research - Granthaalayah, 5(11), 187-97.
[2] Perkins C and Hage R (1949). Airplane performance, stability and control, Chapter 2, John Wiley and Sons.
[3] Anderson J D Jr., Fundamentals of Aerodynamics, Fifth Edition, McGraw Hill Education (India) Private Limited, 2010.
[4] Gunston B, Cambridge Aerospace Dictionary, Cambridge. Cambridge University Press 2004.
[5] Jacobs E N, Ward K E and Pinkerton R M. NACA Report No. 460, The characteristics of 78 related airfoil sections from tests in the variable-density wind tunnel. NACA, 1933.
[6] Hurt H H Jr. Aerodynamics for Naval Aviators. U.S. Government Printing Office, Washington, D.C.: U.S. Navy, Aviation Training Division. (January 1965).
[7] Abbott, Ira H, von Doenhoff, Albert E (1958). Theory of wing sections. New York: Dover Publications.
[8] Clancy L J (1975), Aerodynamics, Pitman Publishing Limited, London.