Coandă configured aircraft: A preliminary analytical assessment

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Abstract. The interest in the use of flow control for enhanced aerodynamic performance has grown, particularly in the use of jets (continuous, synthetic, pulsed, etc.), compliant surface, vortex-cell, and others. It has been widely documented that these active control concepts can dramatically alter the behaviour of aerodynamic components like airfoils, wings and bodies. In this conjunction, with the present demands of low-cost and efficient flights, the use of Coandă effect as a lift enhancer has attracted a lot of interest. Tangential jets that take advantage of the Coandă effect to closely follow the contours of the body have been considered to be simple and particularly effective. For this case, a large mass of surrounding air can be entrained, hence amplifying the circulation. In an effort to optimize the aerodynamic performance of an aircraft, such effect will be critically reviewed by taking advantage of recent progress. For this purpose, in this study, the design of a Coandă-configured aircraft wing will be mathematically idealized and modelled as a two-dimensional flow problem.

1. Introduction

In the era of globalization and high global concern on energy efficient flights, aircraft manufacturers have to revolutionize beyond conventional designs. Significant efforts have been devoted to the use of advanced technologies for greater energy extraction and conversion, as well as optimized propulsion systems. To fully utilize the technological elements that can contribute to innovations of future design concepts, one should explore the fundamental principles that play key roles in these technologies. One of these technologies that is of interest in this study is the circulation control wing (CCW), which is known to be a means of enhancing the bound circulation [1]. This technology is known to be superior for aerospace applications and has been extensively investigated over many years, both experimentally and numerically [2-12]. In brief, the CCW technique is executed by tangentially blowing high-velocity jet airflow over a highly curved surface. This creates a balance of the pressure and centrifugal forces, causing the boundary layer and the jet sheet to remain attached to the surface without any separation (i.e. phenomenon referred to as Coandă effect). Consequently, the rear stagnation point is repositioned toward the lower airfoil surface, further enhancing the airflow circulation around the entire airfoil. The outer irrotational flow is also turned substantially, leading to a higher value of the lift coefficient that is comparable to that achievable from the use of conventional high lift systems [2]. Figure 1 shows the introduction of a thin jet that is associated with tangential blowing over trailing edge surface, which represents one technique for lift enhancement.
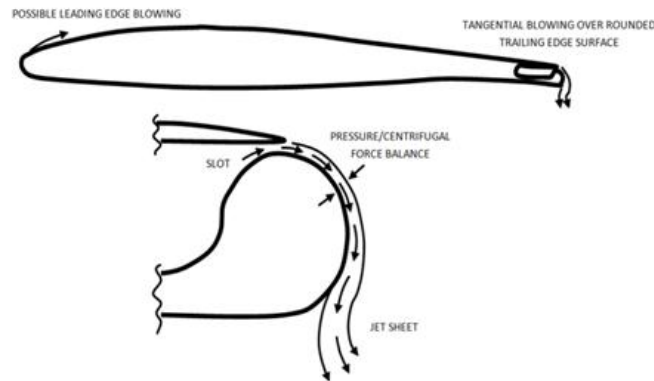
Figure 1: Coandă-jet over trailing edge surface for lift enhancement, adapted from [3]

Early CCW designs typically had a large-radius rounded trailing edge to maximize the lift benefit. These designs, however, also result in high drag penalty when the jet is turned off. One way to tackle this problem is by redesigning the shape of the trailing edge. A numerical simulation has shown that the best lift enhancing effect could be facilitated by designing the lower part of the trailing edge to be a flat surface and preserving the upper surface with a highly curved surface [4]. This curvature on the upper surface produces a large jet turning angle, leading to high generated lift. The progress of high-speed computers has made it possible to use the first-principles-based computational approaches for aerodynamic modelling of propeller blades, for example. Since these approaches are based on the laws of conservation of mass, momentum and energy, they can capture much of the physics in great details [5-7]. However, such approach also requires a considerable computational cost. Therefore, prior to the execution of a much more involved and complex computational model (e.g. via computational fluid dynamics (CFD)), a simple two-dimensional mathematical representation of the model can be drawn to pave the way. Similar approaches on modelling such designs have shown remarkable results [8-10].

In this particular work, the focus is placed on the basic airflow idealization over a two-dimensional (2D) curved rounding-off surface in subsonic flow (airfoil trailing-edge modification). A generalized mathematical model representing the momentum-jet-flow and the changes of pressure over the curved surfaces are drawn and presented for clarity. This simplified model is then analytically evaluated to determine aerodynamic performance of the Coandă-configured aircraft design. It is a kind of blended or hybrid method, combining the results from CFD and analytical models, offering a simple solution to approach such complex design problem. It should be noted that this method is not developed to replace CFD but more as a cheaper alternative to eliminate the repetitive computational cost and the reiteration of modelling procedures required.

2. Methodology

The study presented here is aimed to assist in the preliminary analysis of a Coandă configured aircraft, focusing on the aerodynamic aspect of the design. The starting point is using the 2D representations of a wing (i.e. airfoil). The method used is based on the fundamentals of physics: momentum theory [13] and Bernoulli's principle [14]. The total lift (L_T) is the sum of forces from the free-stream (L_∞) flow over an airfoil (CFD results from Ref. [8]; jet is turned off) plus the lift force generated by the Coandă effect (L_C) at the TE. This is given by Equation 1.

$$L_T = L_\infty + L_c \tag{1}$$

Moreover, the lift force from the Coandă effect consists of two parts: lift due to the jet-momentum (L_j) and lift due to the pressure differential (L_p). This turns Equation 1 into Equation 2.

$$L_T = L_\infty + \left(L_j + L_p\right) = L_\infty + \left(\int \dot{m} v_j \, ds + \int p \, r' \, ds\right) \tag{2}$$

The lift generated by Coandă effect is determined using the surface integral from pressure distribution acting on the airfoil surface. Figure 2 describes the approach taken in this work to arrive at a rounded trailing edge configuration, considering the best effect of the Coandă-jet configuration by redesigning the lower part near the trailing edge (TE) to be a flat surface, as suggested by Ref. [4].
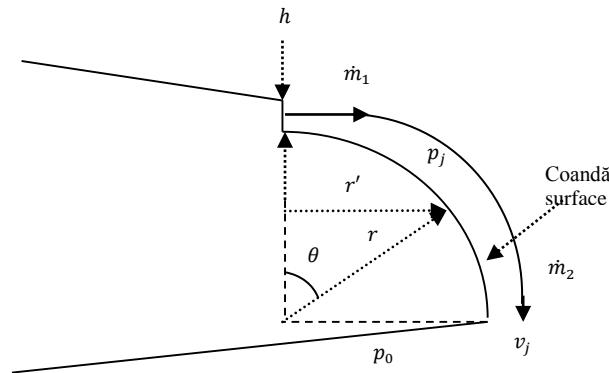

Figure 2: Construction of a rounded curved surface at the vicinity of the airfoil trailing-edge

For the first part, the lift from the momentum jet (bends of the jet flow towards the ground), L_j can be written as Equation 3. Then, based on Ref. [8], the height of jet at TE is taken to be $h = \frac{1}{50} r$. With this information, Equation 3 now becomes Equation 4.

$$L_j = \int \dot{m} v_j \, ds = \int (\rho A v_j) v_j \, ds = \rho v_j^2 \int_0^h dh \tag{3}$$

$$L_j = \frac{1}{50} \rho r v_j^2 \tag{4}$$

For the second part, the lift from pressure differential (between the lower and upper surfaces), L_p is derived from Bernoulli's equation as in Equation 5. The lift force due to pressure differential over the curved surface is then given by Equation 6.

$$p_j + \frac{1}{2} \rho v_j^2 = p_0 \qquad \rightarrow \qquad p = p_0 - p_j \tag{5}$$

$$L_p = \int p \, r' \, ds = p \int_0^{\frac{\pi}{2}} r' \, d\theta \tag{6}$$

From Figure 2, it can be observed that $r' = r \sin \theta$. Substituting this information, the lift generated by the pressure differential on the curved surface can be written as Equation 7.

$$L_p = pr \int_0^{\frac{\pi}{2}} \sin \theta \, d\theta \tag{7}$$

From CFD result of Ref. [8], $L_\infty = 17.41$ N/m. This is the lift force generated at $Re = 1 \times 10^6$ from a Coandă-modified S809 airfoil configuration when the jet flow, v_j is turned off. Inserting this value of L_∞ and substituting Equation 4 and Equation 7 into Equation 2, the component of lift forces from the jet-momentum and the pressure differential is given by Equation 8.

$$L_T = (17.41) + \left(\frac{1}{50} \rho r v_j^2 + \rho r v_j^2 \right) = 17.41 + \left(\frac{51}{50} \rho r v_j^2 \right) \tag{8}$$

The calculation of the difference or error between the CFD result (COMSOL) and the result obtained using Equation 8 can be done using Equation 9.

$$\% \, \text{Error} = \frac{|\text{Calculated} - \text{Simulation}|}{\text{Calculated}} \times 100\% \tag{9}$$

3. Analysis and Discussion

It should be noted that, as to simplify the whole problem and to retain all physical aspects of the flow, few assumptions have been made in this study: the analytical formulation is modelled at the vicinity of the TE (as shown in previous Figure 2), a uniform jet velocity profile has been adopted, the jet size is constant, the jet speed or velocity is taken to be the same or larger than the local velocity at the outer edge of the boundary layer and no flow separation occurs over the curved surfaces. The tabulated results are presented in Table 1, which show the generated lift forces from two respective sources; each with specific design conditions (as indicated in Figure 3). The data in the second column of Table 1 is obtained from previous parametric study on S809 airfoil with the jet turned on, which is available in Ref. [8]. Next to it is the obtained results by combining the CFD result when jet is off [8], plus the analytical result that is obtained by Equation 8. All in all, the tabulated data in Table 1 shows that, as the Coandă-jet speed increases, the lift forces are also increased. The data in the last column shows the respective error between the two approaches at each Coandă-jet (or momentum-jet) design condition.
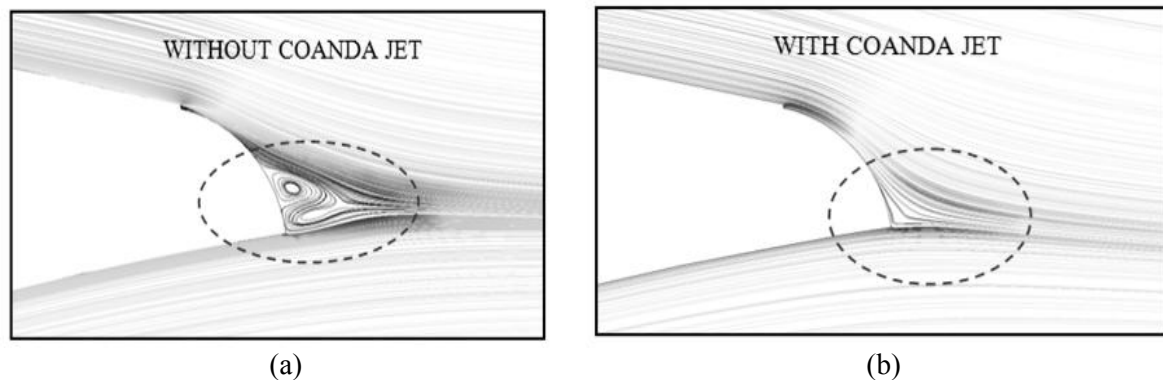

Figure 3: Flow fields of S809 airfoil: (a) with, (b) without - Coandă-jet [8]

Table 1: Lift forces from the analytical and numerical results

Coandă-jet (m/s)	Lift$_{COMSOL}$ (N/m)	Lift$_{Calculated}$ (N/m)	Error (%)
15	25.47	28.66	11.11
20	41.89	37.41	11.99
25	58.50	48.65	20.24
30	75.37	62.40	20.80
35	91.71	78.64	16.62
40	106.95	97.38	9.82

Figure 4 shows that both lines of the lift forces are increasing with the Coandă-jet. The trends for both plotted lines are relatively consistent. At lower Coandă-jet values (i.e. <20 m/s), it shows that the analytical model can give a good prediction. Nonetheless, as the Coandă-jet gets higher (i.e. >20 m/s), the analytical model is shown to give lower values than the numerical model. A plausible explanation for this situation can be the fact that, as the momentum from the Coandă-jet gets higher (i.e. numerical model), the outer irrotational flow will tend to turn. This effectively promotes a substantial increase in the circulation, which eventually leads to the higher generated lift. At present, this analytical model is unable to capture the flow interaction effects from the outer irrotational flow. However, the analytical model of a Coandă-configured aircraft-wing design has presented a simple mathematical correlation to simplify the problem.

4. Conclusion

Implementation of the analytical method offers a simple modelling technique to outfit complex fluid flow problems. It can provide a valuable propulsive (i.e. lift enhancement) modelling technique when the problem is too costly to be computed. The result obtained thus far indicates that the analytical model of the Coandă configured aircraft-wing design is applicable and can be used as an alternative way to estimate the Coandă performance. This approach combines the results from CFD and analytical models, offering cheaper alternative to avoid repetitive computations. In particular, for problems that shares almost similar physical modelling design layout and setup. It is very useful, for instance, to focus on the impact of a single design parameter while retaining the rest at constant; as commonly practiced in a parametric study. A final note is that this study is only valid upon certain designs and assumptions with a limited range of Coandă-jet flow. Thus, more detailed analysis is required since the present analytical work is only valid as to assist in assessing similar models.
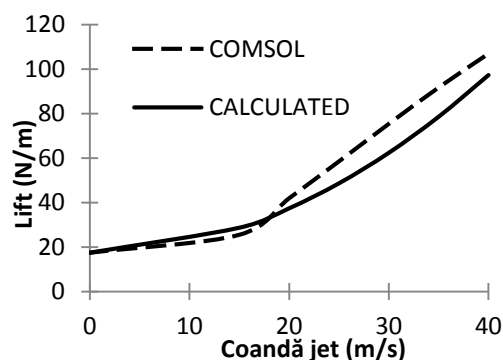

Figure 4: Comparison of the lift generated from the analytical and numerical results

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