

LIFT ENHANCEMENT ON UNCONVENTIONAL AIRFOILS

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ABSTRACT

Lift augmentation on airfoils is a critical task to an aerodynamicist when asked to design new wings. Flow visualization studies on a corrugated airfoil confirm that the trapped vortices lead to a modification of the effective wing shape and an increase in lift. Considerable lift enhancement is found in the experimental measurements on a wing model incorporated with a backward-facing step on the upper surface because of a trapped vortex. Furthermore, a leading-edge rotating cylinder (which behaves like a vortex) effectively extend the lift curve of an airfoil without substantially affecting its slope, thus increasing the maximum lift and delaying stall. While theoretical studies of vortex trapping are limited to airfoils with smooth surfaces, this paper explores the ability of trapping single and multiple vortices on airfoils with surface discontinuities, such as cavities, corrugations, or a rotating cylinder. Streamlines, surface pressure distributions and the vortex trajectories are presented in the hope to advance the knowledge on lift enhancement for flow past unconventional airfoils.

Keywords: Lift enhancement airfoil, aerodynamics.

1.0 INTRODUCTION

An airfoil section, which is the essential part of a wing, has its primary task as a lift generator. The proper functioning of the airfoil is the prerequisite to the satisfactory performance of the lifting surface. An aerodynamicist is often faced with the challenge of optimizing and enhancing its lift without seriously increasing the drag. Over the years, many different methods of enhancing the lift have been proposed, verified by wind-tunnel tests and eventually realized. Typical examples include (a) the multi-element high-lift configuration of the Boeing 727 wing section consisting of a leading-edge slat, Krueger leading-edge flap and triple-slotted flaps in Figure 1a from [1], (b) the Custer Channel Wing aircraft tested by NACA from [2] and (c) the rotating cylinders at the wing-flap junctions of an OV-10A at NASA-Ames [3].

From examining a typical lift curve and the corresponding nature of flow over an airfoil in Figure 2 from [4], the loss of lift at high angles of attack is closely associated with flow separation over the suction surface of the airfoil. Therefore, it is traditionally believed that maintaining attached flow there is critical in lift generation.

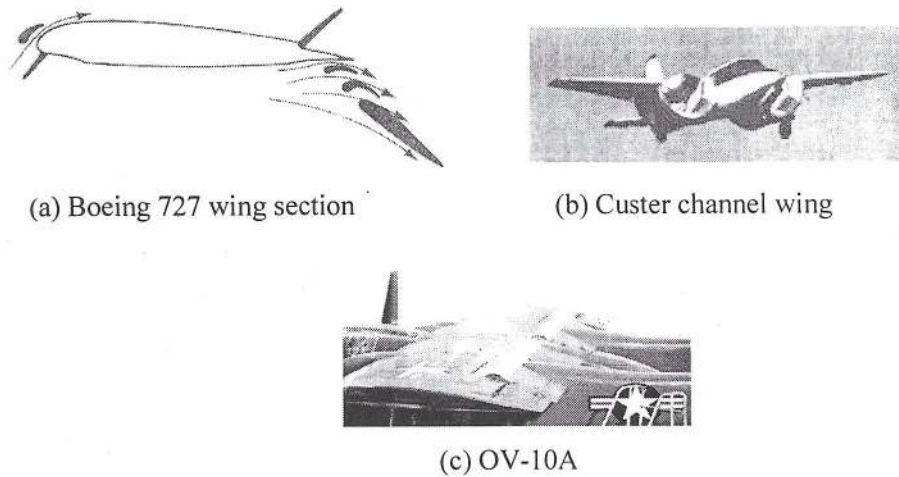


Figure 1: Examples of high-lift devices

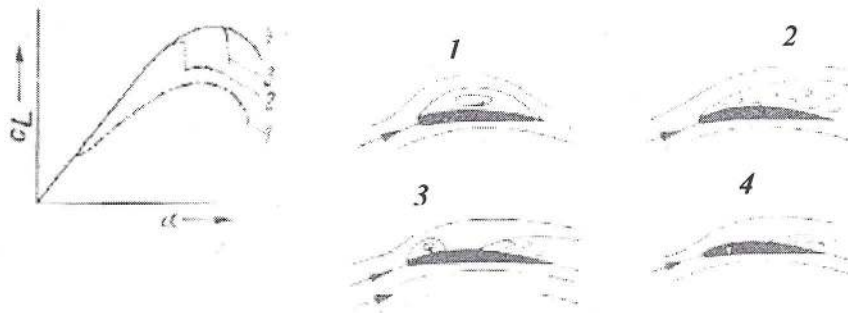


Figure 2: Lift curve variations and nature of flow from [4]

The vortical flow induced by leading-edge separation over the delta wing in Figure 3a & b from [5] has been found beneficial to generating lift. The consequence of this vortical flow, as depicted in Figure 3c from [6], is the production of two large suction peaks due to the high-speed flow induced by these vortices.

Flow visualization studies in [7] on a corrugated airfoil confirm that vortices are trapped on the airfoil (see Figure 4) and they lead to a modification of the effective wing shape and an increase in lift. Considerable lift enhancement is found in the experimental measurements in [8] on a wing model in Figure 5 incorporated with a backward-facing step on the upper surface because of a trapped vortex. As reported in [9], a leading-edge rotating cylinder (which behaves like a stationary vortex) in Figure 6 effectively extend the lift curve of an airfoil without affecting its slope, thus increasing the maximum lift and delaying stall.

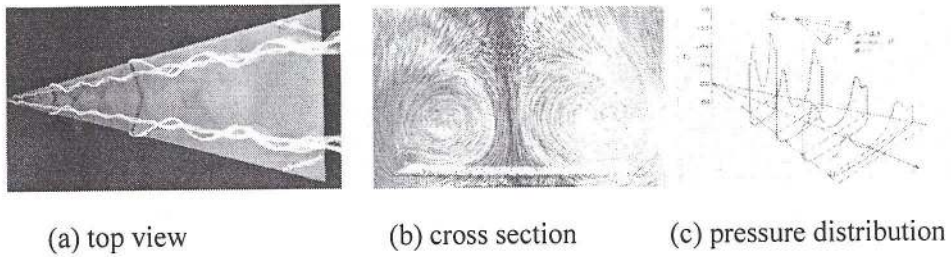


Figure 3: Vortical flow and surface pressure distributions of a delta wing from [5, 6]



Figure 4: Corrugated airfoil from [7]

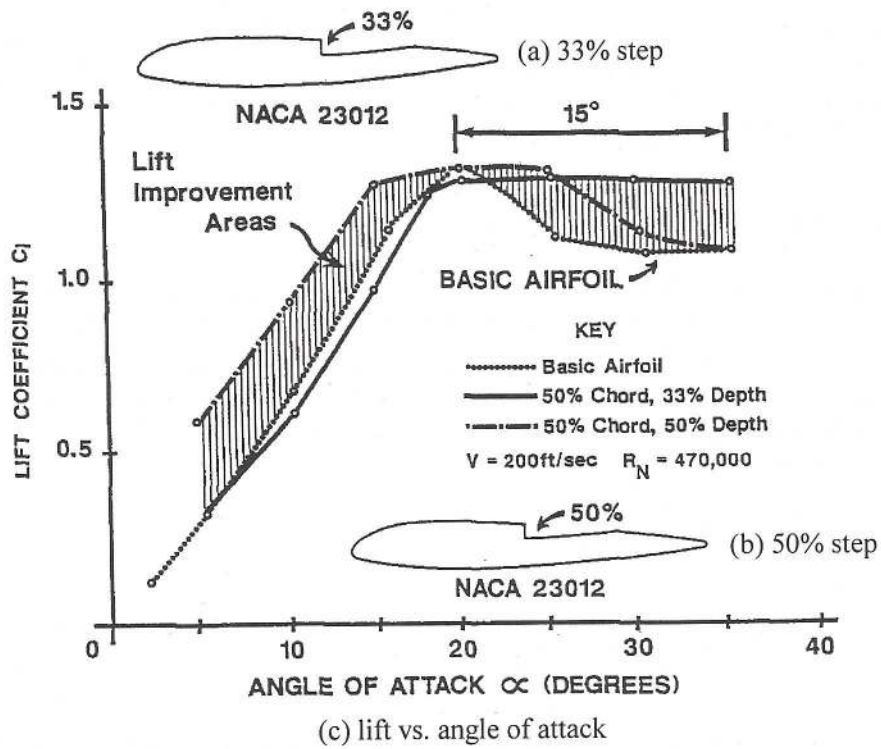
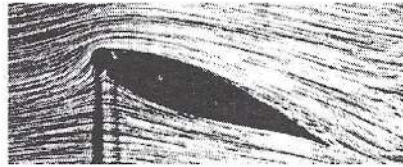
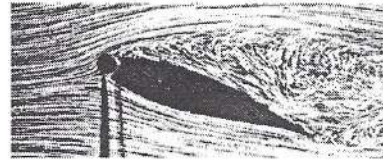


Figure 5: Airfoils with backward-facing steps from [8]



(a) cylinder speed = 0



(b) cylinder speed = 4 times freestream speed

Figure 6: Airfoil with leading-edge rotating cylinder from [9]

As reported by Huang and Chow [10], a free vortex may be theoretically captured by a Joukowski airfoil at certain neighboring positions at which the vortex becomes stationary. The increase in lift can be as high as 200%. Their linear analysis reveals that all equilibrium positions are unstable, except those in a small region near the trailing edge of the airfoil. When the vortex is displaced by a finite, instead of an infinitesimal, distance from the equilibrium position, the vortex always goes away from its equilibrium position [11]. Therefore, the stable equilibrium positions as predicted by the linear theory are all unstable, if the perturbation amplitudes are not small. This paper presents a theoretical study on vortex trapping over an unconventional airfoil which has cavities, corrugations or a rotating cylinder. Calculations show that such a geometrical modification allows not only a single but multiple vortices to be trapped. Suction peaks have been found on the airfoil surface, resulting in lift enhancement.

2.0 SINGLE CAVITY

Consider uniform flow U past a two-dimensional cavity in the physical plane $z = x + iy$, as shown in Fig. 7a. The presence of sharp edges causes the flow to separate at point A and reattach at point B such that inside the cavity the flow is expected to be vortical in nature. In the context of inviscid and incompressible, the complex potential containing a single vortex of strength Γ (i.e. the simplest case) inside the cavity may be written as:

$$F(\zeta) = U\zeta + \frac{i\Gamma}{2\pi} \log \left(\frac{\zeta - \zeta_v}{\zeta - \bar{\zeta}_v} \right) \quad (1)$$

where

$$\zeta = \frac{2i}{n} \cot \left(\frac{2}{n} \tan^{-1} \left(\frac{i}{z} \right) \right) \quad (2)$$

It is noted here that ζ_v represents the location of the vortex in terms of variable ζ , and $\bar{\zeta}_v$ is its complex conjugate. n , which is a real number, determines the depth of

the cavity. In particular, when $n=3$, a semi-circular cavity is formed. The strength and location of the vortex are determined by satisfying the following conditions:

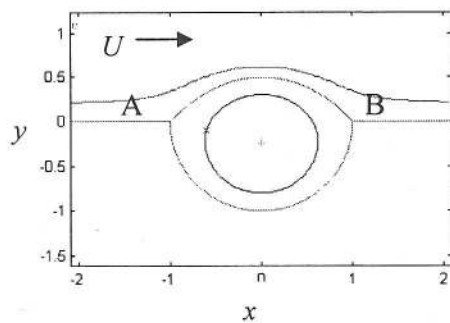
- a) $\frac{dF}{d\zeta} = 0$ at points A and B such that a streamline joining points A and B is created,
- b) $\frac{dF/d\zeta}{dz/d\zeta} - \frac{i\Gamma}{2\pi} \frac{1}{z-z_v} = 0$ at $\zeta = \zeta_v$ (i.e. $z = z_v$) such that the vortex is stationary in

physical plane z .

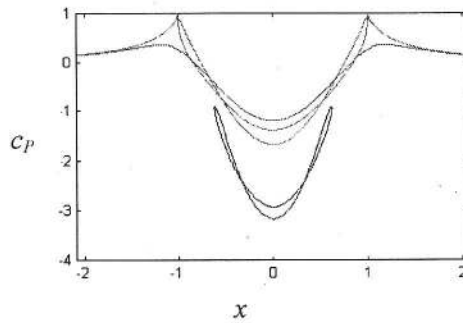
The mean pressure p along the cavity boundary may be computed by using the Bernoulli's equation. When normalized by the undistributed pressure p_∞ and the dynamic pressure $\rho U^2/2$, the usual pressure coefficient $c_p = 2(p - p_\infty)/(\rho U^2)$ results. Based on the Lagrangian description, the trajectory of the vortex, when given a initial finite displacement from the equilibrium point, is found by integrating the equations of motion

$$\frac{dx}{dt} = \text{Re} \left(\frac{dF/d\zeta}{dz/d\zeta} - \frac{i\Gamma}{2\pi} \frac{1}{z-z_v} \right), \quad -\frac{dy}{dt} = \text{Im} \left(\frac{dF/d\zeta}{dz/d\zeta} - \frac{i\Gamma}{2\pi} \frac{1}{z-z_v} \right) \quad (3)$$

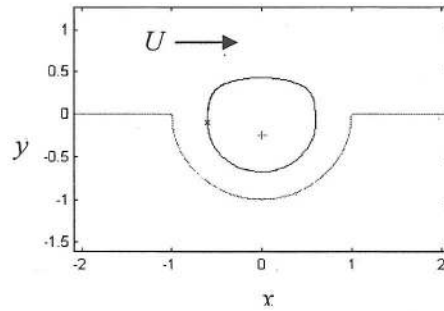
The steady flow pattern, the mean pressure distribution and a typical plot of the vortex trajectory are given in Figure 7. It is noted that the inner streamline in Figure 7a is generally different from the vortex trajectory in Figure 7c, even though they share a common point marked by the cross. Also shown in Figure 7c is that the vortex returns to that position after being displaced by a finite distance away from it. The equilibrium position of the captured vortex is considered to be stable.



(a) steady flow pattern



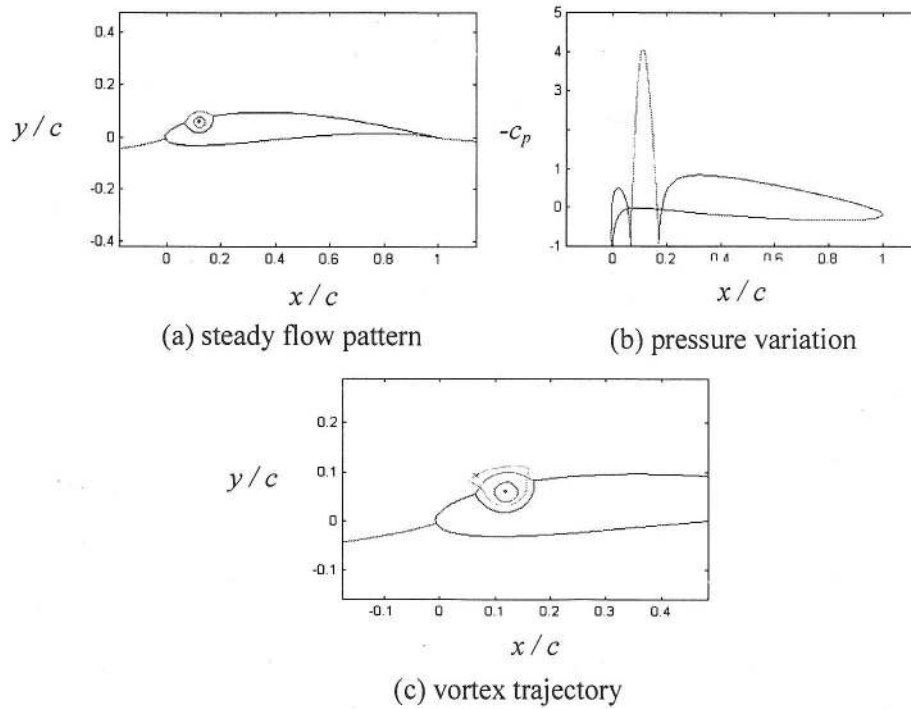
(b) pressure variation



(c) vortex trajectory

Figure 7: Flow past a semi-circular cavity

Using a conformal mapping sequence, such a cavity can be incorporated on to a Joukowski airfoil of chord c , as depicted in Figure 8a. A high suction peak is induced by the standing vortex on the upper surface of the airfoil, as depicted in Figure 8b. An enlarged view of the vortex trajectory in Figure 8c indicates that the equilibrium point inside the cavity is stable.



(a) steady flow pattern

(b) pressure variation

(c) vortex trajectory

Figure 8: Flow past an airfoil with a semi-circular cavity

3.0 CORRUGATION

A single corrugation may be generated on a surface in the physical plane $z = x + iy$, as shown in Fig. 9a, from a flat horizontal boundary from the complex plane ζ by using

$$2\zeta = (z + \lambda) + (z + \lambda)^{1/2} (z - 3\lambda)^{1/2} \quad (4)$$

where λ is a complex number. Successive applications of (4) lead to double and triple corrugations in Fig. 9b and 9c, respectively. If N is the number of vortices involved, then in the presence of a uniform flow (1) is generalized to

$$F(\zeta) = U\zeta + \sum_{j=1}^N \frac{i\Gamma_j}{2\pi} \log \left(\frac{\zeta - \zeta_{vj}}{\zeta - \bar{\zeta}_{vj}} \right) \quad (5)$$

where vortex of strength Γ_j is located at ζ_{vj} . The streamlines in Figure 9 correspond to satisfying (a) flow separation at each sharp edge and (b) the condition of vanishing velocity at the vortex core. The trajectories are obtained by integrating the velocity components. Figure 9 also depicts that each vortex is found to return to its original position around the equilibrium, when given a finite displacement. The pressure distributions in Figure 10 are obtained when single, double and triple corrugations are incorporated onto an airfoil. In each case, the equilibrium is found to be stable.

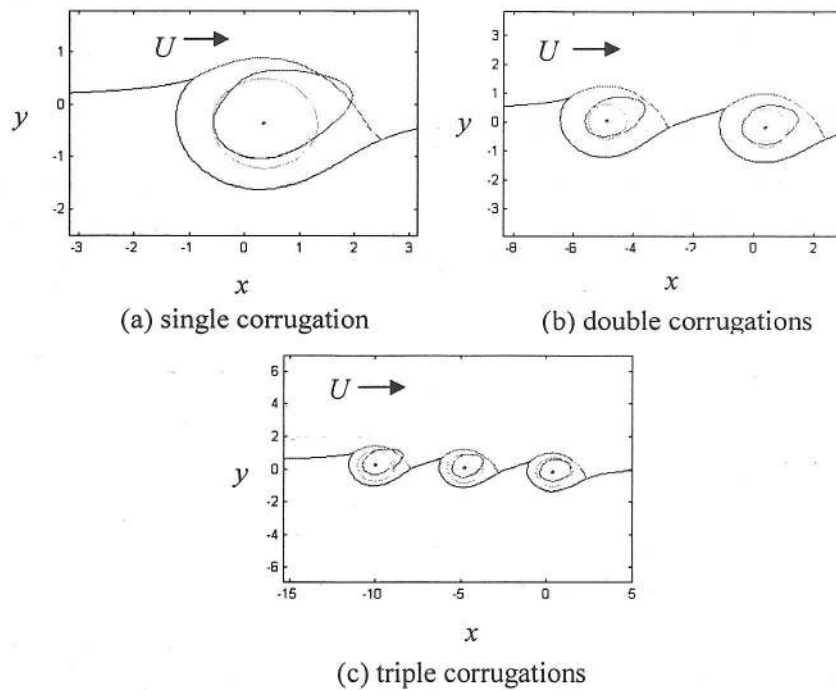


Figure 9: Streamlines and vortex trajectories on corrugated surfaces

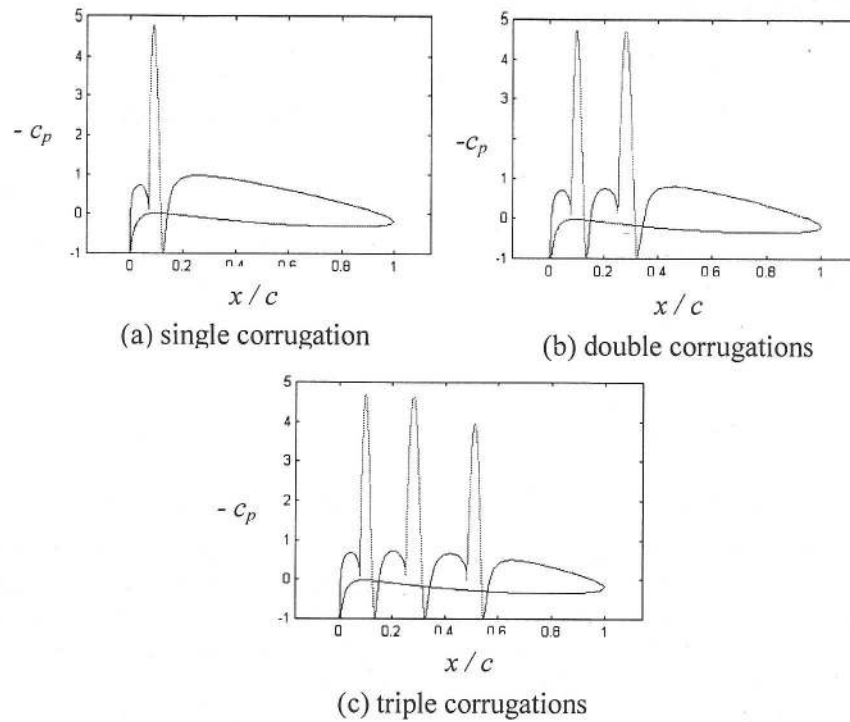


Figure 10: Pressure distributions on corrugated airfoils

4.0 AIRFOIL WITH ROTATING CYLINDER

Equation (4), when combined with the method developed in Yeung and Parkinson [12], can be used to study the flow past an airfoil and a cylinder. An example is given in Figure 11 where the mean streamline pattern and the pressure distribution are shown.

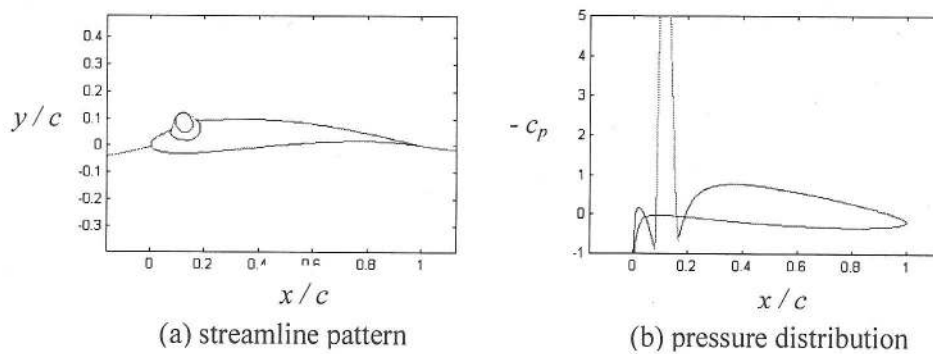


Figure 11: Flow model for airfoil with cylinder

5.0 CONCLUSION

In this study, a few theoretical models of unconventional airfoils are presented. The one having the highest lift is that of the triple corrugations, achieving a 10% more than that of a Joukowsky airfoil having the same thickness, camber and angle of attack. The presence of the standing vortices is the cause of the lift enhancement.

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7. CONCLUSIONS

The purpose of this study was to explore the ethical dimensions of the business case for sustainability. The study was conducted through a series of focus group discussions with business leaders and academics. The findings suggest that the business case for sustainability is not just about financial performance, but also about social and environmental performance. The study also found that business leaders are increasingly aware of the importance of sustainability and are taking steps to integrate it into their business strategy.

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