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Research paper

Lift force for cylindrical and elliptical Coandă aircraft design

Mohd Faisal Abdul Hamid*, Azmin Shakrine Mohd Rafie, Ezanee Gires, Abd. Rahim Abu Talib

Department of Aerospace Engineering, Faculty of Engineering, Universiti Putra Malaysia, 43400 Serdang, Selangor, Malaysia.
**Corresponding author E-mail: mohd_faisal@upm.edu.my*

Abstract

Small aerial vehicles possess advantages in terms of size and accessibility in performing a variety of tasks. Presently, their design and performance is dependent on variations of conventional aerodynamic configurations (fixed- and rotary-wing). A disadvantage for these configurations is the aerodynamic potential between the mainstream airflow and the body surfaces are not fully utilized. To solve this issue, the Coandă effect is proposed whereby a high-velocity jet is blown tangentially over a curved surface to increase circulation and lift. Prior to the costly approach (experimental and numerical), an analytical formulation (via control volume analysis) to predict the aerodynamic Coandă lift force of the design concept is developed. This is an extended version of the existing mathematical formulations, capturing viscous flow effects. It is also pertinent for circular and elliptical-shaped designs. The results obtained show that the total lift force is dependent on the jet velocity, outflow angle, dimensions of the jet slot, the projected surface area, and the viscous effect. The approach has demonstrated how this modelling technique is effective in calculating the lift force for cylindrical and elliptical Coandă aircraft design.

Keywords: *Coandă effect; flow control; aircraft design; aerodynamic lift; jet momentum.*

1. Introduction

Small aerial vehicles have attracted a lot of interest from many research institutions, companies and agencies all over the world [1-6]; in line with the needs of delivering sensors, transmitting information, reconnaissance missions in areas otherwise inaccessible, etc. Typically, for their small size, they operate at relatively low Reynolds number, and their design by far is still reliant on conventional aerodynamic machines (such as fixed- and rotary-wing aircraft) [7-9]. For these aircraft, much of the concern is on their poor aerodynamic performance (e.g. endurance for hovering and indoor flight), in which the aerodynamic potential between the main stream airflow and the body surfaces of the aircraft are not fully utilized.

A unique approach to revamp this is by developing a methodology that enables full control of the airflow over the lift surfaces for achieving optimum aerodynamic performance [10]. There are various methods of flow control that have been developed and applied to dramatically alter the aerodynamic characteristics of aircraft component (e.g. wings, fuselage and empennage). These include continuous, synthetic and pulsed jets, compliant surfaces, vortex cells and the likes [11]. The active flow control via Coandă effect is implemented by tangentially blowing a small high velocity jet over a highly curved surface [10-12]. This produces a balance between the radial pressure gradient and centrifugal forces, causing the boundary layer and the jet sheet to remain attached along the curved surface; presented in Figure 1. As a result, the jet will turn without separation. In addition, the outer irrotational flow is also turned substantially, boosting the amount of lift comparable to that achieved from conventional high lift systems.

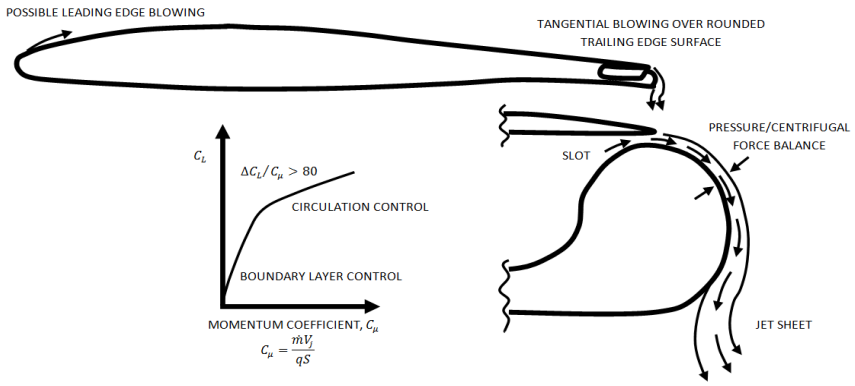


Fig. 1: Basics of circulation control aerodynamics [3]

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Two versions of analytical formulation using control volume approach for the cylindrical Coandă aircraft have been presented by Schroijen and Van Tooren [8] and Ahmed *et al*. [13]. In the first version [8], it has been concluded that the lift force is dependent on the jet velocity, outflow angle, dimensions of the jet slot, and introducing an efficiency parameter to capture the viscous effect. Also, it has been stated that the contribution of pressure integral (pressure differential) is included in the fluid force term, however, the formulation is unclear. The contribution of lift force is seems only derived from the jet-momentum. On the other hand, from the second version [13], it has clearly formulated the contributions of the pressure differential. While the effects due to the changes of the outflow angle and viscous flow effects are not included. This is because of the assumptions made, as to simplify the model; i.e. for circular shape with constant, uniform, and ideal jet flow (no losses). Thus, by bridging these two versions, a more comprehensive analytical formulation can be derived. In which, could also be expanded to accommodate circular as well as elliptical shapes of the design.

In this paper, an extended version of analytical model to analyse the aerodynamic performance of circular (and elliptical) Coandă aircraft is presented. The starting point of the present study is based on a simple model of a long twin-cylindrical shape aircraft design concept, evaluated analytically via control volume approach. This will provide an initial assessment on the extent of Coandă aircraft performances following the changes of the design sizing parameters involved. It is attempted to set a basis and warrant the efficacy of this design concept for future development of the circular and elliptical Coandă configured aircraft.

2. Development of the analytical model

The study presented here is aimed to provide basis in the preliminary analysis of Coandă aircraft, focusing on the aerodynamic aspect of the design (as illustrated in Figure 2). The method used is based on the fundamentals of physics: control volume analysis utilizing momentum theory [14] and Bernoulli's principle [15]. The analysis is as follows,

$$Lift_{Coandă} = Lift_{jet-momentum} + Lift_{pressure\ differential}$$

The total Coandă lift (L_c) is the sum of forces from both left and right rounded cylindrical shape Coandă configured aircraft. The lift force from each side consists of two parts: lift due to the jet-momentum (L_j), and lift due to the pressure differential (L_p). Here, for simplicity, both left and right of the cylindrical shape Coandă aircraft are analysed together, placed side-by-side, forming one-long single part (or unit). The net force acting on a control volume of fluid can expressed as given by Eqn. 1.

$$L_c = L_j + L_p \tag{1}$$

Referring to the control volume as depicted in Figure 3, the problem can be exemplified via the conservation of mass principle. By momentum-force balance,

$$F_j = \frac{d}{dt}(mV) = \int (\rho V.\,ds)\,V \tag{2}$$

Thus, solving the vertical component of the lift force,

$$\begin{aligned} F_j &= \rho h l v_{j-out}\left(\begin{bmatrix} v_{j,x} \\ 0 \end{bmatrix}_{in} - \begin{bmatrix} v_{j,x} \\ -v_{j,y} \end{bmatrix}_{out}\right) \\ &= \rho h l v_{j-in} v_{j-out}\left(\begin{bmatrix} 1 \\ 0 \end{bmatrix}_{in} - \begin{bmatrix} \sin\theta \\ -\cos\theta \end{bmatrix}_{out}\right) \end{aligned} \tag{3}$$

where ρ is the air density, h is the jet height, l is the length of the aircraft, θ is the angle of the jet outflow, with v_{j-in} and v_{j-out} are the jet flow velocity entering and leaving the system, respectively.

From the conservation of mass ($\dot{m}_{in} = \dot{m}_{out}$), concerning the rate of mass flow in and out of the system,

$$v_{j-out} = \left(\frac{h}{t}\right) v_{j-in} \tag{4}$$

The lift (y-direction) generated by the momentum jet,

$$L_j = \left(\frac{h}{t}\right)^2 \rho h l {v_{j-in}}^2 \cos\theta \tag{5}$$

For the second part, the lift due to the pressure differential, L_p,

$$\boldsymbol{F}_p(L_p, D_p) = \int p\,ds \;\rightarrow\; L_p = L_{p-lower} - L_{p-upper} \tag{6}$$

With reference to the control volume given in Figure 3, the lift generated from pressure differential is calculated from the pressure difference between the lower and the upper surface,

$$\begin{aligned} L_p = &\int_0^{\pi/2} p_a\, l R_x \cos\theta\, d\theta \\ &- \int_0^{\pi/2} \left(p_a - \frac{h}{R_y}\rho {v_{j-out}}^2\right) l R_x \cos\theta\, d\theta \end{aligned} \tag{7}$$

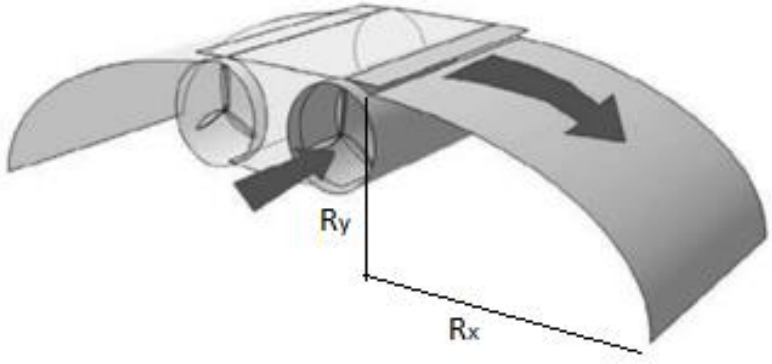


Fig. 2: Cylindrical/Elliptical Coandă configured aircraft model (adapted from Schroijen and van Tooren [8])

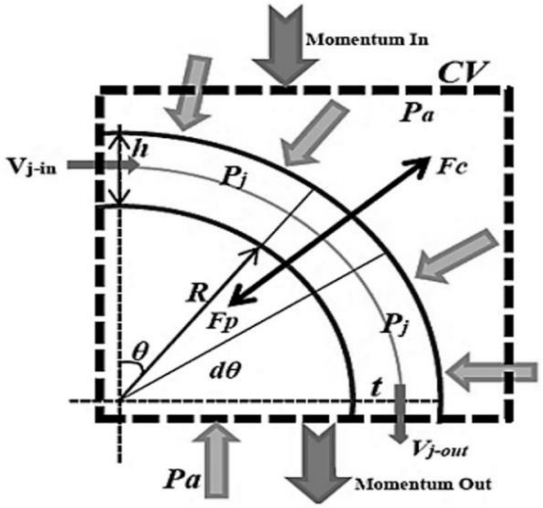


Fig. 3: Pressure forces effect on two-dimensional cylindrical Coandă aircraft [13]

So, by solving Eqn. 7, the lift force due to the pressure differential on the curved surface, and for lift (y-direction), and from Eqn. 4,

$$L_p = \int_0^{\pi/2} \left(\frac{R_x}{R_y}\right) hl\rho {v_{j-out}}^2 \cos\theta \, d\theta$$
$$= \left(\frac{R_x}{R_y}\right) \rho hl {v_{j-out}}^2 \quad (8)$$
$$= \left(\frac{R_x}{R_y}\right) \rho hl \left(\frac{h}{t} v_{j-in}\right)^2$$

By taking the sum from both two parts, as given in Eqn. 1, and by substituting Eqn. 5 and Eqn. 8 for the component of lift forces due to the jet-momentum (L_j) and the pressure differential (L_p), respectively, the total Coandă lift/thrust is expressed as,

$$L_c = \left[\left(\frac{h}{t}\right)^2 \rho hl {v_{j-in}}^2 \cos\theta\right] + \left[\left(\frac{R_x}{R_y}\right)\left(\frac{h}{t}\right)^2 \rho hl {v_{j-in}}^2\right] \quad (9)$$

For circular shape $(R_x = R_y)$ and for elliptical shape $(R_x > R_y)$. In which, Rx and Ry are the semi minor axis and semi major axis of the design, respectively. With Rx/Ry is the length ratio of the design model.

It is assumed that the ratio of $\frac{h}{t}$ will get smaller due to the increasing of jet thickness height, t. Hence, an efficiency parameter is introduced, $\eta_j = \left(\frac{h}{t}\right)^2$ to model this relation, which is primarily due to the viscosity effect.

Thus, Eqn. 9 deduced to,

$$L_j = \eta_j \rho hl {v_{j-in}}^2 \left[\cos\theta + \left(\frac{R_x}{R_y}\right)\right] \quad (10)$$

Derivation of the analytical formulation, given by Eqn. 10, is an extended version for cylindrical Coandă aircraft as presented earlier by Schroijen and van Tooren [8] and Ahmed *et al.* [13].

3. Analysis and discussion

The formulation given here have includes several design parameters, capturing most of the important physical aspects of the fluid flow, which is crucial for the performance estimation of the model. From the analytical expression given in this analysis, it shows that the lift due to the Coandă effect is dependent on the jet velocity v_{j-in}, outflow angle θ, dimensions (or sizing) of the jet slot hl, the increase of jet height t due to the viscous effect, and the ratio of R_x/R_y. This is a ratio between the semi-minor R_y and semi-major R_x axis of an ellipse's, which can be expanded for an elliptical design of the Coandă aircraft model.

Figure 4 is produced to validate and compare the present theoretical formulation with the case presented by Ahmed *et. al.* [13] and Schroijen and van Tooren [8] for two-dimensional cylindrical Coandă design model. From Figure 4, the result (solid line) have shown a good correlation and in agreement with the CFD data [3]. With the increases of the ratio of the projected area (Rx / Ry) > 1, much bigger surface area seeing from the top/plan view, hence, potentially more lift), it shows that the amount of lift is increased (i.e. dotted and long dotted lines). This is consistent with the result presented by Schroijen and van Tooren [8], which is the lift for the elliptical is higher than for the circular shape design.

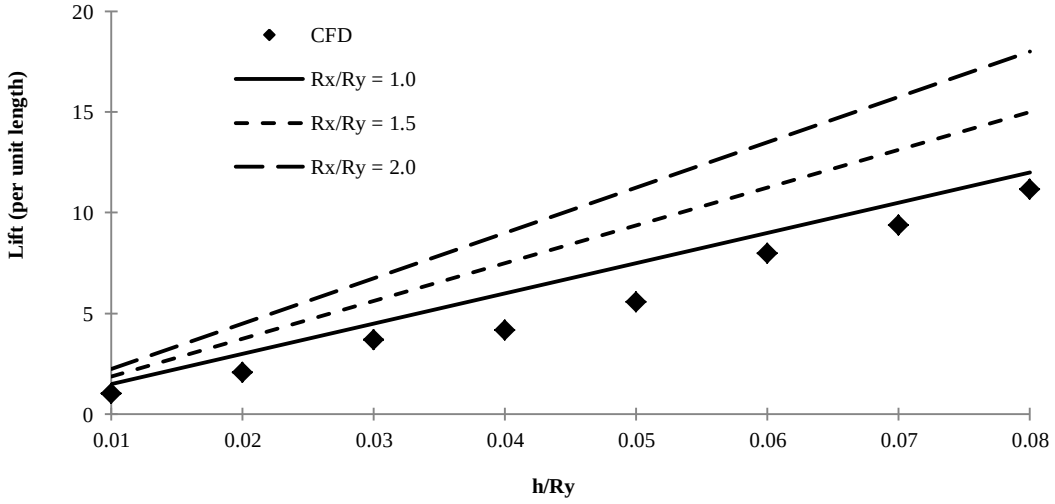


Fig. 4: Validation and comparison with the numerical analysis (CFD) presented by Ahmed *et al.* [13] for two-dimensional cylindrical Coandă design model. The solid line is for the circular design (Rx/Ry = 1.0), while the short-and long-dotted lines are both for the elliptical shape design (Rx/Ry = 1.5 and Rx/Ry = 2.0)

Crucially, from Figure 5, it shows that the amount of lift will reduced to half, as the outflow angle is increased to 90 degrees. This is due to the fact that, $\cos 90° = 0$, hence, the amount of lift is now solely come from the force produced by the pressure differential on the curved surface. This is also valid for the elliptical shape design.

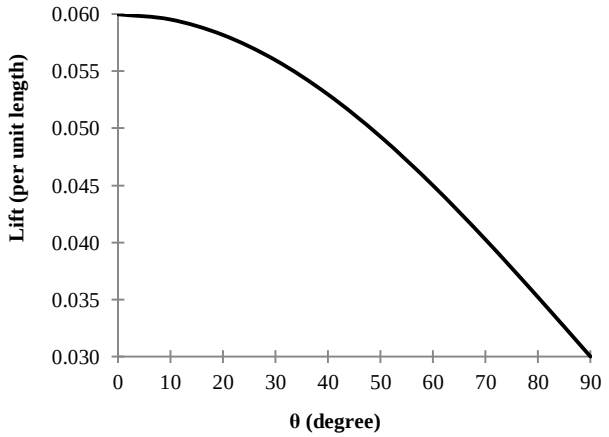


Fig. 5: Changes of the lift force of Coandă design model with increasing of outflow angle, θ; with $\frac{R_x}{R_y} = 1$,$v_{j-in} = 5\ m/s$, and $h = 0.001\ m$.

4. Conclusions and future work

The analytical study carried out in this work serves as a first step towards better understanding of the characteristics of Coandă effect and how it can be best utilized. It is devoted only to two-dimensional cylindrical and/or elliptical shape Coandă aircraft performance studies, and has been motivated by works related to Coandă-jet circulation control for improved performance of new generation of lift and propulsion systems.

The implementation of the analytical model offers a simple modelling technique to outfit complex fluid flow problems, which can served as a good platform to predict the performance of Coandă aircraft design model. It can provide a valuable propulsive (lift enhancement) modelling technique if a more sophisticated numerical approach for the entire system is too detailed to be used in practice. The result obtained thus far shows that, the total lift force is dependent on the jet velocity, outflow angle, dimensions (or sizing) of the jet slot, the projected surface area, and the viscous effect. Here, from the mathematical model and the analysis, it is shown that the viscous effect and the jet outflow angle are the key points in generating lift. Optimizing the viscous effect $\eta_j = 1$ could potentially maximize the jet outflow angle θ, which would then balancing the radial pressure gradient and centrifugal forces, causing the jet sheet to remain attached. This would allow the system to harness the full potential of the jet flow momentum in producing lift force.

The approach presented here has demonstrated how this modelling technique is effective in calculating the lift force. In the future, this model can be further expanded to estimate the power required and also to include some other fluid physics. For now, it is limited by the predetermined assumptions and only valid as to assist in assessing similar model. Thus, as to make it more realistic model, more analysis is required since the present model is served as an ideal representation of the design concept.

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