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A Proposed Method for Generating Tabulated Data for Wall Interference Correction in Unsteady Subsonic Wind Tunnel Testing

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Abstract: In the current research, the results of some wind tunnel experiments on a moving airfoil with plunging motion are presented. The experiments have been conducted in two different configurations which are tunnels with conventional and slotted walls. In both cases, pressure coefficients of different points on the upper surface of the airfoil have been measured during the plunging oscillation. The difference between the outputs is considered as the wall effect. The mentioned difference is extracted and regulated as a function of some non-dimensional parameters to provide a data-base for correction of the results of experiments on oscillating airfoils conducted in conventional wind tunnels. The correction is only considered for points located in the front portion of the airfoil to make sure there is no flow separation in that region. Finally, numerical experiments are employed to show the performance of the method.

Key words: Subsonic wind · Oscillating airfoil · Wind tunnel testing · Wall effect correction

INTRODUCTION

Unsteady aerodynamics as an important aspect of aerodynamics plays a vital role in design and perdition of aerodynamic loads exerted on helicopter blades, wind turbines and compressor blades. Numerous trials have been done to extend the knowledge of unsteady aerodynamics and its relevant phenomena. In 1935, the general theory of unsteady flow and its application to flutter was stated by Theodorsen [1]. He was able to extend the theory of two-dimensional thin airfoil from steady to unsteady flows and solve the flow-field for different flow conditions. Many fundamental studies regarding different aspects of unsteady aerodynamics have been conducted so far from which Vandyke *et al.* [2], McCroskey [3] and Ericsson *et al.* [4] are well-known ground- breaking studies in this field. Lee *et al.* [5], in 1998, used hot film sensors over an oscillating NACA0012 airfoil to investigate the boundary layer growth and revealed that flow separation would be delayed with increasing incidence angle. In 2002, Schreck *et al.* [6] measured the surface tension near the leading edge of an oscillating airfoil and specified the following stages in boundary-layer behavior: flow reversal, primary reattachment, main reattachment and formation of leading edge vortex. Mani *et al.* [7, 8, 9], in 2008, investigated the effect of reduced frequency on the pressure coefficient of an oscillating airfoil. In 2009, they measured the flow characteristics behind an oscillating airfoil using a hot wire anemometry system and in 2010, they investigated the effect of reduced frequency near the static stall angle. It was shown by Mani *et al.* that there was a direct relationship between reduced frequency and the size of hysteresis loops. They also showed the formation of dynamic starting vortex near the leading edge when the equivalent angle of attack passed the static stall angle.

Parallel to development of computational technology, numerical simulation of unsteady flows has been widely employed by many researchers. Yang *et al.* [10], in 2006, computed the subsonic compressible flow around an oscillating airfoil and showed the capability of Euler equations to predict physical result for pressure distribution around an oscillating airfoil. In 2007, Kanchi *et al.* [11] proposed a new method for solving three-dimensional unsteady flow using a moving mesh scheme. Alisadeghi *et al.* [12] used a background grid arrangement, in which the main computational grid is located, to solve two-dimensional flow around an airfoil with arbitrary motion.

Although the above developments have been very useful and practical, a common problem is still present in experimental investigation of unsteady flows which can

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cause undesired effects on measurements: wall effect in wind tunnels. In 1998, Kong *et al.* [13] worked on a passive correction of unsteady testing and showed that using some special configuration of wind tunnel walls, porous walls with specific porosity jointed with a plenum chamber, could lead to considerable correction to the results of the experiment and provide a condition close to free flight condition. Duraisamy *et al.* [14] showed that the results of linear theory and also solution full Navier-Stokes equations well matched to those of experiments when highly none linear phenomena such as dynamic stall are not present in flow field.

The aim of the present work is to propose a method for generating tabulated data-base for correcting (removing the wall effects) the results of unsteady flow experiments conducted in conventional wind tunnels. Thus, after description of experimental configuration, the results of the experiment on a plunging airfoil in two different test sections are presented. Then, a method is proposed to correct the suction peak of hysteresis loops of pressure coefficient obtained from conventional wind tunnel tests. In order to investigate the performance of the correction methodology, some numerical experiments are presented.

Unsteady Motion and Experimental Condition: The plunging motion is exerted on the airfoil through a sinusoidal oscillation perpendicular to free stream direction which is stated by Eq. (1):

$$h = \bar{h}\sin(2\pi ft) \tag{1}$$

In which h is the distance from the trim position, $\bar{h}$ is the oscillation amplitude, f is the oscillation frequency and t is time.

The sinusoidal motion will induce an incidence angle which is called the equivalent angle of attack and is introduced by Eq. (2):

$$\alpha_{eq.} = \frac{-2\pi\bar{h}\cos(2\pi ft)}{U_\infty} \tag{2}$$

In which the denominator is the free stream velocity and other terms have the same definition as introduced in Eq. (1). The initial incidence angle is set to be zero in all test cases and the only contribution of the actual incidence angle is the one introduced by Eq. (2).

The sinusoidal motion is produced by a crank mechanism which is shown in Fig. 1. The oscillation frequency can vary from 0.5 to 3 Hz.

Fig. 1: Crank mechanism to produce sinusoidal oscillation

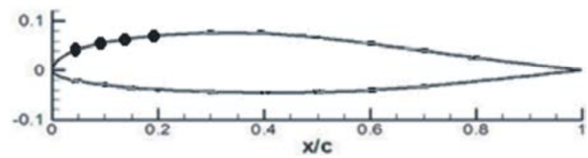
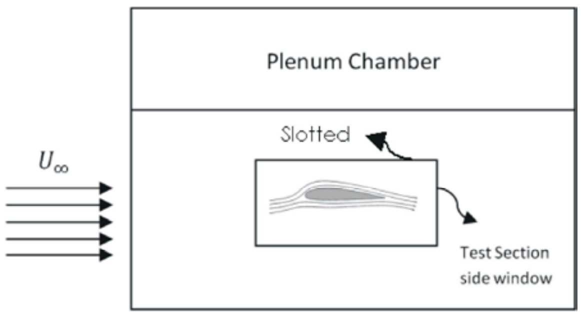


Fig. 2: Schematic view of Eppler 361 with the pressure taps on its surfaces

The wind tunnel used for conducting the experiments is a low speed subsonic low turbulence close circuit wind tunnel with a test section of 45cm×45cm cross area and 1.2 m length in flow direction. The free stream velocity can vary from 5 to 45 m/s. The initial angle of attack is set to be 0 in all cases. Two oscillation amplitudes are used in the experiments which are 6 and 8 cm. The testing airfoil is an Eppler 361 model which is commonly used in helicopter blade's section. The chord of the testing airfoil is 15cm. In spanwise direction, the airfoil covers the entire width of the test section to avoid wing tip vortices. Measurements are also done along the center line of the airfoil which is the closest location to two-dimensional condition. Four points in the first 20% of the upper surface of the airfoil are used to measure the pressure coefficient during the oscillation. The pressure coefficients are measured by differential pressure transducers with 100 KHz sampling frequency to provide the time history of pressure coefficient during the oscillation. The reason of choosing the measuring points

(a) Upper view of slotted wall



(b) Test section with plenum chamber

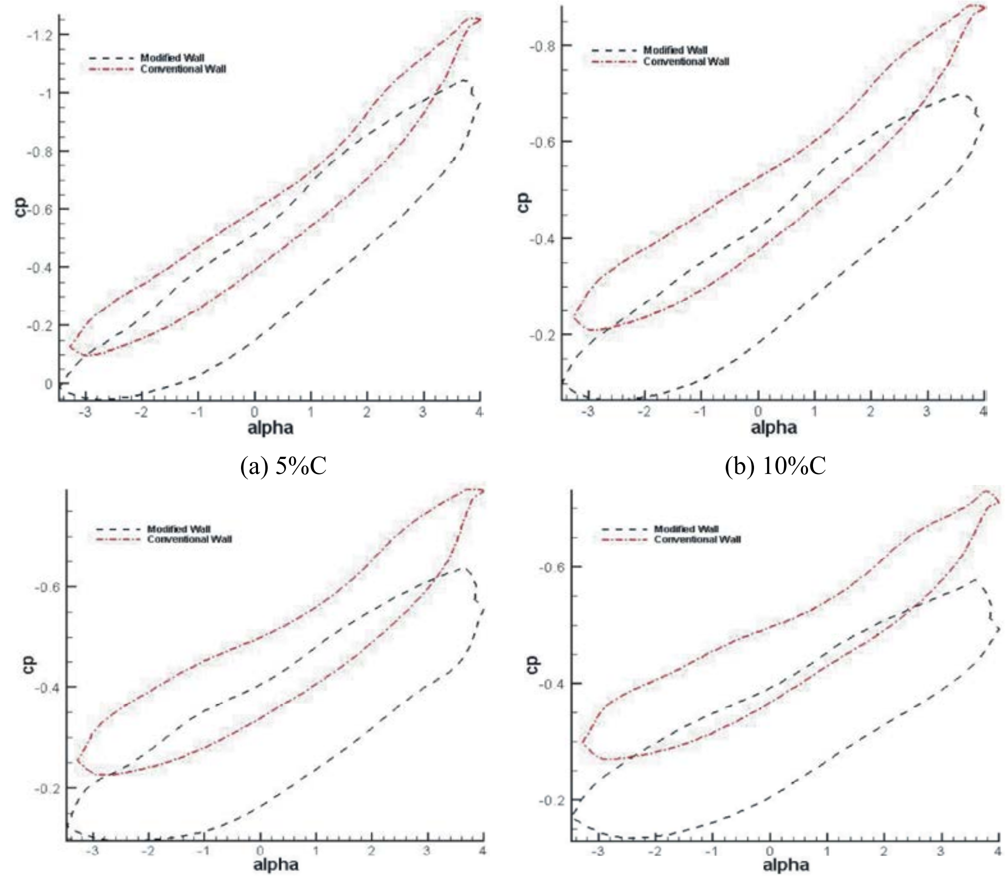
Fig. 3: Schematic view of the new test section with slotted walls with porosity according to [11]

in the first 20% of the airfoil is to ensure there will be no highly non-linear phenomenon like flow separation. Figure 2 shows the schematic view of the testing airfoil and measuring points.

The original conventional wind tunnel has solid walls in the test section which interact with fluid flow and cause deviation from free stream flow. One of the solutions proposed to remove, or more realistically to reduce, the wall effect is the use of slotted walls. In this research we built a new test section with slotted upper wall. Figure 3 shows the schematic of the new test section with the slotted wall. According to [11], the porosity ratio of 30% has been chosen. The slotted wall is only used for the upper wall of the test section. As mentioned in [15], correcting the upper wall of wind tunnel will diminish a considerable amount of wall interference. Since the goal of this research is to examine a methodology for wall interference correction and for the sake of simplicity, only the upper wall of the test section has slotted configuration. Thus, measurement of pressure coefficient is only done for the upper wall of the airfoil. As stated before, four points located in the first 20% of the upper surface will be considered to avoid any possible flow separation.

Comparison of Outputs from Two Test Section Configurations: Two different test cases are chosen to be presented in this part. Figure 4 shows the hysteresis loops for pressure coefficient at four different points on the upper surface of the airfoil at k = 0.094 and $\bar{h}$ = 6cm. It should be noted that all these points are located in the beginning 20% of the chord length to avoid flow separation. As evident in this figure, the general trend of the diagrams obtained from experiment in two different test sections (two wind tunnel configurations) are close to each other and two loops have almost the same inclination. The most obvious difference in these diagrams is the shift that hysteresis loops experience in the new test section. This phenomenon can be interpreted as the result of allowing the streamlines to follow their natural path and minimizing solid blockage. Thus, the local increase in velocity above the airfoil, which is present in conventional test sections, is diminished and consequently the pressure coefficient is decreased. This change is due to the slotted wall and plenum chamber configuration of the new test section which vanishes the wall effects and makes the results close to free stream ones. However, the value of shift is different at different location and varies from almost 20% to 40%. This phenomenon can be due to the vortex structure formed at the leading edge of the airfoil in vertical motion. The maximum shifting is occurred at x/c=20%. It can be explained regarding the fact that the vortex started from the leading edge becomes larger as at getting farther from the leading edge and the interaction of vortex with the solid wall becomes stronger. In Fig. 5, which presents the results at k = 0.094 and $\bar{h}$ = 8cm, the same trend is observable. However the shifting value is from almost 30% to 50%. This increase in the shifting value shows the effect of oscillation amplitude: the higher the amplitude, the higher the wall effect. Again, the maximum shifting occurs at x/c=20% which is the farthest point from the leading edge.

Proposing a Method to Generate Data-Base for Correcting the Experimental Data: As shown in the previous section, the difference between the results of experiments obtained from two test sections was mainly a shift of the pressure coefficient for each point of the hysteresis loop. As mentioned in [12], for unsteady flow such as flow around an airfoil with plunging motion, the output from experiments well matches to those obtained from linear theory when there is no non-linear phenomenon such as dynamic stall. Considering this fact and also the results presented in the previous section,



(a) 5%C (b) 10%C

(c) 15%C (d) 20%C

Fig. 4: Comparison of C_p hysteresis loops at various locations, k = 0.094 & $\bar{h}$ = 6cm

we are going to consider the wall effect as a superimposed addition to the original results. In other word, the difference between the hysteresis loops, in similar points, can be considered as the wall effect. Thus, this effect can be calculated by subtraction of the results with and without wall effect and considered as correction factor for future wind tunnel experiments. In order to consider the correction factor properly, the important parameters affecting the flow field in unsteady experiments have to be clarified.

Major parameters which can affect any unsteady flow around a plunging airfoil are mainly free stream velocity, oscillation frequency, oscillation amplitude, time and incidence angle which are listed in as a functional relationship in expression 3.

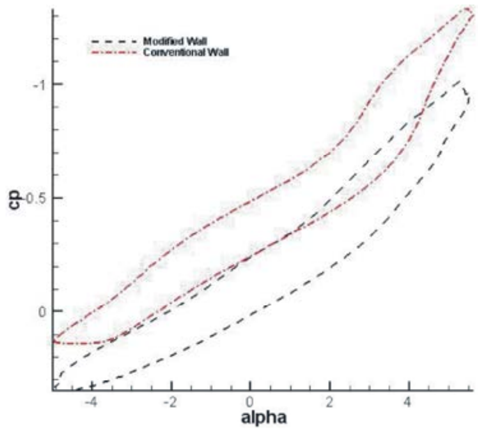
$$\text{Unsteady flow condition} = f(V_{\infty}, f, \bar{h}, t, \alpha) \qquad (3)$$

On the other hand, if a sinusoidal motion is exerted to the plunging airfoil, as previously stated in Eq. 1, an equivalent angle of attack will be induced to the airfoil, stated by Eq. 2, which correlates the mentioned parameters to each other. Thus, it is obvious that equivalent angle of attack is one main parameter affecting unsteady flow condition and the difference between two loops must be subtracted from each other at the same equivalent angle of attack.

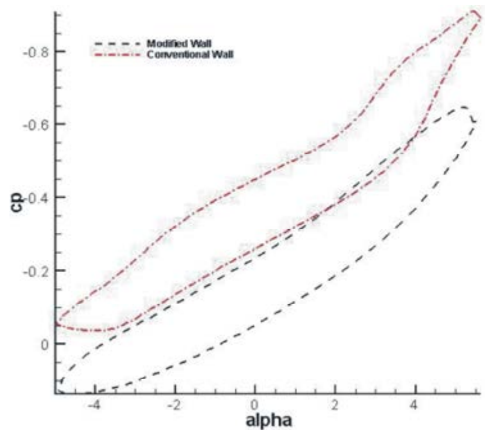
Reduced frequency is another well-known parameter which correlates the oscillating frequency, velocity and the airfoil size to each other.

The distance from the wall of the test section is another influential parameter which can certainly affect the flow field. Obviously as the distance from the wall decreases, more wall effect would be present in the flow field. Thus, a non dimensional parameter is defined which shows the relative distance of the airfoil from the wall. We adopt the name λ for this parameter which is introduced by Eq. 4.

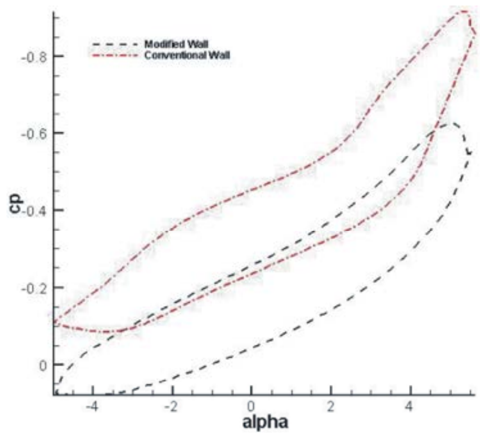
$$\lambda = \frac{\text{Minimum distance of the airfoll from tunnel wall}}{\text{Airfoil chord}} \qquad (4)$$



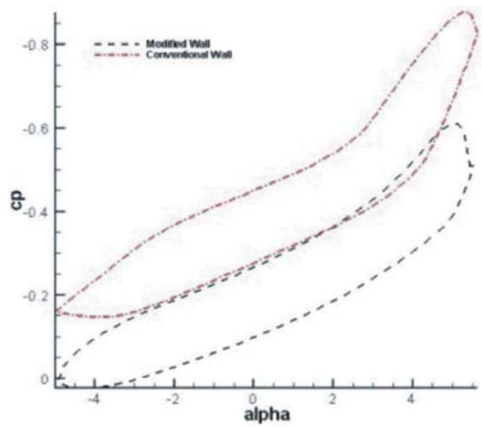
(a) 5%C



(b)10%C



(c) 15%C



(d) 20%C

Fig. 5: Comparison of C_p hysteresis loops at various locations, k = 0.094 & $\bar{h}$ =8cm

The difference between the hysteresis loops is named Δ and is stated in Eq. 5. Δ should be extracted through subtraction of experimental outputs obtained from experiments with both test sections to from the correction data-base for experimental.

$$\Delta = (C_{pmodifid\ wall}) + (C_{pconvertional\ wall}) \quad (5)$$

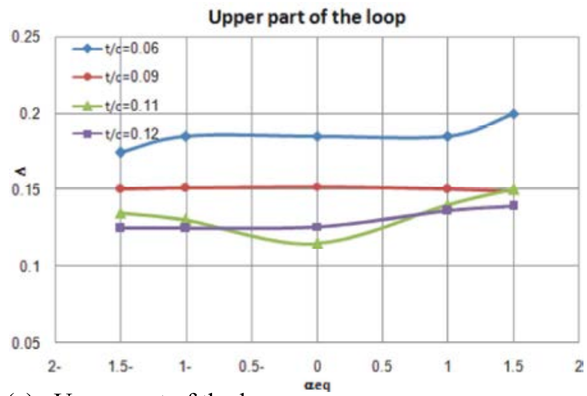
To make the functional relationship more general, different points of the airfoil in which Δ is extracted are considered with their relative thickness. By the above description, Δ should be specified in points with fixed parameters that are given in equation 8.

$$\Delta = f(\alpha_{eq}., k, \lambda, t / c) \quad (6)$$

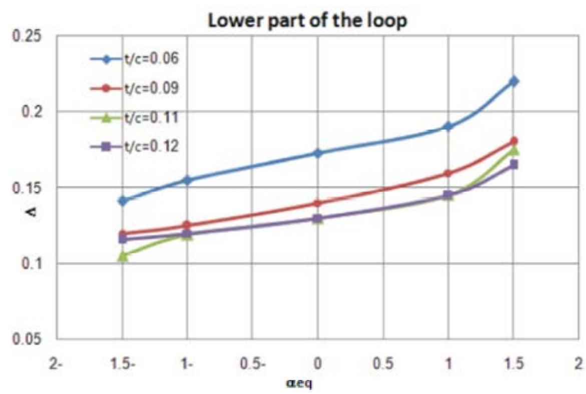
Now, by considering the above functional relationship, a data-base can be generated to be used for future unsteady experiments. In Fig. 6, a sample data set is shown. Since there are two C_ps in hysteresis loops for each equivalent angle of attack, Δ is extracted for the lower part and upper part of the C_p loop to be used in proper condition. Regarding these curves, one can refer to the appropriate diagram and extract the value of Δ and then use it to correct the experimental data from unsteady tests.

It should be noticed that this method is only stated for regions with no dynamic stall or flow separation. Thus, the sample data set which is shown in Fig. 6 is for points in the first 20% of the airfoil specified with their relative thickness. In the next section, numerical experiments are done to test the proposed method.

Numerical Experiment to Validate the Proposed Correction Method: In this section the proposed method in the previous part is examined. Since the only available data is the experimental data from the above two test sections, numerical simulation is employed to correct the



(a) Upper part of the loop



(b) Lower part of the loop

Fig. 6: Values of Δ for λ, k=0.047

data from conventional wall. To do this, the flow is simulated in a 2-D wind tunnel with conventional walls at the same experimental condition (including tunnel dimensions and flow parametrs) and in free stream condition as well. All the numerical parameters are kept the same for wind tunnel and free stream simulations. We used GAMBIT 2.0 for generating the discretized domain and FLUENT 6.3 is used to solve the flow field around the oscillating airfoil.

In order to apply the plunging motion in the numerical simulation, dynamic mesh should be used that, regarding the limitation of the used software, makes the use of unstructured grid necessary for mesh generation at each time step. In the following, the strategies for mesh generation are introduced.

The simplest way to exert the oscillation on the airfoil is to move the airfoil separately and regenerate the computational cells around the airfoil with respect to its new position. This means new grid generation at each time step. In order to minimize the new grid generation at each and every time step, the plunging motion is also

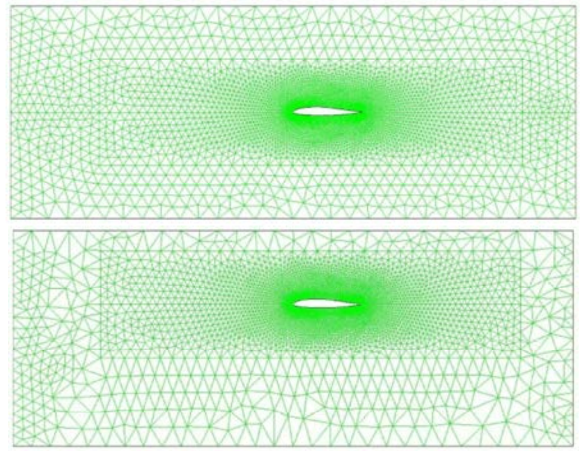


Fig. 8: Grid used to descritize the domain

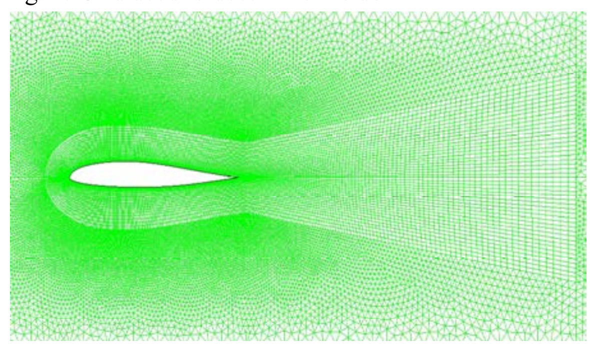


Fig. 9: Structured grid around the arifoil in the moving zone

exerted to the portion of the domain around the airfoil. In this scenario there will be no relative motion between the airfoil and the mentioned portion of the grid. In Figure 8 the domain is shown at two different times.

As evident in Figure 8, this strategy will reduce the effect of re-meshing associated with cells around the airfoil. Since the inner region of grid that is moved with the airfoil remains unchanged, structured grid can also be used in this region which enables us to increase the solution precision and resolve the boundary layer. The structured grid can also be extended to the rear portion of the airfoil to provide high resolution grid in vortex shedding area behind the airfoil. Figure 9 shows the structured grid around the airfoil and behind it which are located in the moving part.

Since the cells located out of the moving zone are regenerated after each time steps and to avoid inconsistency between the outer edge of the moving zone and the outer grids, a small portion of the moving rectangular is discretised with unstructured grid to increase the consistency between the outer and inner cells. This portion is shown in Fig. 10.

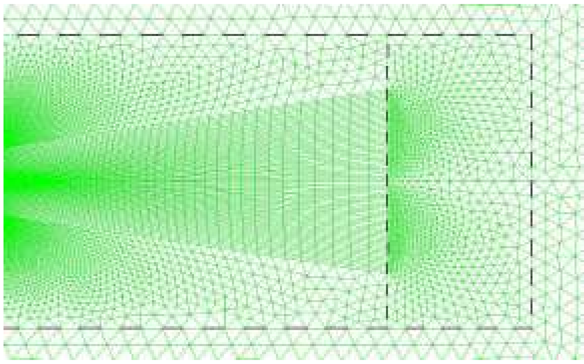


Fig. 10: Unstructured grid in the rear portion of moving zone

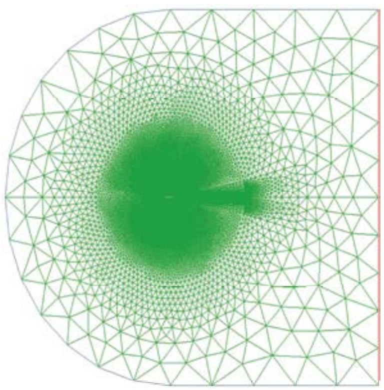
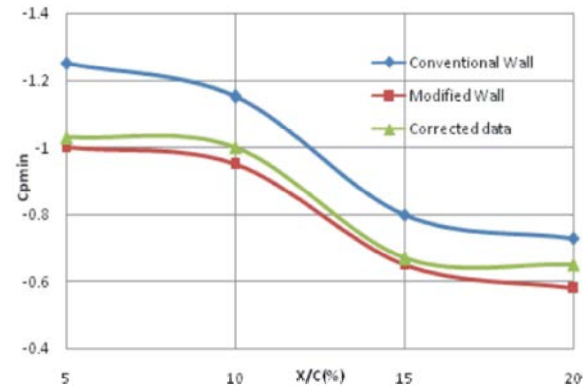


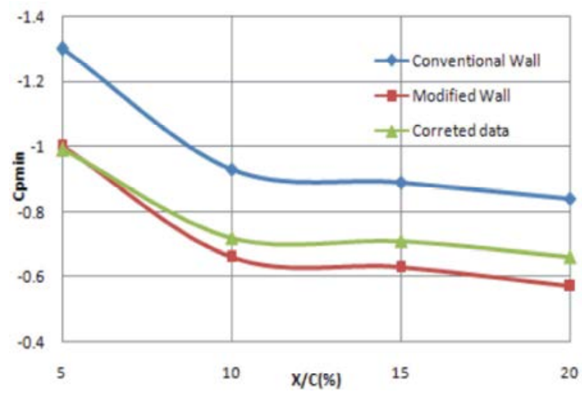
Fig. 11: Free stream computational domain

For free stream case, the same grid will be used around the airfoil but dimensions of the computational domain will be extended to 10 times of the airfoil chord in all directions. The entire computational domain is shown if Fig. 11.

Boundary Condition and Numerical Schemes: Wall boundary condition is considered for airfoil surfaces and also for upper and lower walls of the wind tunnel model. Velocity inlet condition is set for inlet boundary and pressure outlet is considered for the outlet boundary. The flow is assumed to be unsteady, incompressible and turbulent. Employed equations include. Since there is no heat transfer in the fluid, only continuity and momentum conservation equations are solved and temperature is considered constant during the simulation. For modeling the viscous turbulent flow, two equation eddy-viscosity model, RNG k-ε turbulence model, is applied. Two transformation equations (partial differential equations) are solved in this model, one for turbulent kinetic energy (k) and the other for damping rate of turbulent kinetic energy (ε) to find the eddy viscosity and close the RANS equations. SIMPLE algorithm is applied for pressure



(a) k=0.094 & H=6cm



(b) k=0.094 & H=8cm

Fig. 12: Comparison of corrected data, conventional wind tunnel data and modified wind tunnel data

velocity coupling. Enhanced wall functions are also used for near wall regions. Physical conditions for numerical solution, including temperature, airfoil dimensions, free stream velocity and oscillation frequency are simulated according to the relevant experiments.

Two different domains have been used for simulations: wind tunnel and free stream condition. All the numerical parameters are kept the same for both cases. Since the only difference between two simulations is the domain-size, the difference between two solutions has been considered as the wall effect. Thus, this difference, according to the previous section, is added to the results obtained from experiments with conventional wall to correct its data. The correction has been done for the maximum suction point (head of the hysteresis cycle) of two test cases. The results are shown in Fig. 12. As evident in Fig. 12, the corrected data in both data sets is made much closer to those from experiments with modified wall that shows the performance of the proposed method in the examined region.

Regarding the above results, it is recommended to conduct a series of experiments in two wind tunnel configurations and at different conditions. The difference between the results should then be subtracted according to the proposed method to provide a correction data-base. That data-base can be used to correct the output of wind tunnel experiments on moving (plunging) airfoils.

CONCLUSION

A new test section with slotted wall with 30% porosity is built and wind tunnel tests for a plunging airfoil are conducted in the mentioned test section and also in a test section with conventional walls. Pressure coefficients at four points on the upper surface of the airfoil were measured. The difference between C_p hysteresis loops obtained from two wind tunnel configurations was majorly a shift in C_p loops. Then, it was proposed to extract the difference between the results obtained from two test-section configurations to be considered as wall effect. Thus, this data can be tabulated with regard to some non dimensional numbers and establish a data-base for correction of wind tunnel tests. It was also mentioned that this data-base is only valid in the regions with no flow separation or dynamic stall. The method was examined for minimum pressure point (suction peak) of hysteresis loops at different points and it was shown to be working for the examined region.

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Nomenclature:

C : Airfoil chord
C_p : Pressure coefficient
f : Oscillation frequency
$\bar{h}$: Oscillation amplitude
K : reduced frequency
t : Time
t/c : Relative thickness
V_∞ : Free stream velocity
α : Incidence angle
α_{eq} : Rquivalent angle of attack
λ : Non dimensional distance from test section wall

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