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Steady and unsteady flow simulation of a combined jet flap and Coanda jet effects on a 2D airfoil aerodynamic performance

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Abstract - *Two-dimensional numerical flow simulations were performed to investigate the combined effects of two types of trailing edge blowing jets upon the aerodynamic performance of a supercritical airfoil. One of the two (Coanda jet) was blown tangentially around a Coanda surface (round trailing edge) while the other one (jet flap) was blown normally off the Coanda surface at a given angle. Steady and time-accurate viscous flow simulations were performed and demonstrated stable flow solutions. Results obtained for four different airfoil configurations (no-jets, Coanda jet only, jet flap only, combined Coanda jet and jet flap) showed that the combined jets configuration presented the best aerodynamic performance.*

1. INTRODUCTION

In the continuing search for improvements in the aerodynamic efficiency of wind turbines, many aerodynamic enhancements to the blades of conventional turbines have been proposed and studied. Numerous techniques have been studied to increase the lift to drag ratio of the blades and hence their overall efficiency at extracting power from the wind. To this end, techniques such as blowing air over the blade trailing edge [1], blowing air through the trailing edge (jet flap) [2] and the use of a Coanda surface at the trailing edge with tangential blowing [3] are known to produce substantial increases in lift. Many experimental investigations have also been conducted on these three types of concepts in the past [2, 3].

A jet flap is characterized by a high-velocity air jet that is blown straight out of the airfoil trailing edge at a controlled angle. Its potential benefits originate in the more global influence that the deflected jet sheet has upon the surrounding flowfield. An aerodynamic Coanda effect is generated when a high-velocity air jet is blown tangentially along a curved surface. The circumferential air jet remains attached to the surface owing to the balance between the low static pressures generated by the jet itself on the surface and the centrifugal force acting on the jet. These two aerodynamic techniques are classically well established for aeronautical applications [2]. Extending circulation control towards wind turbine applications, there is ongoing research in this topic with an aim towards increased power generation [1]. More recently, the availability of convenient and economic modeling, to study larger performance matrices due to increased (and lower cost) computational power, has meant that the investigation of trailing edge blowing (jet flap) and Coanda surfaces using Computational Fluid Dynamics has received greater attention [1].

In the current numerical investigation, we believe that a combination of jet flap and Coanda effect may lead to an additive effect and substantial increase in the airfoil lift. To prove the concept, the present investigation was carried out on low Mach number flow over a supercritical airfoil with a round trailing edge, where a jet flap and a Coanda jet are applied concurrently. Results in terms of Mach number distribution, pressure coefficient profiles and force coefficients (lift and drag) are presented.

2. PROBLEM DESCRIPTION AND NUMERICAL SOLUTIONS

The free stream flow conditions, in this investigation, are consistent for a Reynolds number of 1 million, a Mach number of 0.14 and an angle of attack of 5° and 10°. The study concentrated on the WTEA airfoil section [4] with 16 % (t_{max} / c) with 1 % thick trailing edge. A structured

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multi-block mesh topology was constructed using a far field of 50 chords away from the airfoil. As shown in Figure 1, a Coanda jet and a jet flap were applied at the trail edge. As a measure of the jets strength, a jet momentum coefficient is introduced as:

$$C_\mu = \frac{\int_{h_j} \rho_j V_j^2 \, ds}{1/2 \rho_\infty V_\infty^2 A} \tag{1}$$

In the present study, flow rate jets were prescribed such that the resulting momentum coefficients at the jets exits are $C_{\mu c} = 0.0515$ for the Coanda jet and by $C_{\mu jf} = 0.0244$ for the jet flap. Another Coanda jet momentum coefficient $C_{\mu c} = 0.0220$ was also selected as an additional example.

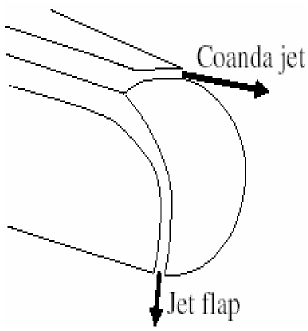


Fig. 1: WTEA airfoil trailing edge topology showing the air jet ducts

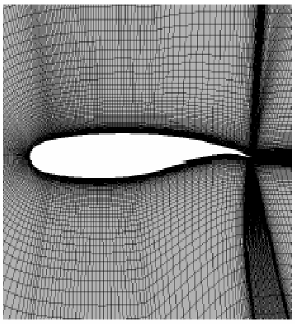


Fig. 2: Mesh around the WTEA airfoil

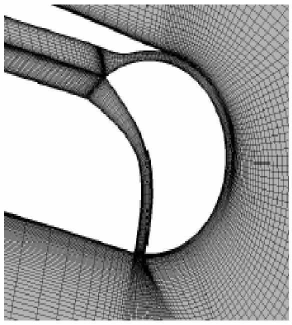


Fig. 3: Mesh around the trailing edge and inside the air jet ducts

The viscous mesh used in this study is shown in Figures 2 and 3. The grid around the airfoil is a combined C and O grid. There are 258 points distributed on the upper and lower surfaces of the airfoil, 140 points in the normal direction and 138 points along the Coanda surface. The CFD-FASTRAN solver [5] was used to compute the numerical solutions in steady and unsteady modes. The discretized version of the Navier-Stokes equations with the Menter SST- $k\omega$ turbulence model were utilized.

3. RESULTS AND DISCUSSION

In order to asses the validity of the flow solver, a predicted pressure coefficient profile obtained for $Ma = 0.25$, $\alpha = 5°$ and $Re_c = 2\times10^6$ was compared to the experimental measured data [4] with a good agreement, as shown in Figure 4. To examine the effect of the prescribed trailing edge blowing jets on the airfoil aerodynamic performance, four flow configurations were considered. In the first flow configuration (no-jets), both jets were turned off. The Coanda jet was turned on in the second configuration and the jet flap alone was turned on in the third configuration. In the fourth one, both Coanda jet and jet flap were turned on. Figure 5 shows the computed pressure coefficient profiles for the four flow configurations, and Table 1 reports the lift and the drag coefficients. For an angle of attack of 5°, the computed results show that, based on the lift to drag ratio alone, the fourth configuration exhibited the most desirable aerodynamic performance. For an angle of attack of 10°, the fourth flow configuration showed a slight increase in the lift owing to a mild trailing edge flow separation on the upper surface of the airfoil.

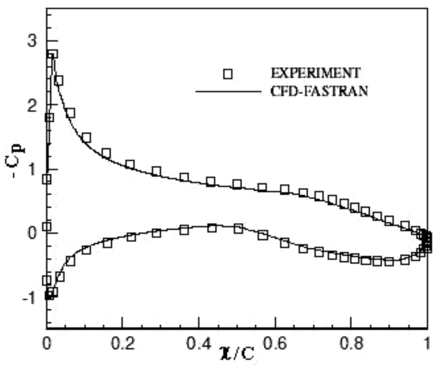


Fig. 4: Pressure coefficient profile for not-jet flow configuration obtained for $Ma = 0.25$, $\alpha = 5°$ and $Re_C = 2 \times 10^6$

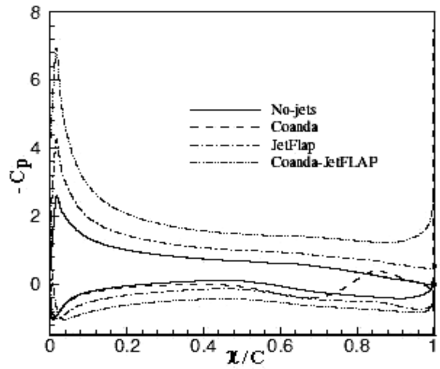


Fig. 5: Pressure coefficient profiles for different flow configurations obtained for $Ma = 0.14$, $\alpha = 5°$ and $Re_C = 10^6$

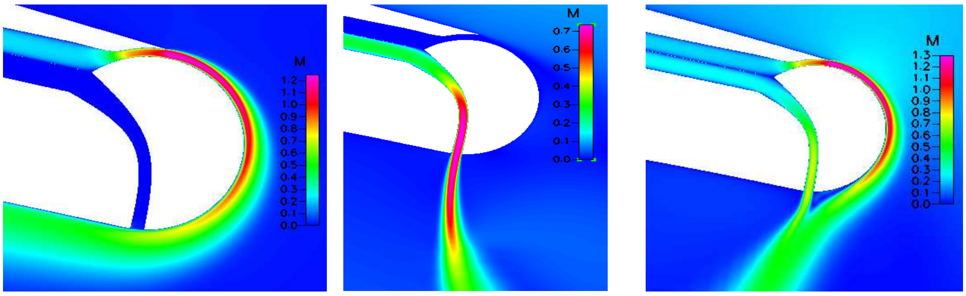
With an aim to further analyse and verify the quality of the aerodynamic performance of each of the above four configurations, additional results in terms of the flow field Mach number distribution are displayed in Figure 6. The complementary streamlines from these same cases are shown in Figure 7. While discussing these results, a particular note should be made of the reference no-jets configuration flow patterns, as accounted for in **Table 1** and further addressed in both Figures 5 and 7a. For the singular Coanda jet flow configuration, Table 1 shows lower lift coefficient with relatively high drag. Referring to Figures 6a and 7b, it is seen that the jet remains attached to the Coanda surface for almost the full circular arc of the trailing edge such that the jet is ultimately directed in an upstream direction on the lower surface of the airfloil. The jet is progressively diffused and weakened as it collides with the external flow which is moving downstream and following the lower surface. Essentially, the jet causes the boundary layer that has developed on the lower surface of the airfoil to stagnate and then separate. This flow behaviour created a large flow recirculation below the airfoil (not shown here). Owing to the reduced surface pressure resulting from the jet flow beneath the airfoil, the lift force was decreased as observed in **Table 1** when compared to the no-jet flow configuration. This is also clear from the pressure coefficient profile in Figure 5. Furthermore, the momentum effect resulting from having a jet flow pointing in an upstream direction would understandably lead to an increase in drag.

Table 1: Airfoil aerodynamic performance (* Results obtained with $C_{\mu c} = 0.0220$)

	C_L		C_D		C_L / C_D	
Configuration	5°	10°	5°	10°	5°	10°
No-jets	0.891	1.356	0.0281	0.0400	31.71	33.83
Coandajet	0.846	1.161	0.0465	0.0497	18.19	23.36
Jet flap	1.608	2.067	0.0281	0.0447	57.22	46.22
Coanda and jet flap	2.576 2.122 *	2.721	0.0353 0.0297 *	0.0564	72.97 71.46 *	48.29

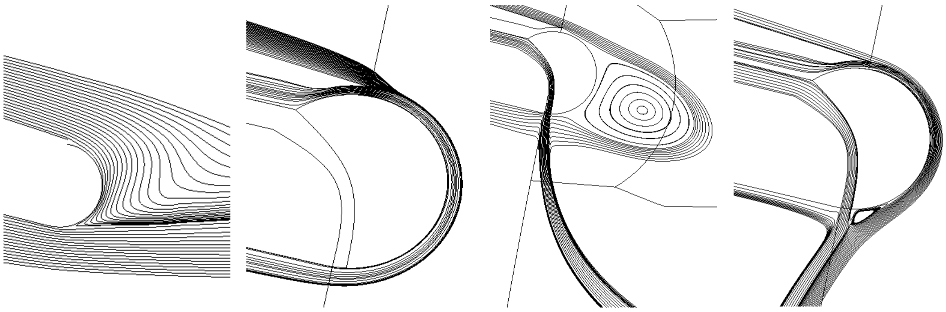
For the second flow configuration (the simple jet flap), as shown in Figure 6b near the trailing edge, the flow about the airfoil exhibited increased circulation as would be observed if a simple flap had been deflected downward at the trailing edge, leading to increased suction on the top of the airfoil, while at the same time causing the pressure to increase below the airfoil as seen in Figure 5. This flow behaviour resulted in a net increase in the lift coefficient (see **Table 1**). As the jet flap angle was about 96.6° from the chord line, the jet was diverted downward causing a significant local flow recirculation near the round trailing edge, as displayed in figures 7c by the streamlines.

For the combined jets configuration, the Coanda jet remains attached to the curved surface and merges with the jet flap flow resulting in an amplified jet flap. This jets combination appears to benefit from the transformation of the Coanda jet into a jet flap, (see Fig. 6c). This is clearly illustrated by the Mach number distribution in Figure 6c and by the streamlines in Figure 7d. This flow pattern also increased the circulation about the airfoil leading to lower pressure on the upper surface and higher pressure on the lower surface (Fig. 5). As a result, a high lift coefficient is obtained as shown in **Table 1**. The flow patterns in Figures 6c and 7d showed a region of recirculating flow near the junction of the two jets. For a higher angle of attack, $\alpha = 10°$, owing to a mild trailing edge flow separation, the combined jet configuration did not show a significant increase in the lift coefficient (see **Table 1**) when compared to that obtained for $\alpha = 5°$.



(a) Coanda jet (b) Jet flap (c) Coanda jet and Jet flap

Fig. 6: Mach number distribution around the airfoil trailing edge for $Ma = 0.14$, $\alpha = 5°$ and $Re_C = 10^6$



(a) No-jets (b) Coanda jet (c) Jet flap (d) Coanda jet and Jet flap

Fig. 7: Flow streamlines around the airfoil trailing and inside the jets ducts

Estimates of the net power gain resulting from the application of the combined Coanda jet and jet flap on a simple horizontal axis wind turbine (HAWT) were performed next. For this simple study, a blade element situated at a radial location on the blade of this simple HAWT was selected as a representative indicator of the blade's performance with and without the combined Coanda jet and jet flap. Based on the turbine blade specification [1], a rectangular untwisted blade with a pitch angle of 12°, rotating at 71.63 rpm was chosen. The radial location and the inflow at the rotor were chosen such the local Mach number and angle of attack match the corresponding values under present study ($Ma = 0.14$ and $\alpha = 5°, 10°$). The power generated by a blade element ($c \times dr$) at a given radial location is given by :

$$\frac{dP}{dr} = \left(L\sin\phi - D\cos\phi\right)\omega r \tag{2}$$

where $\phi = \theta + \alpha$ is the angle formed by the local incoming flow velocity with respect to the plane of rotation. The power consumed to produce the jets with a source that generates compressed air is given by:

$$\frac{dP}{dr} = \int_{h_j} \frac{1}{2} C \rho_j V_j^3 \, ds \tag{3}$$

where $C = 1.3$ is a parameter that takes into account the total power required to produce the jets and ds is an infinitesimal span length of the blade.

The net power gain per span unit is given by the total turbine power generated by the blade element with both jets minus the power generated by the blade element without the two jets with a further reduction to account for the power consumed in the production of the air jets. When comparing the sectional power generated for the blade element obtained without jets, it was found that for jet momentum coefficients of $C_{\mu c} = 0.0515$ and $C_{\mu jf} = 0.0244$ the net power gain (above the no-jets case) was found to be about 10.1 % for $\alpha = 5°$ and 5.2 % for $\alpha = 10°$. Clearly, the power required to produce the jets was excessive for these magnitudes of jet momentum coefficient, such that the net gain in power produced was not too substantial. However, when the Coanda jet flow rate was reduced by 25 %, resulting in a lower jet momentum coefficient of $C_{\mu c} = 0.0220$, a net gain in blade sectional power of 75.4 % was predicted.

4. CONCLUSIONS

The present computational fluid dynamic investigation, based on viscous flow simulations, showed that a combined Coanda jet and jet flap resulted in lift coefficients larger than that produced by an individual jet for two representative angles of attack. The present investigation is very much preliminary in nature and does not address the added complexities of blade geometry in terms of taper, twist and aspect ratio. The increase in net blade sectional power as observed in the blade element example appears to hold promise for useful application of this technology to HAWT. A further investigation into the effects of the jet momentum coefficients and jet flap angle is recommended to identify the optimum flow configuration that may result in larger net power benefits.

NOMENCLATURE

c	Chord length 0.3048 m	Re_c	Reynolds number, 10^6
C_μ	Jet momentum coefficient	r	Blade radial location
C	Jet power production coefficient	V_j	Local jet velocity
D	Drag force	α	Angle of attack
dP/dr	Radial blade element power	ω	Rotational speed
h_j	Thickness of the jets	θ	Blade pitch angle
L	Lift force	∞	Refers to free stream condition
Ma	Mach number		

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