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Research Article

Transonic shockwave/boundary layer interactions on NACA 5 series -24112

S.V.S.A.Hema Sai Chand [Ȧ*], K. Giridhar [Ȧ], T. Keerthi Goud [Ȧ], B. Vamshi bhargav [Ȧ] and P. Srinivas Rao [Ȧ]

[Ȧ] Aeronautical Engineering, Vardhaman College of Engineering, Hyderabad, India.

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Abstract

The present paper reports theoretical and computational study of interaction of a shockwave with a boundary layer. This type of shockwave boundary layer interaction describes a shockwave interaction with a boundary layer induced by another shockwave. Geometrical shock dynamics is used for theoretical analysis of the shockwave and boundary layer interaction. This paper gives a general understanding of the aerodynamic processes that occur in and around SBLIs, concentrating as much as possible on the physics of these flows. Aerodynamic loads are estimated to explain which factors determine their structure under a variety of circumstances and also show how they impact on other parts of their flowfield, influencing parameters such as the drag, the surface flux distributions, and the overall body flow. The data show that weak shock waves induce an unsteady pressure distribution that can be predicted quite well, while stronger shock waves cause complex frequency-dependent distributions due to flow separation. It demonstrates how the present state of our understanding has resulted through contributions from computational fluid dynamics (CFD). Because of their significance for many practical applications, SBLIs are the focus of numerous studies spanning several decades. Hence, there is a considerable body of literature on the subject.

Keywords: *Shockwave, Boundary layer, Airfoil, Interactions.*

1. Introduction

A boundary layer is the layer of fluid in the immediate vicinity of a bounding surface where the effects of viscosity are significant. The planetary boundary layer is the air layer near the ground affected by diurnal heat, moisture or momentum transfer to or from the surface .A surface can have multiple types of boundary layer simultaneously.

A shockwave is a type of propagating disturbance. It is a like an ordinary wave, it carries energy and can propagate through a medium across a shock there is always an extremely rapid rise in pressure, temperature and density of the flow .It travels through most media at a higher speed than an ordinary wave. The energy of a shock wave dissipates relatively quickly with distance. [F. Sharipov.et.al].

When a shock wave interacted with a boundary layer, its main effect is to cause a sudden retardation of the flow the subsequent thickening and, in many cases, there will be a separation of the boundary layer. There will be at low frequency unsteadiness associated with intermittent flow separation can cause strong buffeting of the aircraft structures ,which may lead to failure by structural fatigue.
On an air craft wing the boundary layer is the part of the flow close to the wing, where viscous forces will distort the surroundings non viscous flow. This allows a closed form solutions for the flow. The significant simplification to the full Navier-stoke equation .The pressure distribution remains constant throughout the boundary layer.

In aeronautical engineering, boundary layer control refers to a number of methods of controlling the boundary layer of air on the main wing of an aircraft. In doing so, parasitic drag can be greatly reduced and performance likewise increased, while the usable angle of attack can be greatly increased, thereby dramatically improving lift at slow speeds. An aircraft with a boundary layer control system thus has greatly improved performance over a similar plane without such a system, often offering the otherwise contradictory features of STOL performance and high cruising speeds.

The deduction of the boundary layer equations was one of the most important advances in the fluid dynamics. The equation was derived from Navier-stokes equations. The continuity for 2D are given by

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \qquad \text{Eq.1}$$

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=-\frac{1}{\rho}\frac{\partial p}{\partial x}+\nu\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right) \qquad \text{Eq.2}$$

$$u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}=-\frac{1}{\rho}\frac{\partial p}{\partial y}+\nu\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right) \qquad \text{Eq.3}$$

Where u and v are the velocity components, ρ is the density, p is the pressure, and ν is the kinematic viscosity of the fluid at a point. [G. N. Markelov.et.al]
By using Reynolds's number and scale analysis the motion reduced within boundary layer

*Corresponding author: **S.V.S.A.Hema Sai Chand**

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0$$
Eq.4
$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=-\frac{1}{\rho}\frac{\partial p}{\partial x}+\nu\frac{\partial^2 u}{\partial y^2}$$
Eq.5
If fluid is incompressible then
For the extreme pressure the application of Bernoulli's equation is
$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=u_0\frac{\partial u_0}{\partial x}+\nu\frac{\partial^2 u}{\partial y^2}$$
Eq.6
Where u and u_0 are both parallel
Boundary layer equation is
$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0$$
Eq.7
Then
Pressure doesn't change in the direction-then
$$\frac{\partial p}{\partial x}=0$$
Eq.8
So u_0 remains constant
Therefore the equation of motion simplifies
$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=\nu\frac{\partial^2 u}{\partial y^2}$$
Eq.9
The above equations are for laminar and turbulent boundary layer. The thickness of the boundary layer δ is a function of the Reynolds number for laminar flow. [M. S. Holden. et. al.]
$$\delta \approx \frac{5.0 * x}{\sqrt{Re}}$$
Eq.10
δ = the thickness of the boundary layer: the region of flow where the velocity is less than 99% of the far field velocity v_∞; x is position along the semi-infinite plate, and Re is the Reynolds Number given by $\rho v_\infty x/\mu$ (ρ = density and μ =dynamic viscosity).
This effect was exploited in the Tesla turbine, patented by Nikola Tesla in 1913. It is referred to as a bladeless turbine because it uses the boundary layer effect and not a fluid impinging upon the blades as in a conventional turbine. Boundary layer turbines are also known as cohesion-type turbine, bladeless turbine, and layer turbine (after Ludwig prandtl's) [H. Takeuchi.et.al].

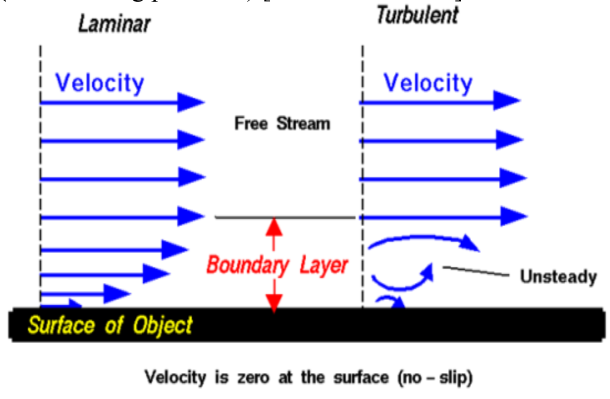

Fig1: different types of flows with boundary layer (Source: Wikipedia.org)

The repercussions of a shock wave–boundary layer interaction (SBLI) occurring within a flow are numerous and frequently can be a critical factor in determining the performance of a vehicle or a propulsion system. SBLIs occur on external or internal surfaces, and their structure is inevitably complex. On the one hand, the boundary layer is subjected to an intense adverse pressure gradient that is imposed by the shock. On the other hand, the shock must propagate through a multilayered viscous and in viscid flow structure. If the flow is not laminar, the production of turbulence is enhanced, which amplifies the viscous dissipation and leads to a substantial rise in the drag of wings or if it occurs in an engine a drop in efficiency due to degrading the performance of the blades and increasing the internal flow losses. The adverse pressure gradient distorts the boundary layer velocity profile, causing it to become less full (i.e., the shape parameter increases). (As shown in fig 1&2). [J. R. Torczynski.et.al].

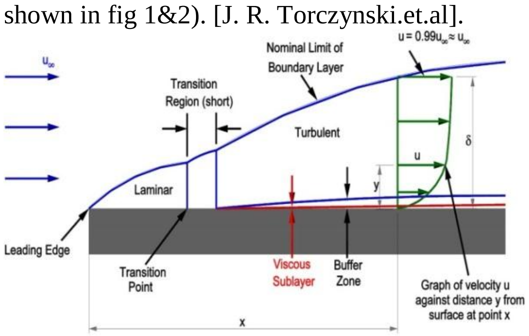

Fig 2: Boundary layer explanation (source: Wikipedia.org)

Shock Waves

Shock wave is formed when the speed of a fluid changes by more than the speed of sound. .It occurs in the region where the sound wave travels against the flow reach a point where they cannot travel any further upstream. The high pressure shock wave rapidly forms. The shock wave is one of several different ways in which a gas in a supersonic flow. Flow appearances of pressure drag on supersonic aircraft is mostly due to the effect of shock compression on the flow. [J. K. Harvey.et.al]

2. Mathematical Modeling

Shock wave boundary layer interactions (SBLIs) occur when a shock wave and a boundary layer converge and, since both can be found in almost every supersonic flow, these interactions are commonplace. The most obvious way for them to arise is for an externally generated shock wave to impinge onto a surface on which there is a boundary layer. [J. K. Harvey et.al]

Five basic interactions can occur between a shock wave and a boundary layer in two-dimensional flows. These occur when there is:

An impinging oblique-shock reflection, a ramp flow (fig.3), a normal shock (fig.3), an imposed pressure jump (fig.4), An oblique shock induced by a forward-facing step (fig.4).
Shock wave and boundary layers: The confrontation

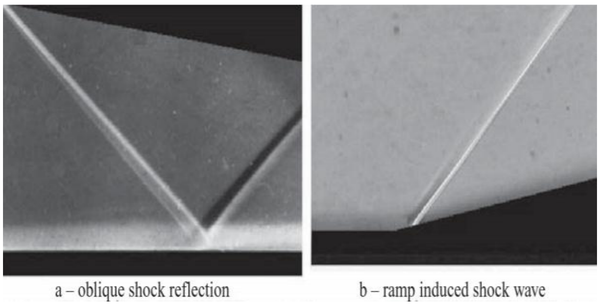

Fig.3 (different types of shockwaves)

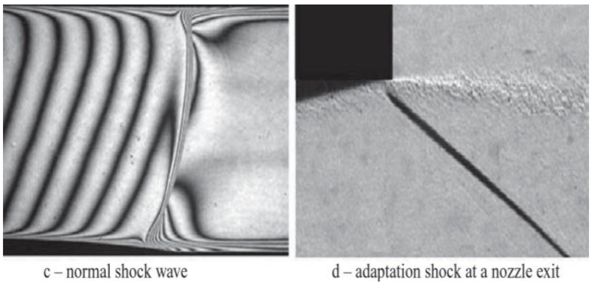

Fig.4(different types of shockwaves)

Concerning the response of the boundary layer to the shock, there are no basic differences between all of these situations except perhaps case 4 in which the interacting flow communicates with an atmosphere. Therefore do not distinguish among cases when discussing the viscous flow behavior in subsequent sections. The major distinctions are between interactions with and without separation. [J. N. Moss .et.al]

The Boundary Layer Shock Pressure Jump Competition SBLI can be viewed as a competition between a variable property flow the boundary layer, in which viscous forces are (or have been) at work and an abrupt pressure rise. The result of this conflict depends on the pressure rise amplitude and the boundary layer characteristics. It is typical to distinguish between laminar and turbulent interactions according to the nature of the boundary layer meeting the shock wave. There are no basic differences between the two types of flow relative to the overall physics and topology of the flow. Thus, any description of the interaction of one nature can be applied, mutatis mutandis, to the interaction of the other type. Therefore, in subsequent sections laminar and turbulent interactions are examined globally with the choice of the more commonly occurring turbulent interaction used to illustrate the description. Dramatic differences between laminar and turbulent flows render the nature of the incoming boundary layer an essential parameter. [B. Chanetz. et.al]

The boundary-layer equation for the stream wise momentum for a steady flow is as follows:

$$\rho\, u\frac{\partial u}{\partial x}+\rho\, v\frac{\partial u}{\partial y}=\frac{\partial}{\partial x}\left(\rho u^2\right)+\frac{\partial}{\partial y}(\rho u v)=-\frac{dp}{dx}+\frac{\partial \tau}{\partial y},$$ Eq.11

Where ρ is the density, u and v are the x-wise and y-wise velocity components (y is normal to the wall), p is the pressure, and τ is the shear stress. The central part of this equation expresses the stream wise derivative of the flow momentum. Forces at work in a Shockwave boundary layer interaction:

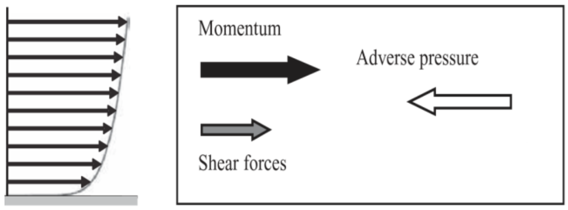

Fig.5 velocity profile gradient(source: Wikipedia.org)

A more simplistic analysis can be proposed by neglecting the contribution of the normal velocity component that is, by considering the boundary layer as a parallel flow then:

$$\rho\, u\frac{\partial u}{\partial x}=\frac{\partial}{\partial x}\left(\rho u^2\right)=-\frac{dp}{dx}+\frac{\partial \tau}{\partial y}$$

Eq.12

Hence, by integrating between a lower boundary δi close to the wall and the boundary layer outer edge, the following relationship could be obtained

$$\frac{d}{dx}\int_{\delta_i}^{\delta}\rho u^2 dy=-\frac{dp}{dx}(\delta-\delta_i)+(\tau_\delta-\tau_{\delta_i})\approx-\frac{dp}{dx}(\delta-\delta_i)\approx-\frac{dp}{dx}\delta$$

Eq.13

In this equation, the shear stress is neglected and the inner boundary is assumed to be very close to the wall (δ << δ I).

Normal Shock and Transonic Interactions:

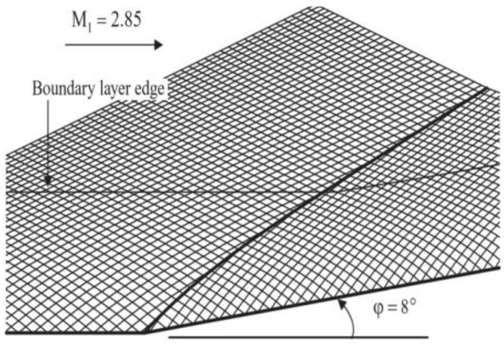

Fig.6

Method of characteristic calculation of a ramp-induced shock. Wave system and shock turbulent boundary layer profile (upstream Mach number 2.85, ramp deflection 8◦).

Interactions without separation: Shadowgraph visualization of ramp induced shock in a Mach 2.85

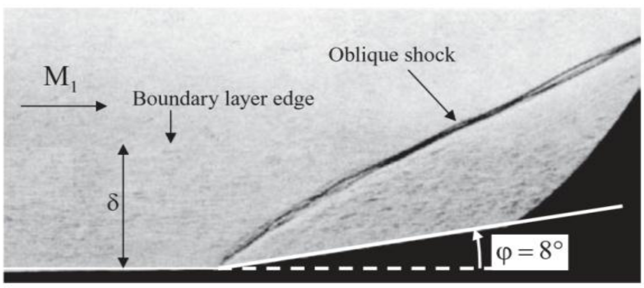

Fig.7

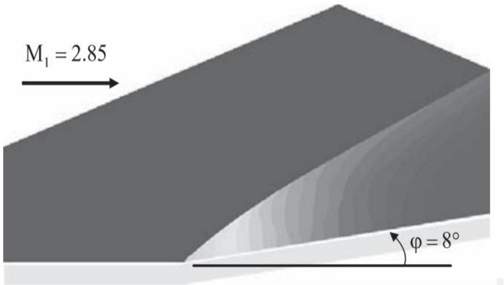

Fig.8

Method of characteristic calculation of a ramp induced shock. Static pressure contours. Turbulent boundary layer profile (upstream Mach number 2.85, ramp deflection 8◦).

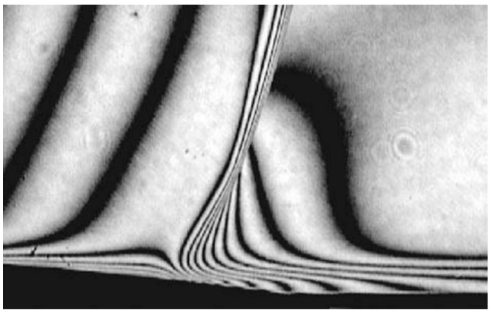

Fig.9

Normal shock interaction without separation. Interferogram of flow field,

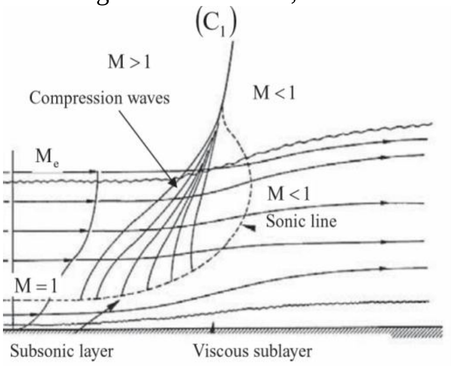

Fig.10

Normal shock interaction without separation. Sketch of flow field.

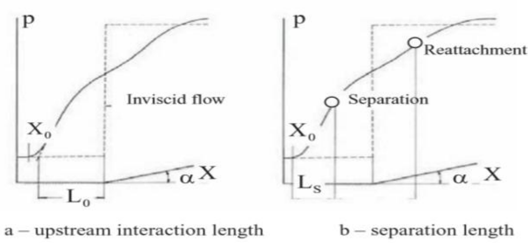

Fig.11
Characteristic lengths of a supersonic interaction.

3. Results and Discussion

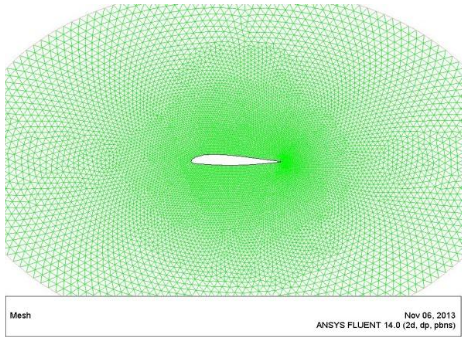

Fig.12: Computational Domain

Description:
The NACA 5series airfoil is considered for the study shockwave and boundary layer interaction

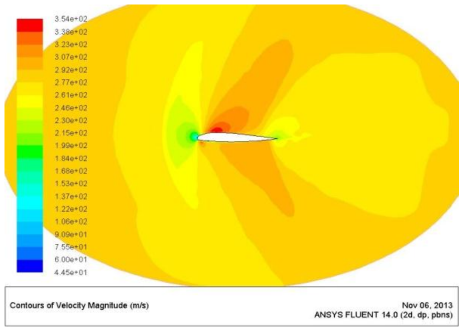

Fig.13

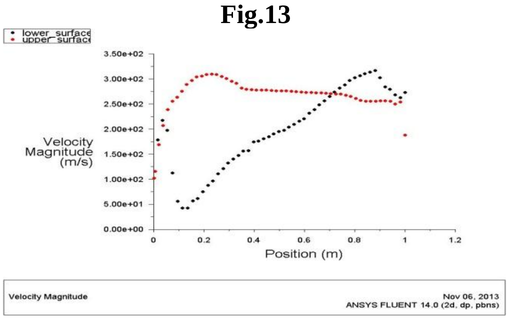

Fig.14

The velocity magnitude on the upper surface is increasing slightly and maintain certain constant position at 2.50e+02 then its tries to decrease .and again maintain certain value till the end.At 1.50e+02 .The velocity magnitude on the lower surface suddenly falls to a value at 5.00e+01 and gradually increasing from certain point 5.00e+01of position till the end.

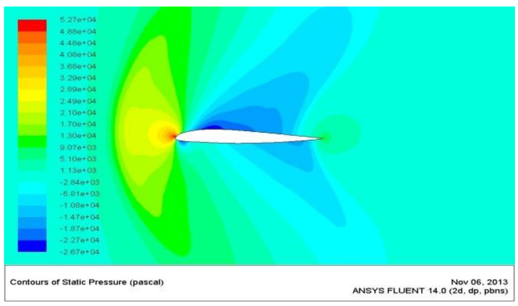

Fig.15

Pressure Coefficient is a dimensionless in the above figure it can see outline representation of static pressure on an airfoil, which is considered.

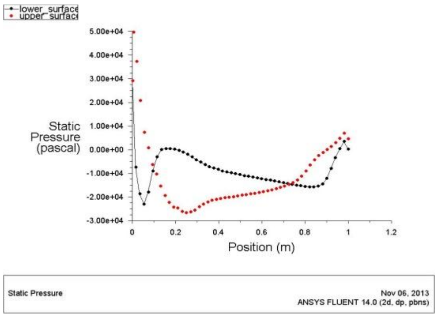

Fig.16

The static pressure on the upper surface gradually reach to a negative value-2.00e+04 and tries to rise its position to positive figure at 0.00e+00.The static pressure on the lower surface treats to be a constant value at 0.00e+00 with respect to position(changes may not be considered).

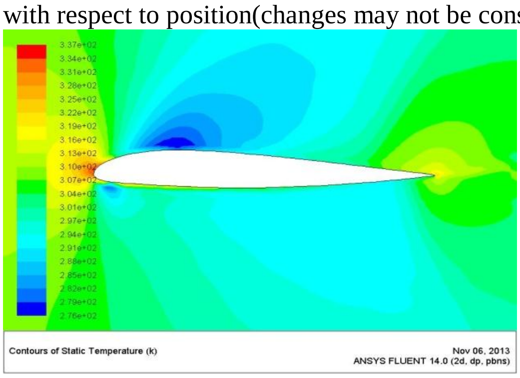

Fig.17

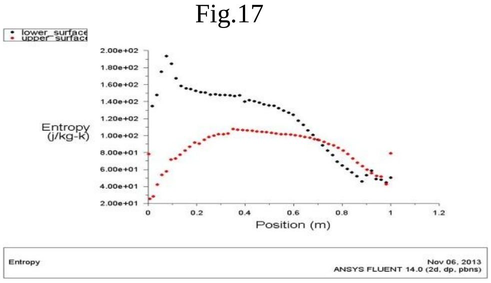

Fig.18

The entropy on the upper surface slightly increases at 1.00e+02 and forms a parabolic path .The entropy on the lower surface has a sudden increase followed by a gradually decrease at 1.00e+02with respect to position.

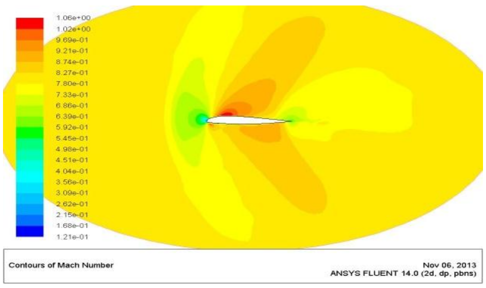

Fig.19

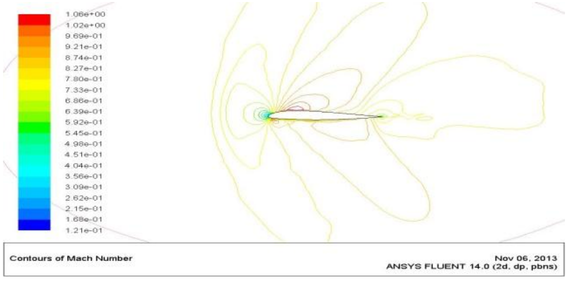

Fig.20

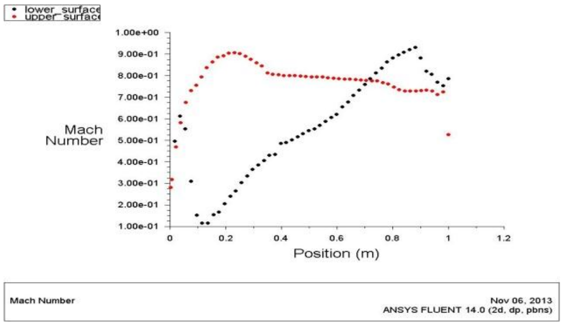

Fig.21

The characteristics of Mach number on the upper surface is slightly increases and then its peak value is 9.00e-01 and its average value is 8.00e-01 then its least value is 5.00e-01.The characteristics of mach number on the lower surface it as a sudden fall then it gradually increases to a peak value and then it fall to its peak value is 9.00e-01 and its average value.

4. Conclusion

The data presented in the paper shows that the shockwave boundary layer interactions have an important effect on the unsteady pressure distribution and loads on the airfoils. The weak interactions can be estimated with sufficiently good accuracy using the computational fluid dynamics. However, the flow separation at sufficiently high speeds the variation of the unsteady flow distribution on the airfoil limits the understanding of the interaction of shockwave with the boundary layer. Detailed experimental analysis is required to completely understand the transonic shockwave interaction with the boundary layer.

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