Improving the Lift Characteristics of Supersonic Double Wedge Airfoil at Low Speed Using Passive-Active Flow Controlling Methods

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Received on: 28/9/2014 & Accepted on: 8/1/2015

ABSTRACT

The supersonic double wedge airfoil performs quite excellent in the supersonic speed regime but would lead to poor performance at subsonic speed regime due to sharp edges stall. For this purpose a theoretical and experimental study was undertaken to improve performance characteristics of the supersonic double wedge airfoil at low speed by using passive-active flow controlling methods. The proposed passive method was a shape modification through changing the sharp leading edge and mid- section upperand lower surface apex to smooth curved control segment actived during subsonic flight regime; and the blowing technique was used as an active method. ANSYS FLUENT CFD package was used to simulate the flow around the standard and modified airfoils. Low speed wind tunnel tests were also conducted in order to measure pressures and velocities chordal-wise the model airfoils fabricated to accomplish these wind tunnel tests.The results had proven that theproposed flow controlling methods had improved the performance of the double wedge airfoil at low speed. The maximum lift coefficient $C_{l,max}$ was increased by about (38%) and the stall angle for $C_{l,max}$ was jumped from $(12°)$ for the standard airfoil to $(18°)$ for the modified airfoil with blowing. The experimental results coincide well with the theoretical results.

Keywords:Supersonic airfoil;passive-active flow control; boundary layer control.

تحسين خصائص الرفع لمطيار الاسفين المزدوج فوق الصوتي عند السرع الواطئة باستخدام وسائل سلبيه وفعاله للسيطرة على الجريان

https://doi.org/10.30684/etj.33.1A.19
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الخلاصة

صمم مطيار الاسفين المزدوج فوق الصوتي للعمل بأداء عالي عند السرع فوق الصوتية في حين ينخفض اداءه بشكل كبير عند السرع الواطئة تحت الصوتية بسبب انهواء الجريان عند الحافات الحاده للمطيار, لهذا الغرض تم اجراء دراسة نظريه وعمليه للتحقق من امكانيه رفع اداء مطيار الاسفين المزدوج فوق الصوتي عند السرع الواطئةباستخدام وسائل سيطرة على الجريان سلبيه وفعاله. نفذت الوسيلةالسلبيةللسيطرة على الجريان عن طريق تغيير الحافات الحاده الأمامية والعليا للمطيار بسطوح سيطرة منحنيه يتم تفعيلها اثناء الطيران تحت الصوتي, في حين تمثلت الوسيلةالفعالة بطريقة النفث. تم توظيفحقيبة برمجيات ANSYS FLUENT CFDلمحاكاة الجريان حول المطيار القياسي والمعدل وتم اجراء التجارب في نفق ريح ذو سرعه واطئة على نماذج للمطيار صنعت خصيصاً للعمل الحالي.اثبتت النتائج ان الوسائل المقترحةللسيطرة على الجريان قد حسنت من اداء المطيار في السرع الواطئة, حيث ازداد معامل الرفع الاقصى بنسبه (38%) وارتفعت زاويه معامل الرفع الاقصى من(12°) للمطيار القياسي الى (18°) درجه بالمطيار المعدل مع النفث. كان التطابق جيد بين النتائج النظريةوالعملية.

Nomenclature

$\boldsymbol{b}$	Wing Span	$\boldsymbol{m}$
$\boldsymbol{C}$	Wing Chord	m
$\boldsymbol{C_N}$	Normal Force Coefficient	-
$\boldsymbol{C_T}$	Tangential force coefficient	-
$\boldsymbol{C_d}$	Drag Coefficient	-
$\boldsymbol{C_l}$	Lift Coefficient	-
$\boldsymbol{C_p}$	Pressure coefficient	-
$\vec{\boldsymbol{F}}$	External body force	N
$\boldsymbol{G_k}$	Generation of turbulence kinetic energy due to velocity gradient	$kg/m.s^3$
$\boldsymbol{H}$	Manometer head	m
$\boldsymbol{k}$	Turbulent kinetic energy per unit mass	m^2/s^2
$\boldsymbol{p}$	Static pressure	N/m^2
$\boldsymbol{p_\infty}$	Static pressure for free stream	N/m^2
$\boldsymbol{S}$	modulus of the mean rate-of-strain tensor	-
$\boldsymbol{S_F}$	Source term in momentum equations.	N/m^3
$\boldsymbol{S_k, S_\epsilon}$	Source terms in k & ϵ equations	-
$\boldsymbol{u_\infty}$	Free stream velocity	m/sec
$\vec{\boldsymbol{v}}$	Velocity vector	m/s
$\boldsymbol{x, y}$	Cartesian Coordinate	-

α	Angle of attack	$degree$
ϵ	Dissipation of turbulent kinetic energy per unit mass	m^2/s^3
μ	Dynamic viscosity	$kg/m.s$
μ_t	Turbulent (eddy) viscosity	$kg/m.s$
υ	Kinematic viscosity	m^2/sec
ρ	Density	kg/m^3
$\sigma_k, \sigma_\epsilon$	Turbulent Prandtl / Schmidt number for $k-equation$ and $\epsilon-equation$	-
σ_t	Turbulent Prandtl / Schmidt number for momentum –equation	-
$\vec{\tau}$	Stress tensor	N/m^2

Subscript

Letter	**Definition**
s	Static
t	Total
$lower$	Lower surface
$upper$	Upper surface

INTRODUCTION

Supersonic airfoils such as double arc and double wedge shape are the most efficient airfoils for supersonic aircraft at supersonic speed. These airfoils are common with sharp leading edge and convex surfaces or apexes to form oblique and expansion shocks which are responsible for the producing of the aerodynamic characteristics during flight at higher Mach number. The wave drag is reduced considerably due to these types of shocks than for a bow shock that will be formed for a curved leading edge airfoil.

The pressure distribution around such airfoils in the supersonic mode is very much simpler than that in the subsonic mode, each of the four faces of the diamond cross-section experiencing virtually constant pressure, as shown in figure (1) Barnard, et. al, [1].The shape and the sharpness of the supersonic airfoils, however, affect the aerodynamic characteristics in an undesirable manner at low speeds due to the separation of flow at leading edge and surfaces apexes which leads to a low lift coefficient, which intern demands a high takeoff speed and a long takeoff distance.

There are many approaches to flow control proposed by researchers concerning the problem of improving the lift characteristics of supersonic airfoil at low speeds.Pollok, et. al, [2] presented a study of methods to increase the lift of a double wedge supersonic airfoils at low speeds. Their results indicate that the nose flap had an appreciable effect on preventing separation and thus increasing the lift and split flaps give an increment of lift as it would be expected while blowing the boundary layer at the top surface improve lift and drag characteristics.Bacon, [3] investigated the blowing method as a means of increasing the maximum lift of supersonic wings at low subsonic speeds and he concluded that the blowing method is promising to improve double wedge supersonic airfoil aerodynamic characteristics. Miranda,et.al, [4] performed active control of fully separated flow over a symmetrical circular-arc airfoil at high angle of attack.

The experiments were carried out in a low-speed, open-circuit wind tunnel with the airfoil at angles of attack from $10°$to $40°$. Low power input, unsteady excitation was applied to the leading or trailing edge. Pressure measurements over the airfoil show that flow control increased the normal forces coefficient by up to 70%. Edward,[5] confirmed that the sharp leading edge and mid-chord maximum thickness location of supersonic airfoils combine to create complex flow features at low speeds.

Separation bubbles form at very low angles of attack and grow tremendously as incidence is increased further. These separated regions can have a large influence on the performance characteristics of the airfoil and are very sensitive to the ambient flow conditions.Mashud,et. al. [6] observed that the flow over sharp-edged wings is almost always separated. The control of separated flows, not flow separation, is possible and benefits can be achieved but only in a time average sense.

A new design of periodic blowing technique was designed and tested which can achieve a wide range velocity, unlike a traditional synthetic jet. The actuator can achieve a considerable amount of jet vectoring, thus aligning the disturbance with the leading edge shear layer. Results indicate that unsteady mini-jet actuation is an effective actuation device capable of increasing the lift in the stall region of the airfoil.

In the present research, the interest isfocused on the supersonic double wedge airfoil.This type of wing sections performs quite excellent in the supersonic speed regime but would lead to disastrous performance at low speed due to sharp edges stall as shown in figure(2).Therefore a theoretical and experimental study was undertaken to determine the improvement of the performance of the double wedge airfoil at low speed by the addition of the following passive-active flow controlling methods:

1) Passive flow controlling method through changing sharp leading edge and mid-section upper and lower surface apex to a smooth curved segment during subsonic flight regime by means of adjustable control surfaces as shown in figure(3). These control surfaces enable the airfoil to act as a subsonic low speed airfoil,while at supersonic speed the airfoil regain its origin geometry.
2) Blowing technique was used as an active flow controlling method to energize the boundary layer flow in order to delay flow separation.

It was hoped that the implementation of these techniques for the airfoil under consideration will made the maximum lift coefficient $C_{l,max}$ would show significant increase.

Airfoil Geometry
Two geometries were considered for the present theoretical and experimental study as shown in figure (3), namely:

1- A standard double wedge airfoil of thickness to chord ratio (10%), chord length of (180 mm) and semi wedge angle of (5.71°).

2- A modified double wedge airfoil of smooth curved upper and lower surface apex and rounded leading edge similar to leading edge of the standard NACA6 digits series airfoils. It was assumed that the adjustable control surfaces, shown in figure (3), were already activated by internal mechanism which is beyond the scope of this work.

Theoretical Analysis
To access the full picture of the impact of changing the shape and blowing effect, ANSYS FLUENT (14.5) CFD package was used to simulate the flow around the airfoils under consideration. The flow is assumed to be two dimensional, incompressible,turbulentand steady.
Computational Domain:the computation domain is formed by real borders which are the airfoil upper and lower surfaces and the imaginary borders which enclose the external environment. The computation domain extends 9times the chord lengths upstream,14times the chord lengths downstream and 10 chord lengths for the upper and lower far surrounding boundaries, see figure(4). The far distance is chosen to assure a still atmospheric air condition, as recommended byVelazques, et. al. [9].

Discretization of the domain: -The geometry shown in figure (5) is d iscretized using anunstructured mesh of (54076)quadrilateralelements, this mesh has been also supplemented with a very small elements in the vicinity of the surface of the airfoil forming a boundary layer with a grow factor of (1.2). The refined mesh is necessary to capture velocity and pressure gradient near airfoil surfaces. The domain and themesh were created using the workbench ANSYS FLUENT version 14.5. In order to obtain the lift and drag as a function of angle of attack, unconstructed cells meshes were created for each angle of attack ranged from (0°to 21°). Thesemeshes were created for the standard airfoil, modified airfoil with curved leading edge and modified airfoil with curved leading edge and curved upper and lower surface apex.

Governing Equation: -Since this problem does not involve heat transfer or compressibility effect the equation for energy conservation is not required with no buoyancy contribution, then the proposed flow governing equations that used by the software package solver are listed as follows:

- Continuity equation:

$$\nabla \cdot \left(\rho \vec{\vartheta}\right) = 0 \qquad \ldots (1)$$

- momentum equations:

$$\nabla \cdot \left(\rho \vec{\vartheta} \vec{\vartheta}\right) = -\nabla p + \nabla \cdot \mu_{eff}\left(\nabla \vec{\vartheta}\right) + S_F \qquad \ldots (2)$$

- Turbulence Model:

$$\nabla.\left(\rho k\vec{\vartheta}\right) = \nabla.\left[\left(\mu+\frac{\mu_t}{\sigma_k}\right)(\nabla k)\right] + G_k - \rho\epsilon \quad ...(3)$$

$$\nabla.\left(\rho\epsilon\vec{\vartheta}\right) = \nabla.\left[\left(\mu+\frac{\mu_t}{\sigma_\epsilon}\right)(\nabla\epsilon)\right] + C_{1\epsilon}\frac{\epsilon}{k}G_k - C_{2\epsilon}\rho\frac{\epsilon^2}{k} \quad ...(4)$$

$$G_k = \mu_t S^2$$
$$S = \sqrt{2S_{ij}S_{ij}}$$
$$S_{ij} = \left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right)$$
$$\mu_t = \rho C_\mu\frac{k^2}{\epsilon}$$
$$\mu_{eff} = \mu+\frac{\mu_t}{\sigma_t}$$

Where
$= 1.44, C_{2\epsilon} = 1.92$, $C_\mu = 0.09$, $\sigma_k = 1.0$ and $\sigma_\epsilon = 1.3$, $\sigma_t = 1.0$

The standard$(k-\epsilon)$ turbulence model was chosen.It is the simplest "complete model" of turbulence. It is a two-equation models in which the solution of two separate transport equation allows the turbulent eddy viscosity to be independently determined. The standard $(k-\epsilon)$ model in FLUENT has become the workhorse of practical engineering flow calculations in the time since it was proposed by Launder and Spalding. Robustness, economy, and reasonable accuracy for a wide range of turbulent flows explain its popularity in industrial flow and heat transfer simulations. [11].

Convergence Criteria*:*The convergence criteria selected for this problem was recommended by the software package.It is 10^{-3} for all the scaled residuals. Actually the convergence was achieved when the values of C_D and C_L remained constant for a minimum of 700 iterations according to[11].

ExperimentalTechnique

The models were fabricated from hard lightweight wood (beech). Due to the symmetry of the double wedge airfoil model sections had been fabricated by utilizing the upperhalf of section only, as shown in the figure (6). The upper wedge surface contains the pressure and blowing taps. Taps readings for the upper wedge surface for standard airfoil at negative angels of attack represent the pressure distribution on lower surface at positive angels of attack. The first model is the standard double wedge airfoil with maximum thickness to cord ratio of(10%).The model was equipped with (12) static pressure tapes of (0.8)mm diameter as shown in figure (7). These tapeswere connected to multi tube manometer for the direct measurement of surface static pressure distribution on the model.

The second modelis the modified double wedge airfoil with curved apex and rounded nose. In addition to pressure tapes, the modified airfoil contains two holes of (3) mm diameter and located at (15%) cord. These additional holes were used to blow jet of air over upper surface.The air delivered from a compressor of capacity ($0.25m^3$) to the blowing volumetric rate controlsystem, which consists of pressure reducer, pressure gauge, pipes and flow meter[13]. The pressure reducer reduce the compressed air to (2 bar) without effect on the flow rate quantity, then entered to flow meter to meaure and control the air volumetric rate. The flow meter is providing the blowing holes with required flow rate. Four readings of volumetric flow rate are considered in blowing process ((20, 26.5, 33 and 39.5) l/min) to obtain jet velocity of (1.5, 2, 2.5 and 3) times of free stream

The models were mounted in low speed wind tunnel of ($300 * 300$) mm test section as shown in figure (8). The Reynolds number based on the mean velocity and airfoil cord length was ($3.287 * 10^5$), Table (1).The experimental pressure, lift, and drag coefficients were calculated according to the formulas given in Appendix A. All experimental data were corrected for the effect of wind tunnel constraint.

Results and Discussion

Figure (9) shows the calculated and experimental pressure distributions on the standard and modified double wedge airfoils with and without blowing, at moderate and high angles of attack. The calculated and experimental results are in well agreement, with the theoretical method developing slightly less suction over the front of the airfoil. Notes that there is a clear impact of the shape modification and blowing on the pressure distribution, especially at moderate angle ($\alpha = 9°$). The suction peak increased by about (67%) for the modified airfoil without blowing, and by more than (260%) for the modified airfoil with blowing.

The behavior of pressure curves on the front half of the modified airfoil may be explained by observing the velocity field in figure (10) at ($\alpha = 9°$). Several interesting features are observed. A laminar separation and reattachment points are indicated on the front upper surface of modified airfoil without blowing forming a laminar separation bubble. Transition occurred within the length of separation bubble and the flow reattaches to surface as a turbulent boundary layer [12]. The separation bubble is shrieked on the modified airfoil with blowing.

The shape modification and blowing are more effective at higher angle of attacks. The effects of blowing intensity on the pressure and velocity distributions on the modified airfoil at ($\alpha = 21°$) are shown in figures (11) and (12). The typical suction peak near the leading edge on the upper surface followed by recompression toward the trialing edge are the distinctive feature of the distribution of pressure in subsonic mode. These feature are significantly affected by the blowing intensity as shown in figure (11). The nearly constant pressure region downstream of the rear separation point on the upper surface is also shown, figure (12) demonstrate the effect of blowing on the main flow which move on downstream as an attached flow with no separation and a lower pressure field is established at blowing.

Finally, the benefit of shape modification and blowing in the increase of the maximum lift coefficient $C_{l,max}$ is shown in figure (13). The $C_{l,max}$is increased by about (25%) for modified airfoil without blowing and by (38%) for the modified airfoil with blowing also the α for $C_{l,max}$is jumped from (12 deg.) to (18 deg.). The calculated and experimental lift curves are in well agreement.

Conclusion

The results of the present work have proven that the proposed passive-active flow controlling method has improved the performance of the double wedge airfoil at low speed, without fear from early stall. The maximum lift coefficient $C_{l,max}$ was increased by about (38%) and the stall angle for $C_{l,max}$was jumped from (12°) to (18°) for the modified airfoil with blowing.

Appendix A:

The lift and drag coefficient are evaluated from the experimental pressure field as flow:-

To calculate pressure coefficient (c_p):

$$c_p = \frac{P - P_\infty}{\frac{1}{2}\rho U_\infty^2} = \frac{H - H_s}{H - H_t} \qquad \ldots A1$$

The normal and the tangent force components on upper and lower surfaces are:

$$C_N = \int_0^1 \left(c_{p\,lower} - c_{p\,upper}\right) . d\left[\frac{x}{c}\right] \qquad \ldots A2$$

$$C_T = \int_{-y/c}^{y/c} c_p\,.\ d\ \left[\frac{x}{c}\right] \qquad \ldots A3$$

By substation Equation [*A1*] in [*A2*] and [*A3*] Equations:

$$C_N = \int_0^1 \left\{\left(\frac{H - H_s}{H - H_t}\right)_l - \left(\frac{H - H_s}{H - H_t}\right)_u\right\} . d\left[\frac{x}{c}\right] \qquad \ldots A4$$

$$C_T = \int_{-y/c}^{y/c} \left(\frac{H - H_s}{H - H_t}\right).\ d\ \left[\frac{x}{c}\right] \qquad \ldots A5$$

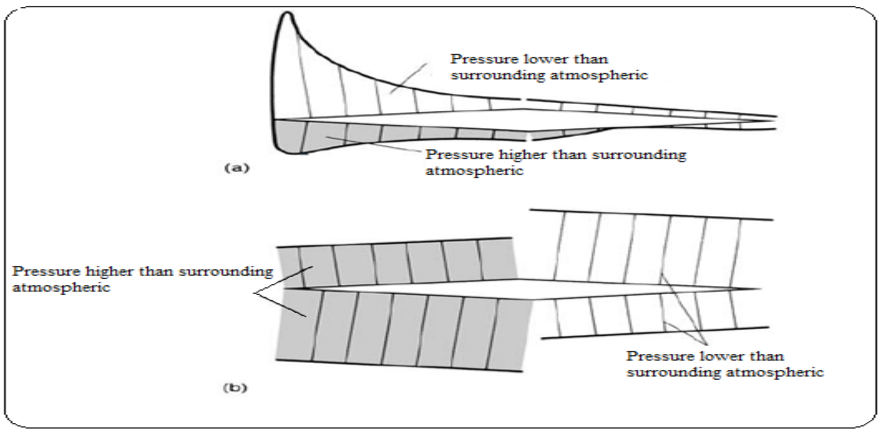
After solving Equations (A4) and (A5) numerically by Simpson rule we get lift and drag coefficient as:

$$C_l = C_N \cos\alpha - C_T \sin\alpha \qquad \ldots A6$$

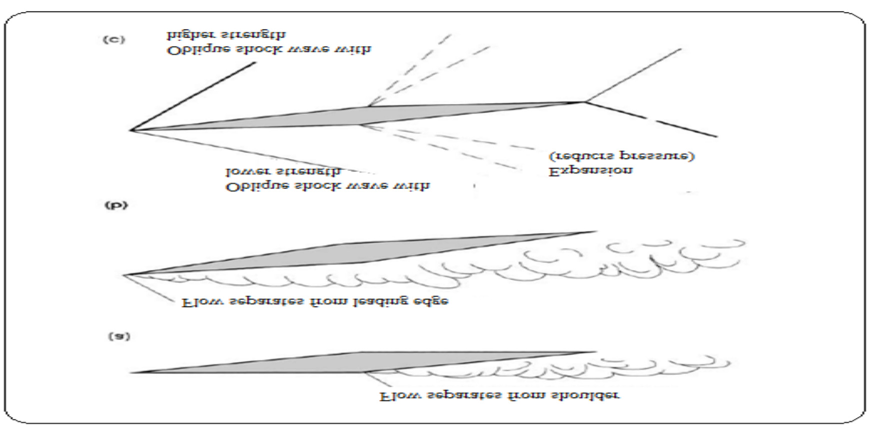
$$C_D = C_N \sin\alpha + C_T \cos\alpha \qquad \ldots A7$$

Table (1) Reynolds number calculation for standard and modified airfoils.

	R_e	$V\ (m/sec)$	$C\ (m)$	$\upsilon\ (m^2/s)$
Standard Airfoil	3.287×10^5	28.5	0.18	1.5605×10^{-5}
Modified Airfoil		31.1	0.165	1.5605×10^{-5}
$R_e = \frac{V \times C}{\upsilon}$				



Figure(1). Pressure distribution on double wedge airfoil. (a) Subsonic mode (b)supersonic mode [1].



Figure(2). Flow behavior on double wedge airfoil. (a) Flow behavior in subsonic speed at low angle of attack. (b) Flow behavior in subsonic speed when increasing angle of attack. (c) Supersonic [1].

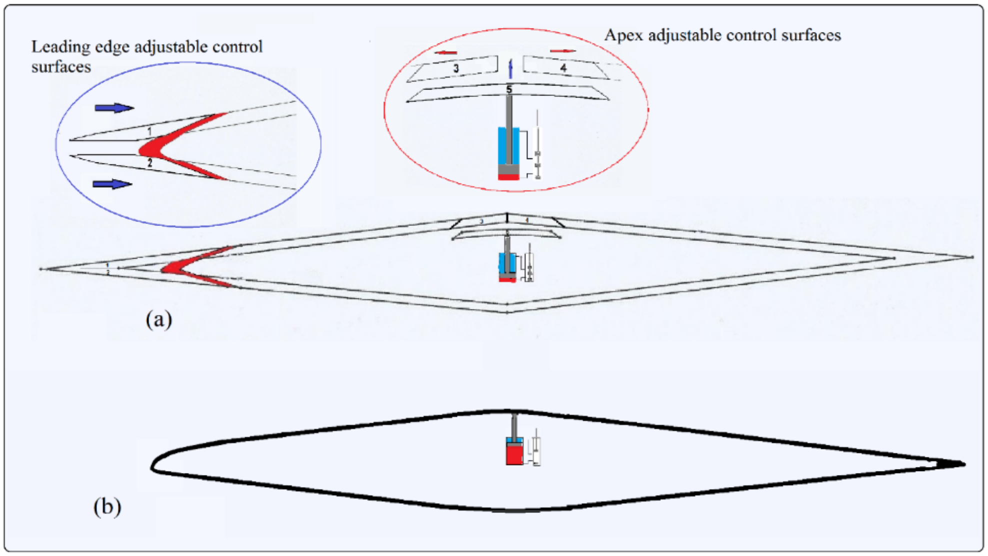
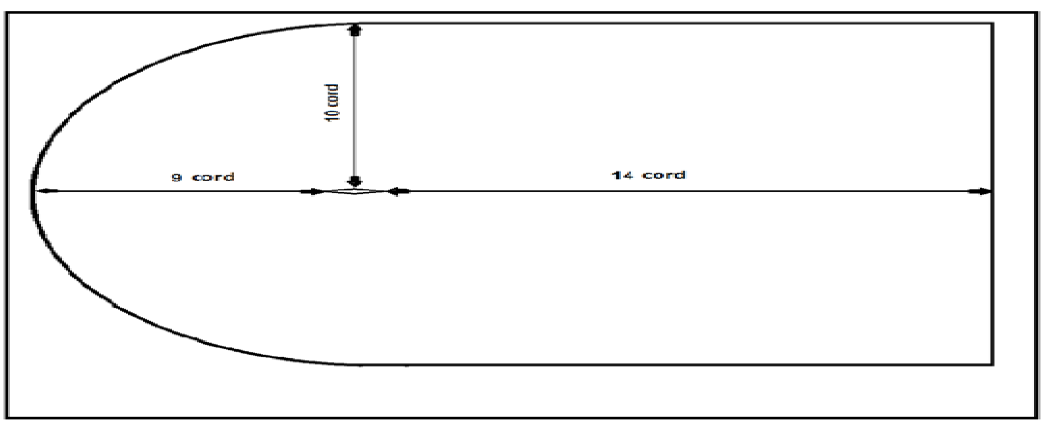
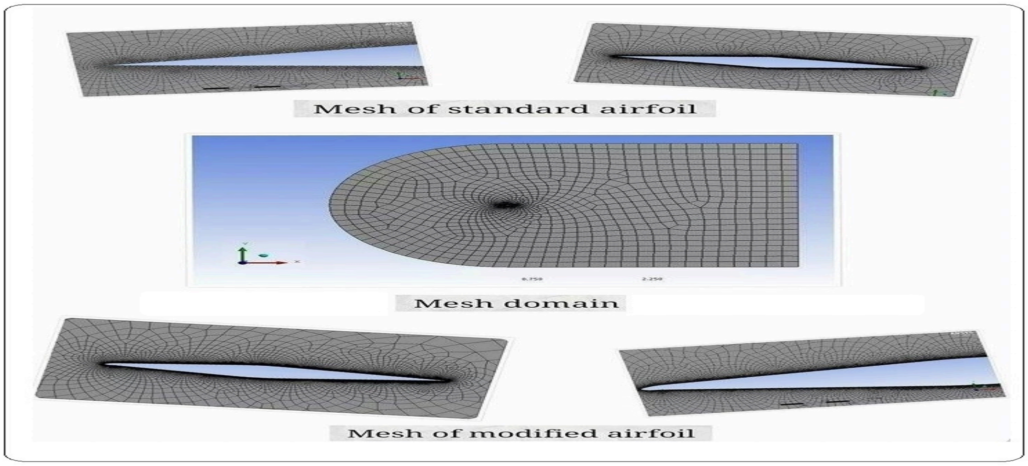


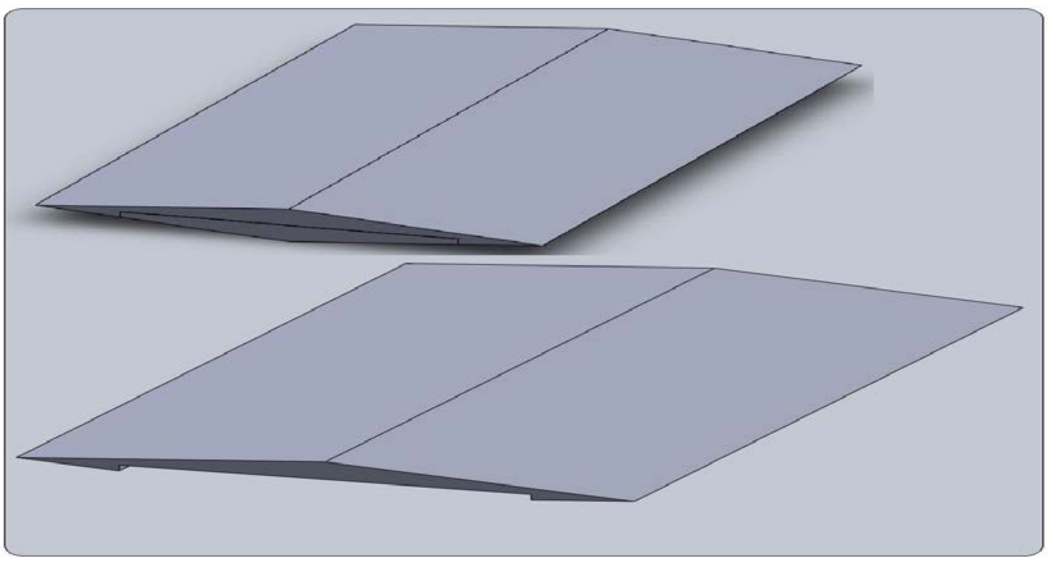
Figure.3. The proposed supersonic-subsonic double wedge airfoil of adjustable control surfaces (a) standard shape; used at supersonic mode. (b) Modified shape; used at subsonic mode. (The control surfaces are activated).



Figure(4).The computation domain for airfoil.



Figure(5).Unstruct ured mesh.



Figure(6). Double wedge airfoil model.

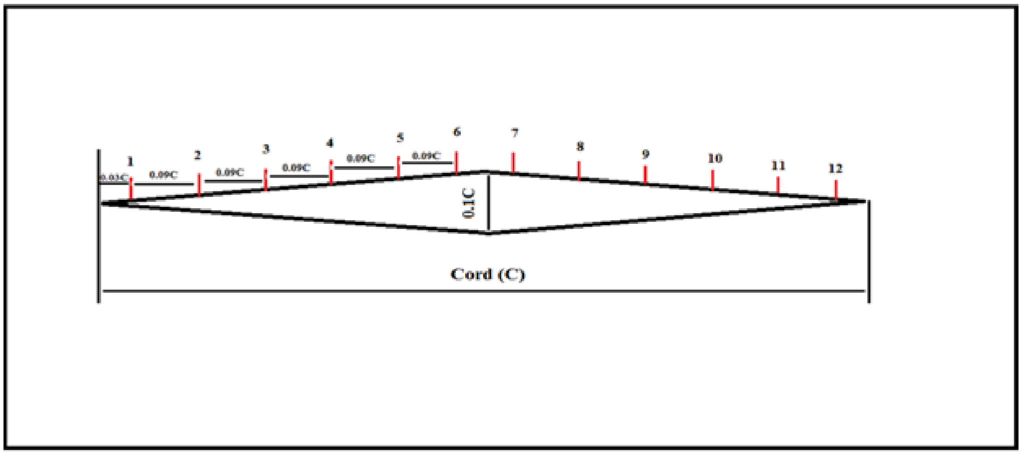
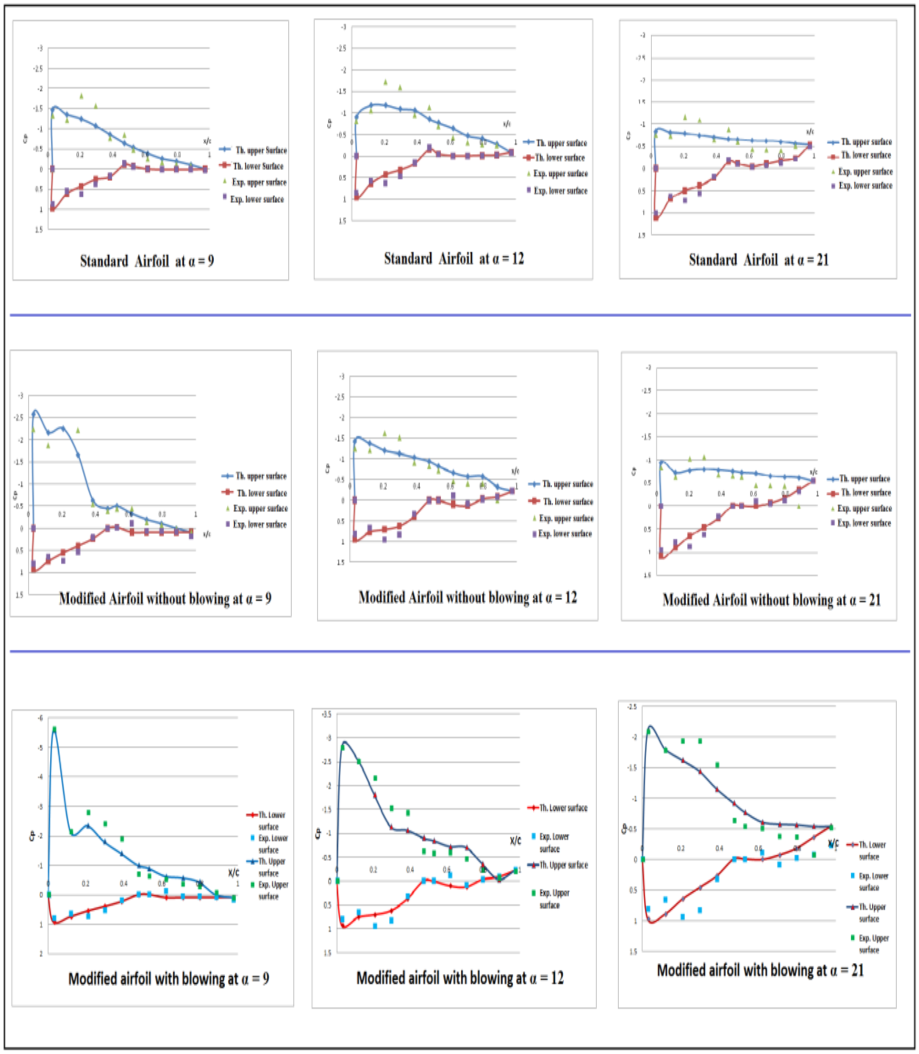
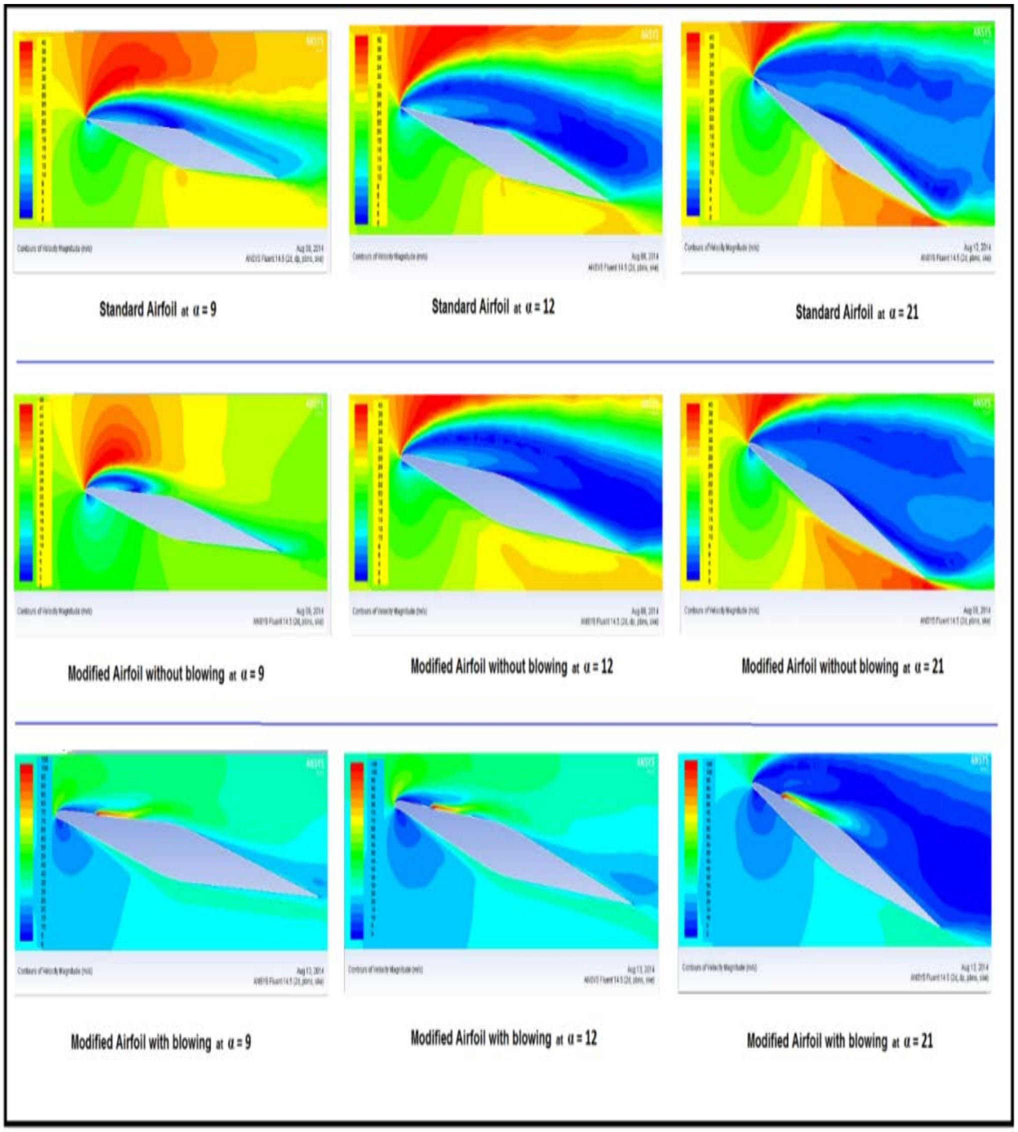


Figure (7). Location of static pressure tapping.

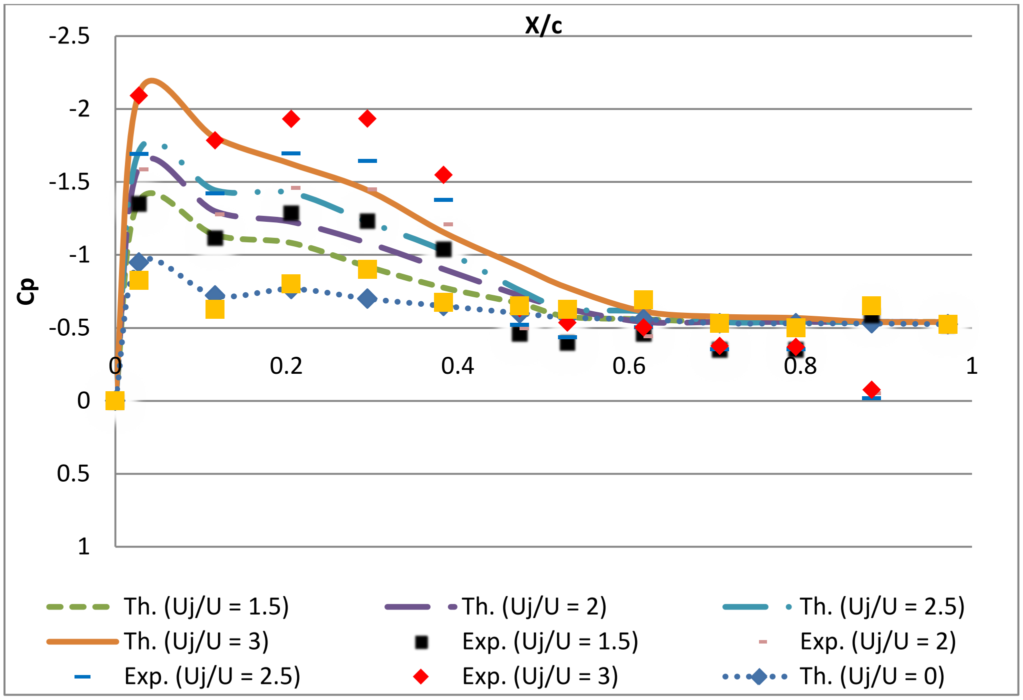
Figure(8). Subsonic wind tunnel and the test section.



Figure(9). Pressure distribution on the standard and modified airfoilsat (R_e = 3.287 * 10^5).



Figure(10). Theoretical velocity distribution contour around standard airfoil with free stream velocity of (31.1 *m/sec*) and modified airfoil with free stream velocity of (28.5 *m/sec*)



Figure(11). Effect of blowing intensity on the pressure distribution on modified airfoil (α = 21; R_e = 3.287*10^5)

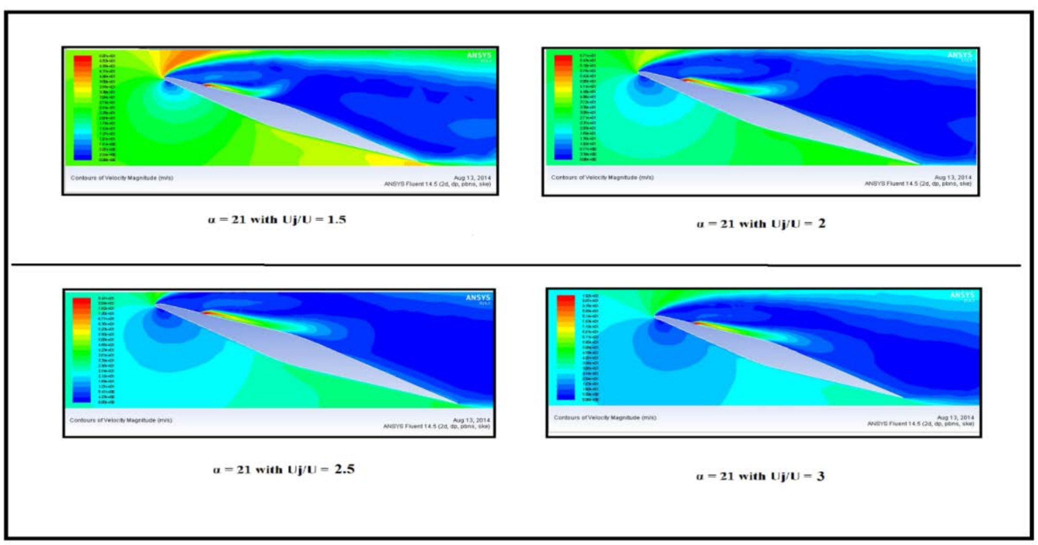
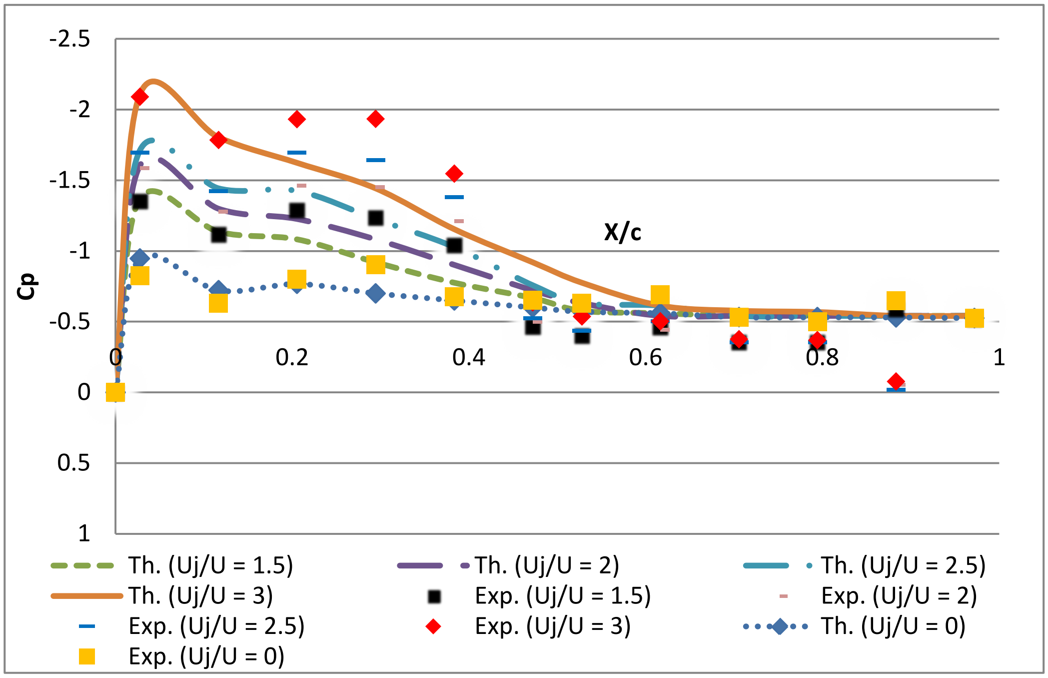


Figure (12). Effect of blowing intensity on velocity distribution on modified airfoil (α = 21; R_e = 3.287*10^5)



Figure(13). Lift coefficient with angle of attack for Standard and modified airfoils with and without blowing at (Re = 3.287 * 10^5

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