Aerodynamic Characteristics of Flow over Two Unsymmetrical Tandemly Arranged Airfoils – Numerical Simulation

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Abstract. There have been many insects having a tandem wing configuration that gives them a major advantage for maneuvering with various desirable speed, such as dragonflies and butterflies, but subsequently have been used for a wider range of applications. So, it is well known that the tandem airfoil arrangement will have better aerodynamic characteristics than those of the single airfoil arrangement. The present work aims at numerically predicting the aerodynamic characteristics of the single airfoil and tandem airfoil arrangements of the Wortmann FX 63-137 airfoil profile at a Reynolds number of 0.5 x 10⁶. The numerical simulations are performed using commercial CFD software, ANSYS-Fluent. Turbulent flows are modeled using the k-ω RANS model with a second-order upwind scheme. The pressure-velocity coupling is done through the SIMPLE algorithm. In the tandem arrangement, airfoils are positively staggered in the flow direction with variable gaps ranging from 0.1m to 0.7m with an increment of 0.2m and the perpendicular distance between the leading edges of two airfoils is fixed at 0.3 m and simulations are performed for a various angle of attacks with a range of 0 to ± 14⁰. The aerodynamic characteristics of the single and tandem arrangements of the same airfoil are compared and the effect of wake from the primary airfoil on a secondary airfoil at different angles of attack is also studied for the same conditions.

1. Introduction
The Tandem arrangement concept was used first in the aircraft named WRIGHT FLYER 1 designed by WRIGHT BROTHERS which was the first-ever successful heavier than airpower aircraft to achieve controlled, sustained flight with a pilot aboard. At that moment it changed history in the aeronautical society and gave birth to all the new technology that is being used. Yet having so many advantages and development the tandem airfoil or wing configuration yet gives a major unique advantage in the ground effect of the aircraft and the reduction of the high stall angle crashes that took place before. This type of technology has a huge scope for applications like MAV, UAV, canard planes, water vehicles with low ground effect and many more. The tandem arranged airfoil/ wing comprises two main wings that are used for generating lift to the aircraft in which one of the wings is situated in front of the other. This type of configuration has many design principles that one has to follow around for designing such aircraft. The Tandem configuration has many types such as biplane, canard, positive staggered, and negative staggered wing. Thereafter the study of tandem configuration has been a field of interest over the past years.

As presented by Scharpf and Mueller [1] at low speed a laminar separation bubble can form when the laminar boundary layer near the leading edge of the airfoil cannot overcome the adverse pressure gradient due to curvature of an airfoil and the result would lead to turbulent flow. Therefore, Reynold's
number above $10^6$ transitions from laminar to turbulent layer occurs without any separation and it does not create any problem for the separation bubble. However, it plays a dominant role in the low Reynolds number. In this numerical study, the tandem airfoil arrangement with Reynolds number $0.5 \times 10^6$ with a gap of 10% to 70% chord length between the two airfoils is simulated using the turbulence $k$-$\omega$ RANS model with a second-order upwind scheme to analyze the effect of wake formation from upstream airfoil to the downstream airfoil that occurs during the flow.

2. Literature survey

Wolkovitch [2] did the study in which the Prandtl-Munk theory predicted that the tandem arrangement of the consecutive wings having a large gap would have a low induced drag than the conventional wing-tail arrangement of the similar span. Their test result of tandem configuration showed lower induced drag values than the predicted and can be used for the VTOL subsonic aircraft. Mathre [3] carried out his research on analyzing the 2-dimensional flow conditions for an incompressible steady flow around different airfoils such as Wortmann FX 63-137 at Reynolds number $0.28 \times 10^6$, $0.5 \times 10^6$, $0.7 \times 10^6$ and the coefficient of lift values were compared for the validations. Scharpf and Muellert [1] performed an experimental study of flow over two identical unsymmetrical airfoils of 6-in chord and 16-in span in a wind tunnel. This resulted in an incremented result of lift and drag coefficients of the single airfoil and tandem arranged airfoils which could be utilized on a closely coupled tandem wing arrangement. Lim et al. [4] researched on the behavior of tandem arranged s11020 airfoil was studied when kept at various flapping conditions in the earlier study at a Re of 10,000 and observed the improvement of the various parameters like lift, thrust and efficiency of the wings with an average value of lift i.e. 4.59 compared to single airfoil i.e. 3.04. Broering and Lian [5] suggested that the tandem wing arrangement may have a better advantage over the single airfoil configuration by doing a numerical study by using incompressible Navier-Stokes solver with an overlapping mesh grid method. By changing the phase angle the result showed that it allows the tandem wing to change the flight mode between high thrust efficiency and high lift efficiency. Mahubub [6] investigated experimentally where the flow-induced lift and drag and Strouhal number of the submerged cylinder was observed at Reynolds number of $9.7 \times 10^4$ to $6.5 \times 10^5$ with the spacing ratio of the cylinders varying from 1.1 to 4.5 i.e. (L/D) and it was noted that the lift, drag and Strouhal number values were very responsive towards Reynolds number due to the change in the flow structure. Husain et al. [7] performed numerical simulation for a tandem arranged airfoils of eagle 150 aircraft and the aerodynamic test was carried out in an open-circuit wind tunnel at 38 m/s. The two tests carried out were to capture the lift coefficient data of a single wing and a second test with a different tandem/staggered position of the airfoils. The boundary layer formation was predicted using the $k$-$\varepsilon$ turbulence model in the computational analysis. This resulted in the generation of wake from leading-edge which disturbed the flow over the trailing airfoil. Also, Fu Jinbin et al. [8] studied numerically on a low Reynolds number NACA6409 airfoil profile with a 2-dimensional RANS model on a structure grid and performed an experimental test to find the design parameters that affect the aerodynamic of the tandem arranged airfoil on the basis of stagger, gap and declare. The result showed that the declage played an important role than the stagger and the gap of the tandem configuration. Yokoi [9] carried out a study in which he focused on the numerical analysis of the tandemly arranged airfoil with the help of the vortex generation method. The airfoil profile of NACA0012 was investigated for various angles of attack. The result showed the lift characteristic in tandem arranged airfoil gave a better result than the single airfoil and irrespective of the angle of attack the lift forces were induced on the airfoil individually. Also, there have been few types of research [10-13] which gave a brief idea about the flow characteristics of the tandemly arranged body with airfoil and cylinders and also the flow characteristics of the single airfoil configuration.

From the literature review, it is found that various aspects of tandem arranged airfoil for symmetrical and unsymmetrical and even cylindrical profiles were studied by various researchers and concluded that the tandem configuration gives a better result than the single arrangement system. Up to the authors’ knowledge, still there is a gap on studying the effects of distance between the two airfoils in tandem arrangements. Hence the objective of the present study is to study the effects of distance between the two airfoils along with various angle of attacks of the upstream and downstream
3. Numerical methodology

3.1 Geometry creation

The Wortmann FX 63-137 [3] airfoil of chord 1 m is used for both the 2-dimensional airfoil and tandem arranged airfoil with a Reynolds number of $0.5 \times 10^6$. For creating the airfoil, CATIA V5 is used and an .IGS file is then imported to ANSYS Fluent. To make the domain around the airfoil, the C-type domain construction is created so that it could capture the curvature effect properly from the leading edge (see Figure 1). The radius of the circular domain is 10 C and the width of the domain is 15 C, where C is the chord length. The configuration of staggered airfoil arrangement is made by keeping a fixed value between the airfoils of 0.3 m in the y-direction. The other parameters such as $\alpha_u$, $\alpha_d$ are the angle of attacks of upstream and downstream airfoils, respectively and the distances (x, y) between the trailing edge from primary airfoil and the leading edge of the secondary airfoil were considered for designing the tandem configuration.

![Figure 1. The schematic diagram of the boundary conditions for the domain.](image)

3.2 Meshing

Using an integrated ICEM, CFD software in ANSYS fluent, a structured mesh is created with proper edge biasing to capture the boundary layer forming inside the viscous layer. The single surface was split into the different smaller domains, as shown in Figure 2, to control grid refinement around the airfoil for better numerical results. The same steps are considered for generating the mesh for various configuration of the gap between the airfoils of 10 to 70 % of C where $\alpha_u$ and $\alpha_d$ are kept at $0^\circ, 6^\circ, 12^\circ, 14^\circ$ and $16^\circ$ simultaneously to capture the stall effect on the airfoils.
3.3 Boundary conditions and solver
As can be seen from Figure 1, the velocity inlet boundary condition is used for free stream velocity and pressure outlet is used at the outlet of the outer domain. For walls including airfoils and top and bottom surfaces of the outer domain, the no-slip boundary condition is assigned. The flow characteristics have been captured through a numerical methodology based on the Finite Volume Method. The velocity and pressure coupling are realized through a pressure-based algorithm called SIMPLE. The Reynolds Averaged Equations (RANS) are solved using a turbulence model, SST k-\omega model. The pressure gradient is discretized using a second-order scheme and the convective terms appearing in the governing equations are discretized using a second-order upwind scheme [14]. The convergence tolerance used for solving the governing equations is $10^{-5}$.

4. Validation – grid independence study
The grid independence study is carried out for a single airfoil configuration for Wortmann FX 63-137 at different grid sized as shown in Figure 3. The lift curve is compared for each grid size with the reference values at various angle of attacks ranging from 0° to 16°. To study the behavior of the airfoil at a negative angle, simulations are carried out up to -8°. The percentage of deviation for three different grids are given in Table 1 and it is noted that the lowest deviation is given by a 3.96 lakh elements grid. However, 1.96 lakh elements grid is fixed for further study with the tandem arranged airfoil in order to get a good trade-off between computational cost and accuracy. As the stall angle was achieved at 14° and has close agreement with that of experimental results so it is not necessary to carry out grid independent study for other higher angle of attacks since once the grid is able to predict the flow at stall angle of attack where there would be complex flow structures with separation etc.
Table 1. Comparison of the coefficient of lift from the present work with a reference value for a single airfoil configuration at near stall angle (i.e. $\alpha=12^\circ$).

| Grid Elements      | Coefficient of lift | Percentage Deviation (%) |
|--------------------|---------------------|--------------------------|
|                    | Present Numerical   | Reference [3]           |
| 0.9 lakh           | 1.7222              | 5.097                    |
| ~1.96 lakh         | 1.71387             | 1.8147                   |
| ~3.96 lakh         | 1.7246              | 4.966                    |

Figure 3. Lift coefficient curve for various grid elements and the reference values for mesh independent study.

5. Result and discussion

The Simulations are carried out for three conditions namely CASE-1 (Upstream and downstream airfoil angle of attacks are changed), CASE-2 (Upstream airfoil angle of attack ($\alpha_u$) is changed and $\alpha_d$ is fixed) and CASE-3 (Upstream airfoil angle of attack ($\alpha_u$) is fixed and $\alpha_d$ is changed) at a fixed Re of $0.5 \times 10^6$. The coefficients of lift and drag values are monitored until they get steady values for each case.

5.1. CASE-1: Upstream and downstream airfoil angle of attacks are changed

In this case, the flow over the tandem arranged airfoil with the change in both $\alpha_u$ and $\alpha_d$ is studied to understand the variation of aerodynamic forces acting on the airfoils with four different gaps ranging
from 10% C to 70% C and the maximum stall angle achieved by this type of configuration is 12°. The variation of lift and drag coefficients with the angle of attacks for the cases are shown in Figures 4 and 5. Here the change in the gap between the upstream and downstream airfoils plays an important role on the lift and drag curve of the tandem configuration. As it can be seen that the maximum lift increment occurs with the gap of 70% C and the drag value changing from 0.125 to 0.155, where the downwash of the upstream airfoil does not affect the downstream airfoil whereas for the 30% C and 10% C the downwash of the upstream airfoil interacts with the downstream airfoil that leads to change in the flow characteristics around the airfoil which in turn increases the drag. This increase in drag value affects the lift generation in the tandemly arranged airfoils.

Figure 4. Lift Coefficient ($C_l$) with respect to change in angle of attack for both airfoils at different gaps of 10% C to 70% C and for single airfoil.

Figure 5. Drag Coefficient ($C_d$) with respect to change in angle of attack for both airfoils at different gaps of 10% C to 70% C and for single airfoil.
Figure 6. Streamlines showing the recirculation zone attached on upstream airfoil near stall angle (i.e. $\alpha=12^\circ$).

Figure 7. Pressure coefficient variation of the tandemly arranged airfoil when both the airfoil angle of attack is kept at $\alpha=12^\circ$.

This change can be attributed by the fact that the separation bubble or the recirculation zone forming on the upstream airfoil affects the flow around the downstream airfoil as shown in streamline plot Figure 6. Also, the pressure coefficient variation is plotted in Figure 7 to see the pressure gradient change on both the airfoil and to understand the effect of the gap between airfoils for a fixed angle of attack for both the airfoils. It can also be noted that all the tandem airfoil arrangements with different gaps have higher lift coefficient values as compared with that of single airfoil configuration. However, the stall occurs well in advance for the tandem airfoil arrangements.

5.1. CASE-2: Upstream airfoil angle of attack ($\alpha_u$) is changed and $\alpha_d$ is fixed

As we could observe the changes in $C_l$ and $C_d$ values from Figures 8 and 9 when the upstream angle of attacks ($\alpha_u$) is changed for different gaps ranging from 10% C to 70% C. The stall angle for all the distances is seen to be $12^\circ$ except for the 30% C gap as it can be seen that there is a shift in stall angle to $14^\circ$ due to the change in flow characteristics i.e. seen behind the upper surface of the upstream airfoil or due to the change in flow separation point. When the upstream airfoil is introduced to the free stream flow gives a better $C_l$ than the single airfoil but at a cost of an increase in the $C_d$ but with respect to the gap, there is a sudden change in the lift value from 2.14 to 1.8 and the drag value from 0.13 to 0.52 for...
70% C gap. Due to the unsymmetrical nature of both the airfoil, the flow gets accelerated from the upstream airfoil affects the flow around the downstream airfoil which leads to the generation of higher pressure gradient of the downstream airfoil than upstream airfoil as shown in the streamline plots, Figures 10 and 11.

5.2. CASE-3: Upstream airfoil angle of attack ($\alpha_u$) is fixed and $\alpha_d$ is changed
By keeping the upstream airfoil stationary to the free stream flow with varying $\alpha_d$, the lift and drag values are plotted in Figures 12 and 13. The $C_l$ curve shows a shift of the stall angle when the gap is less than 50% C distance. The stall angle for the gap which is less than 50% C is 12°, and 14° for the gap which is greater than 50% C with an increase in lift value. The drag value increases for the larger distances than for the smaller distances, as shown in Figure 13, which could be a drawback of this condition. This type of shift in stall angle in tandem arranged airfoil is seen only when the upstream angle of attack is changed with 30% C gap. From the streamline plots, as shown in Figures 14 and 15, it is seen that due to the change in distance between the two airfoils, the velocity changes over the downstream airfoil when the upstream airfoil is fixed at 0°. Due to the change in the angle of attack of the downstream airfoil, the lift coefficient is majorly affected by the change in pressure or velocity gradient over the downstream airfoil. Also, the separation region over the downstream airfoil is increased with increase in angle of attack of the upstream airfoil when the upstream airfoil is fixed at aero angle of attack.

Figure 8. Lift Coefficient ($C_l$) with respect to change in $\alpha_{ua}$ at a different gap of 10% C to 70% C.
Figure 9. Drag Coefficient ($C_d$) with respect to change in $\alpha_{ua}$ at a different gap of 10% C to 70% C.

Figure 10. Velocity streamlines for tandem configuration with 70% chord distance between the airfoil when $\alpha_{ua}$ is at 12° and $\alpha_{da}$ is fixed.

Figure 11. Velocity streamlines for tandem configuration with 30% chord distance between the airfoil when $\alpha_{ua}$ is at 14° and $\alpha_{da}$ is fixed.
Figure 12. Lift Coefficient ($C_l$) with respect to change in $\alpha_{da}$ at different gaps of 10% C to 70% C.

Figure 13. Drag Coefficient ($C_d$) with respect to change in $\alpha_{da}$ at different gaps of 10% C to 70% C.
Figure 14. Velocity streamlines for tandem configuration with 10% chord distance between the airfoils when $\alpha_{da}$ is at 12° and $\alpha_{ua}$ is fixed.

Figure 15. Velocity streamlines for tandem configuration with 50% chord distance between the airfoils when $\alpha_{da}$ is at 14° and $\alpha_{ua}$ is fixed.

6. Conclusion

Numerical simulations have been performed with the Wortmann FX 63-137 airfoil profile for both the single airfoil and tandemly arranged airfoils configurations for a fixed Reynolds number of $0.5 \times 10^6$. Sensitivity analysis has been carried out with combinations of the various angle of attacks for both the airfoils and also with various gaps between airfoils. It has been observed that all the cases are showing a promising result in increasing the lift for the tandemly arranged two unsymmetrical airfoils which could be used for various applications such as MAV, UAV and other aerial vehicles for near ground proximity applications. Yet for a better lift to drag ratio, Case-3 can be considered to give a good aerodynamic performance where the downstream airfoil angle is changed and the variation of a gap can be chosen within the limit allowed based on geometrical constraints of a practical application.

7. References

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