International Journal of Applied Engineering Research ISSN 0973-4562 Volume 10, Number 19 (2015) pp 40726-40733

Performance Enhancement of a 2-D Low Wave Drag Supersonic Busemann Biplane at Off-Design Condition

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Abstract
In this paper, the lift and drag characteristics of a 2-D Busemann biplane for supersonic transport aircraft is analyzed at design and off-design conditions using Computational Fluid Dynamics. This study proposed the 2-D configuration which is reduced the flow chocking and flow hysteresis problems at off design condition of the Busemann biplane. Staggered configurations have been proposed for performance enhancement of these biplanes at off-design conditions. The biplane is designed in such a way that the throat area of the Busemann biplane will increases and reduces the flow chocking characteristics. In this paper we studied the effect of flow chocking and the flow hysteresis in detail. The results of these analyses gave the significant reduction in wave drag at off-design condition of the Busemann biplane and the wave drag is reduces significantly. Finally, the practical strategy is proposed to vary the biplane form from take-off to cruise at design Mach number of 1.7.

Nomenclature
A_t = Throat Area
A_i = Inlet Area
M_∞ = Free stream Mach number
c = chord
C_D = Drag Coefficient
C_L = Lift Coefficient
C_p = Pressure Coefficient
α = angle of attack

Introduction
Concorde (1969 – 2003) was the first and last supersonic transport aircraft has finished its services due to economical (low value of L/D ratio) and environmental (high intensity sonic boom) constraints. Today is the busy world, the requirement to fly faster is a strong need to develop the nextgeneration supersonic transport aircraft, which will satisfy the economical requirement and environmental conditions i. e. low wave drag and low intensity sonic boom, generated due to the shock waves at supersonic speeds.

The Biplane concept is first introduced by the Busemann in 1935 [1]. Busemann proposed two wing elements located one over another, by utilizing the shock interaction between the two elements and eliminated the wave drag produced by the thickness of the airfoil [1, 2]. Licher further extended the idea to reduce the wave drag by changing the thickness of the elements [3]. Recently a group of scientists at Tohoku University Japan has focused their research on the Supersonic biplane. Dr. Kusenose et. al. have studied supersonic biplane configurations similar to the convergent-divergent nozzle, hence the biplane configuration have the chocking phenomenon at a wide range of transonic flow regions and it increases the wave drag at off-design Mach numbers[4, 5]. They introduced airfoil morphing and adaption of fowler motion to reduce the wave drag produces by the Busemann biplane [6, 7].

Biplane airfoils have good characteristics at their Design Mach Number, but they have disadvantage (flow chocking) under off-design conditions. During actual flight the biplane must accelerate at off design Mach number before reaching to the design Mach number, it is very important to understand the characteristics for the flow at off design condition as well. Supersonic biplanes will easily become a reality once the off-design condition obstacles are overcome.

Wave Drag Elimination: A Biplane design concept
Busemann proposed that the wave drag can be easily removed by splitting the diamond airfoil into two elements and placing them in a way that the waves generated by the elements are eliminated [1].

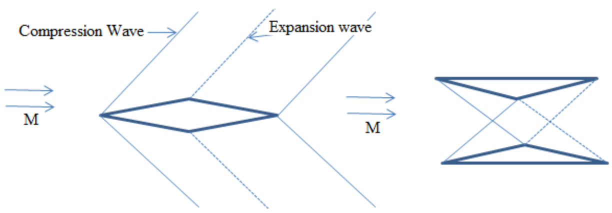


Figure 1. Wave Cancellation Effect in Busemann biplane.

The thickness to chord ratio for the diamond and the Busemann biplane airfoil have been selected as 0.1 at a wedge angle of 5.7 deg. The distance between the elements of the biplane (z/c = 0.5) to minimize the wave drag at design Mach number of 1.7 as shown in figure-1.

Busemann biplane at off design condition: Chocked flow and Flow Hysteresis problems
For the real flight of Busemann biplane, we need to discover the methods that are applicable to a biplane so that we can reduce the wave drag at all Mach numbers. Before biplane analysis it is important to understand the phenomenon of flow of supersonic inlet diffuser, as biplane has the similar flow

characteristics. The inlets to go from unstart condition to start condition; it has to exceed the Mach number set by the Kantrowitz limit given by Eq. (1) [10].

$$\frac{A_t}{A_i} = \left[\frac{(\gamma-1)M_\infty^2+2}{(\gamma+1)M_\infty^2}\right]^{1/2}\left[\frac{2\gamma M_\infty^2-(\gamma-1)}{(\gamma+1)M_\infty^2}\right]^{\frac{1}{(\gamma-1)}} \quad (1)$$

Where A_t is the area of the throat and A_i is the area of inlet. The isentropic concentration limit is calculated by Eq. (2).

$$\frac{A_t}{A_i} = M_\infty\left[\frac{(\gamma-1)M_\infty^2+2}{(\gamma+1)M_\infty^2}\right]^{\frac{-(\gamma+1)}{2(\gamma-1)}} \quad (2)$$

It is reasonable to suppose that this rule is applicable to biplane to avoid the chocked flow and flow hysteresis. In fact CFD analysis gives the good results which are calculated from the Eq. (1) and Eq. (2). A_t/A_i of a Busemann biplane is 0.80.
Let us begin our analysis by confirming the drag characteristics for both diamond and Busemann airfoils for Mach numbers ($0.5 \leq M_\infty \leq 2.2$), figure-2 shows the drag characteristics of the two airfoils at a range of Mach numbers. Figure-2 shows that the drag coefficient for Busemann biplane is lower than the diamond airfoil for a wide range of Mach numbers ($1.65 \leq M_\infty \leq 2.2$). A high wave drag is occurred for $M_\infty \leq 1.64$, this is because of the strong bow shock is generated ahead of the biplane and the flow is accelerate in the downstream location of the throat, this is known as flow chocking phenomenon of the biplane. For the lower Mach number the shock waves generated by the elements are interact and a subsonic region is formed near the throat of the biplane, eventually for the less Mach numbers the subsonic zone is propagated to upstream and forming a bow shock and increases the wave drag as shown in figure-2.

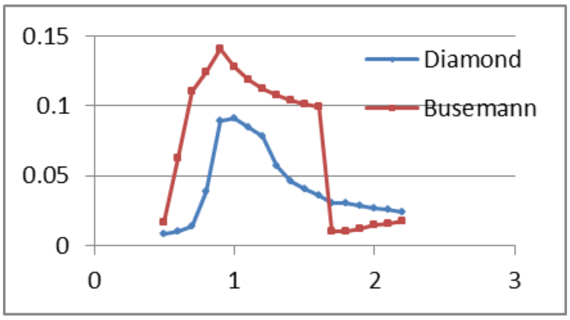


Figure 2. Drag Characteristics of Diamond and Busemann airfoils.

Geometry and Flow Solver

All geometries are created with the distance between the elements is 0.5c and the t/c is 0.05 for each element and the analysis is done for different vales of stagger, x of 0.1c, 0.2c, 0.3c, 0.4c and 0.5c. The multi block unstructured grids are prepared as shown in Figure-5 with the help of ICEMCFD. The total number of elements for the non-staggered configuration is around 3.5×10^5, stretched perpendicular to airfoil surface. The boundary layer mesh has the first cell height of 8.11×10^{-6}m in order to resolve viscous stresses. A second order accurate, steady state results are obtained through time marching solution of coupled, 2-dimesional Navier-Stokes equations using FLUENT. A one-equation turbulence model by Spalart-Allmaras is used to consider the effect of turbulent boundary layer for viscous flow computations.
The Geometry and the mesh element for the proposed study are as shown in Figure 3 and Figure 4.

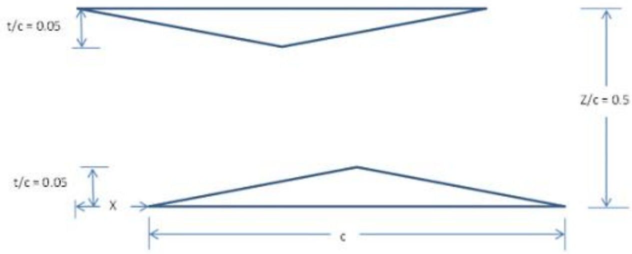


Figure-3 Basic Geometry

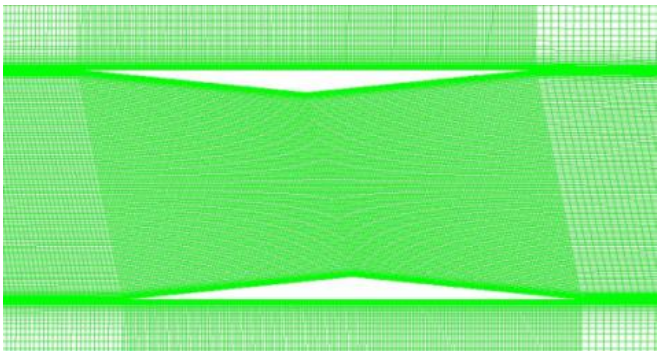


Figure-4 Mesh Element.

Result and Discussion

The result of the biplanes with different values of stagger, x is shown in Figure-3, at off design free stream Mach number varying from 0.5 to 1.7. The Busemann biplane faces the flow chocking at low flight Mach number which reduces its aerodynamic efficiency. Figure 3 shows the variation of wave drag for a wide range of Mach Numbers ($0.5 \leq M_\infty \geq 1.7$). The wave drag is significantly reduced due to the an increase in the area of throat of the Biplane up-to the free stream Mach number of 1.5, where the lift Coefficient is found $C_L > 0.1$ for Mach number range of $1.0 \leq M_\infty \leq 1.4$.

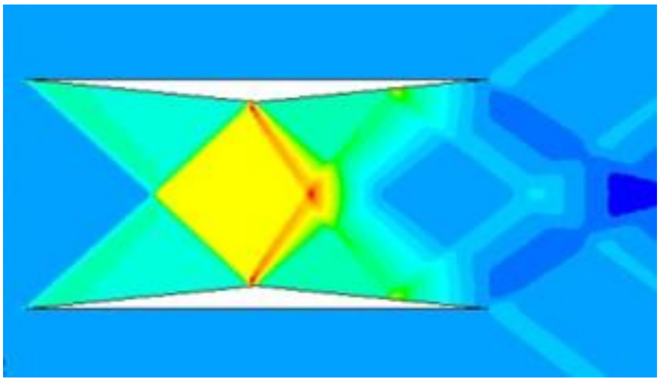
A. Validation of the results

The results of the lifting and non-lifting conditions for the Diamond and Busemann airfoils are optimized. To test the sensitivity, the two cases are studied and found that the results are robust and not very sensitive for the change of angle of attack. The numerical results for total Lift and Drag are calculated for the Diamond and Busemann airfoils are given in the Table 1 at Design Mach number 1.7 and zero and one angle of attack.

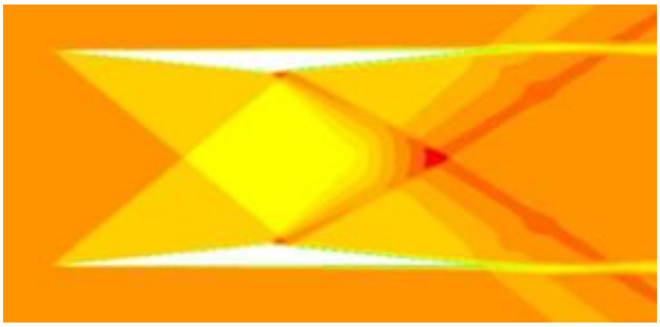
Table 1. Numerical Lift and Drag for Diamond and Busemann airfoils

	α = 0 Degree		α =1 Degree	
	C_L	C_D	C_L	C_D
Diamond	0.0000	0.0308	0.0342	0.0520
Busemann	0.0000	0.0098	0.0593	0.0109

The pressure contours and the Mach number contours around these airfoils are given in the figure 5, shows the wave reduction effect in the Busemann airfoil. It is clear that the total drag due to airfoil thickness is almost completely eliminated, at the 1/3 of the diamond airfoil at zero angle of attack and free stream Mach number of 1.7.



Pressure Contour

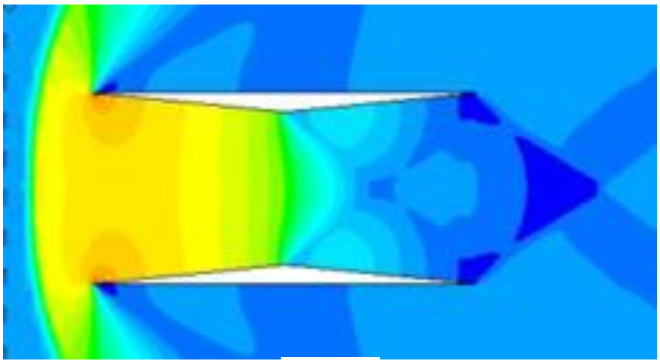


Mach numbar contour

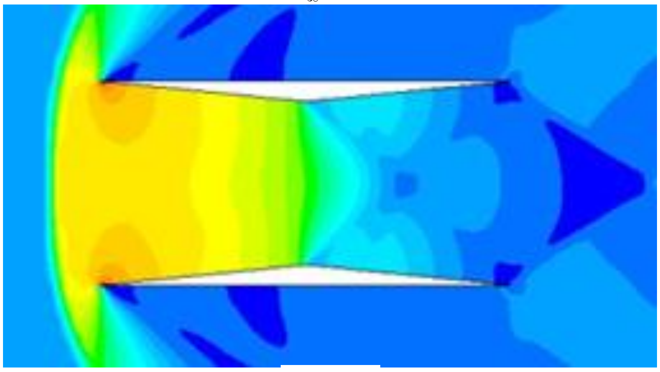
Figure 5. Pressure and Mach number contour (Busemann biplane, M_∞ = 1.7, α = 0 degree).

B. Busemann biplane: Off-Design Condition

The CFD results (Pressure contour and Mach number counter) of the Busemann biplane (with z/c = 0.5 and t/c = 0.05 at zero lift condition) are shown in Figure 6 and 7 at the free stream Mach number of 1.6 and 1.7. Figure 2 shows the detailed drag changes over a range of Mach numbers ($0.5 \leq M\infty \leq 2.2$), including the design Mach number 1.7. At the design Mach number the Drag coefficient is minimum, but at the off design condition ($M_\infty \leq 1.65$) the drag is higher than the diamond airfoil for the same t/c = 0.1. The high drag is caused due to the strong bow shock wave is generated ahead of the Busemann airfoil, shown in the figure 6 and figure 7.

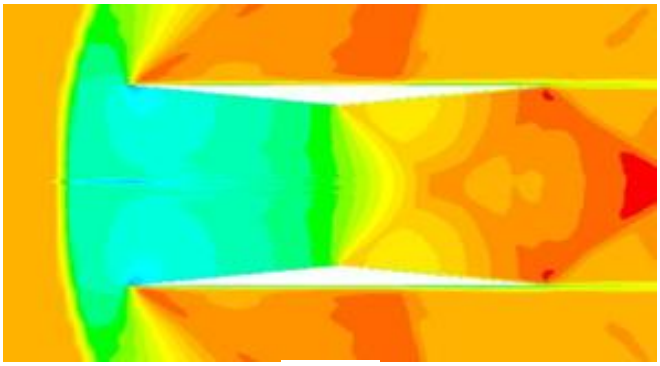


M_∞ = 1.5

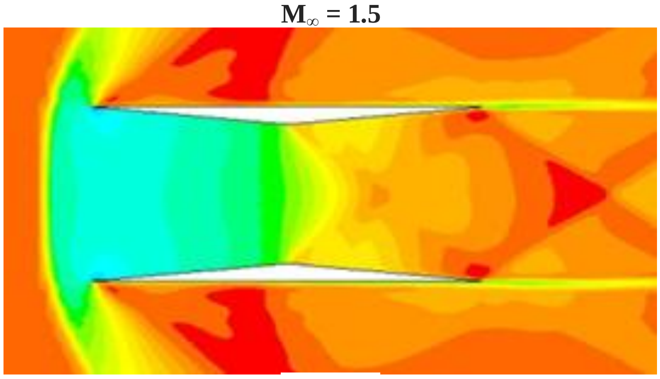


M_∞ = 1.6

Figure 6. C_p contour of Busemann biplane (M_∞ = 1.5 and 1.6)



M_∞ = 1.5

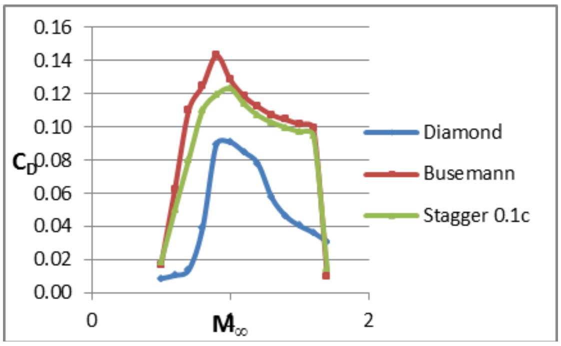


M_∞ = 1.6

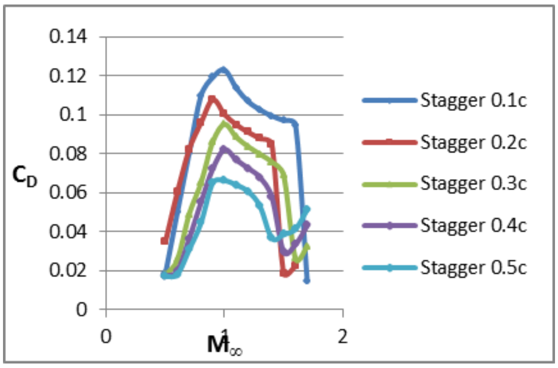
Figure 7. Mach number contour of Busemann biplane (M_∞ = 1.5 and 1.6)

C. Busemann Biplane at Off-Design condition: Stagger Configuration

For a efficient flight it is necessary to avoid the chocking. The chocking condtions for subsonic flow and the supersonic flow are different, for the subsonic flow region the outer section should be change to avoid the supersonic region at a downstream loacation of the throat. Stagger configuration will increaeses the throat area for the same inlet area and reduces the chocking effect for the Busemann biplane airfoil. Stagger configuration also generate the positive lift cofiicient at a wade range of Mach number for off design conditions ($0.5 \leq M_\infty \leq 1.7$). The values of the total lift and drag coefficient are shown in Table 2 and Table 3. Figure 8 shows the details variation of the darg cofficient with different Mach numbers. The pressure plots and the Mach number contour are also shown in figure 9, 10, 11 and 12.



(a)Drag Variation for Diamond, Busemann and Stagger 0.1c.



(b). Drag Variation with Different Stagger position

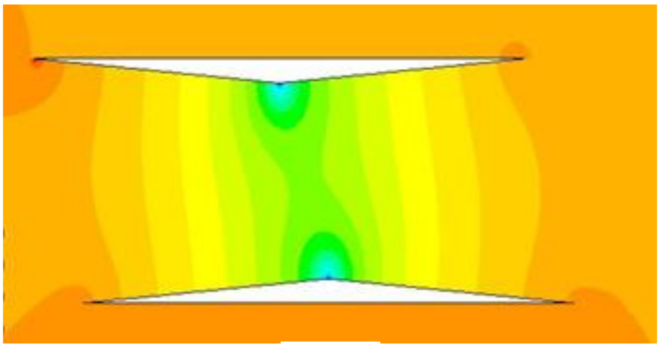
Figure-8. Drag Variation with Free Stream Mach number (M_∞).

Table 2. Lift and Drag Coefficient for Diamond, Busemann and Stagger configuration for $0.5 \leq M_\infty \leq 1.2$

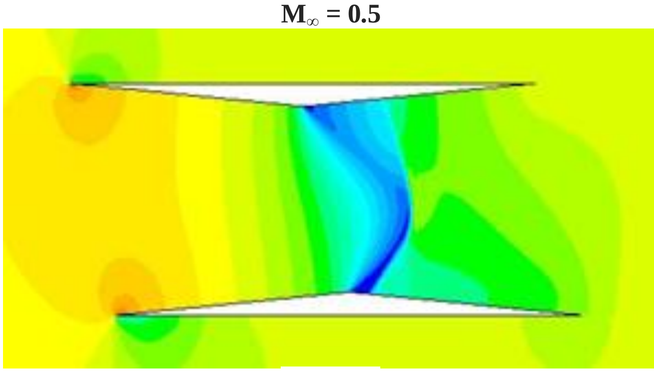
	M_∞=0.5		M_∞=0.9	
	C_L	C_D	C_L	C_D
Diamond	0.0000	0.0088	0.0000	0.0000
Busemann	0.0000	0.0168	0.0000	0.1428
Stagger 0.1c	0.0439	0.0185	0.0502	0.1275
Stagger 0.2c	0.0231	0.0438	0.1330	0.193
Stagger 0.3c	0.1296	0.0117	0.2748	0.0863
Stagger 0.4c	0.1652	0.0172	0.3237	0.0724
Stagger 0.5c	0.1909	0.0170	0.4739	0.0652

Table 3. Lift and Drag Coefficient for Diamond, Busemann and Stagger configuration for $1.4 \leq M_\infty \leq 1.7$

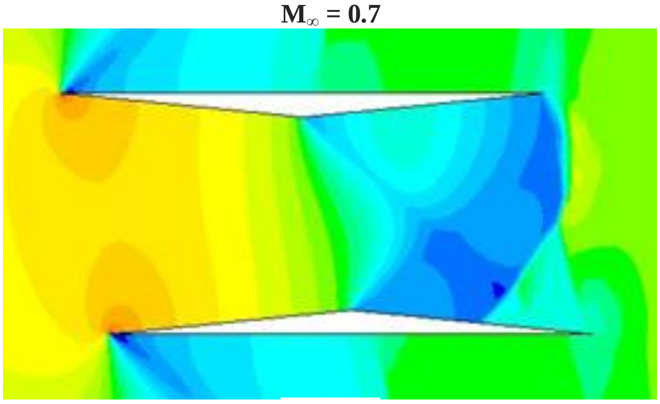
	M_∞=1.4		M_∞=1.7	
	C_L	C_D	C_L	C_D
Diamond	0.0000	0.0465	0.0000	0.0309
Busemann	0.0000	0.1044	0.0000	0.0098
Stagger 0.1c	0.1275	0.0996	0.0146	0.0145
Stagger 0.2c	0.193	0.0879	0.020	0.0224
Stagger 0.3c	0.2179	0.0759	0.0057	0.0325
Stagger 0.4c	0.1585	0.0578	-0.0383	0.0431
Stagger 0.5c	0.0790	0.0367	-0.0621	0.0514



M_∞ = 0.5



M_∞ = 0.7



M_∞ = 0.9

Figure 9(a). C_p contour of Stagger configuration x= 0.1c ($0.5 \leq M_\infty \leq 0.9$)

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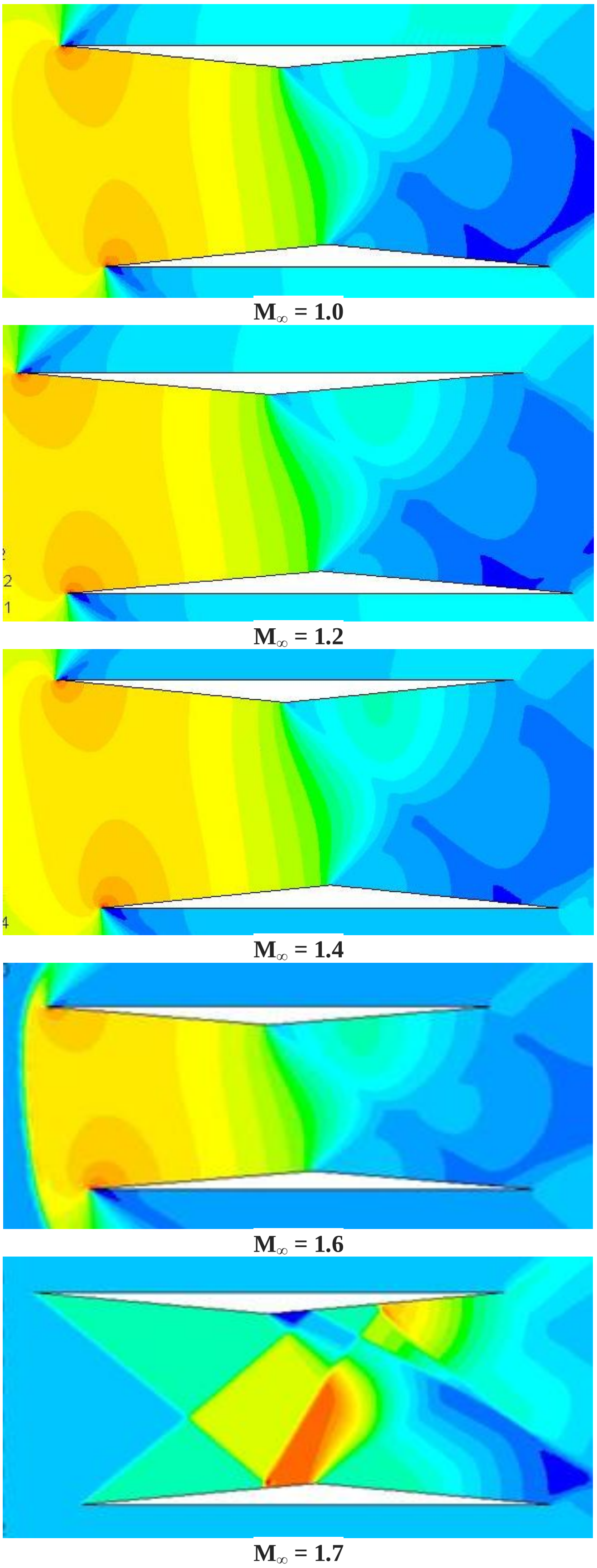


Figure 9(b). C_p contour of Stagger configuration x= 0.1c ($1.0 \le M_\infty \le 1.7$)

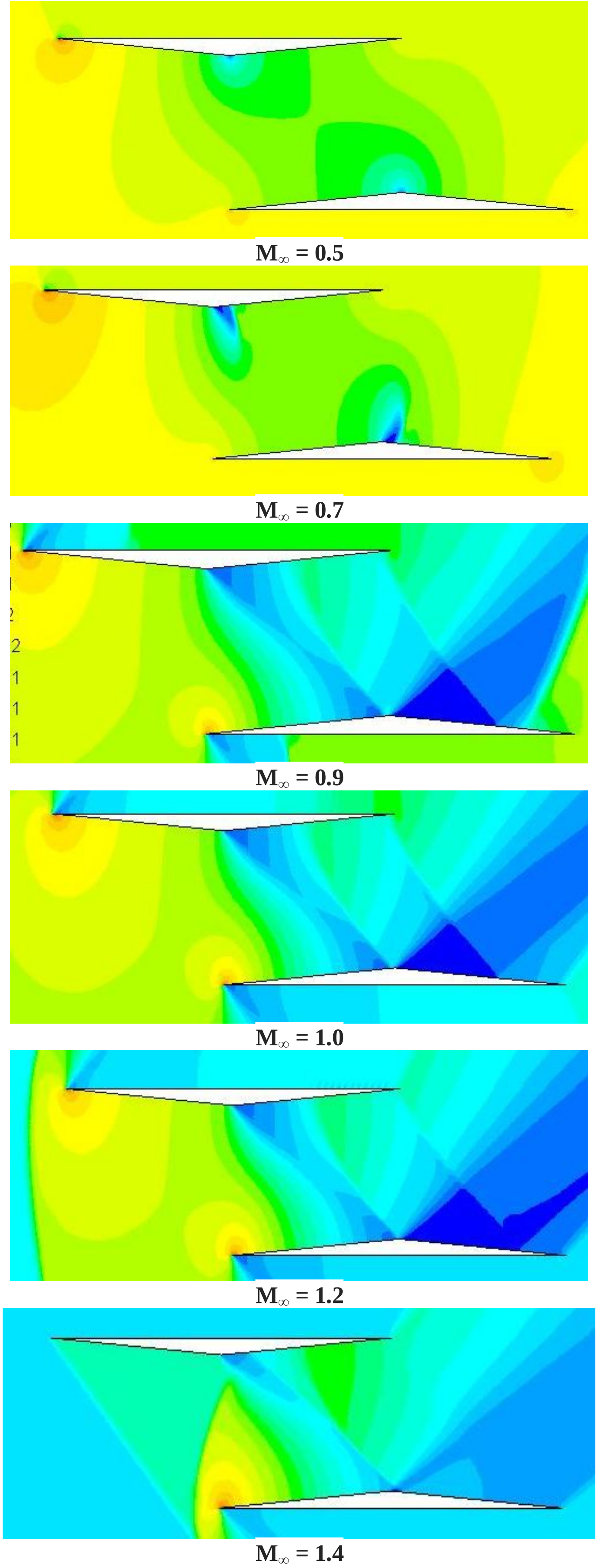
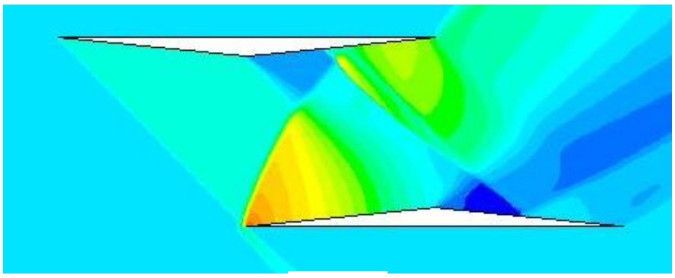
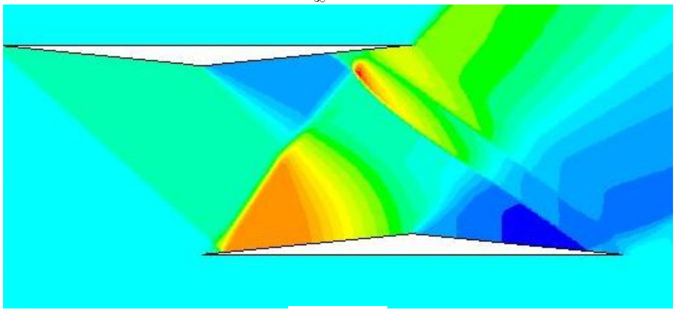


Figure 10(a) . C_p contour of Stagger configuration x = 0.5c ($1.6 \le M_\infty \le 1.7$)

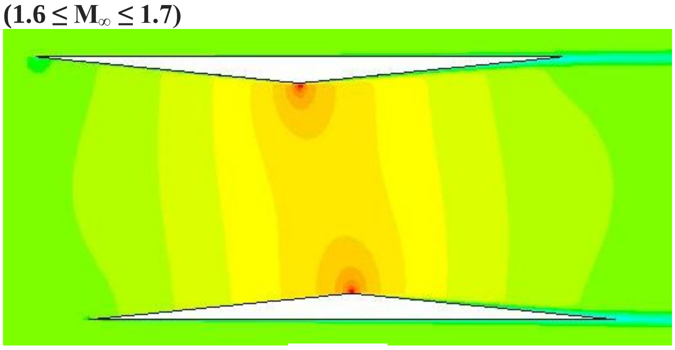


M_∞ = 1.6

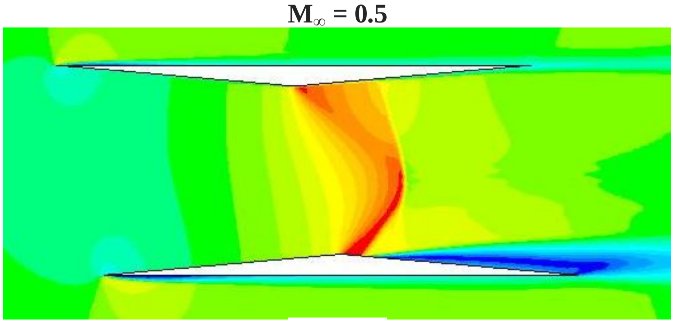


M_∞ = 1.7

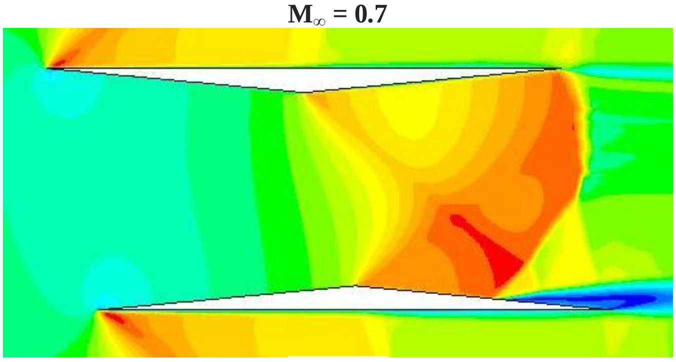
Figure 10(b) . C_p contour of Stagger configuration x = 0.5c ($1.6 \leq M_\infty \leq 1.7$)



M_∞ = 0.5

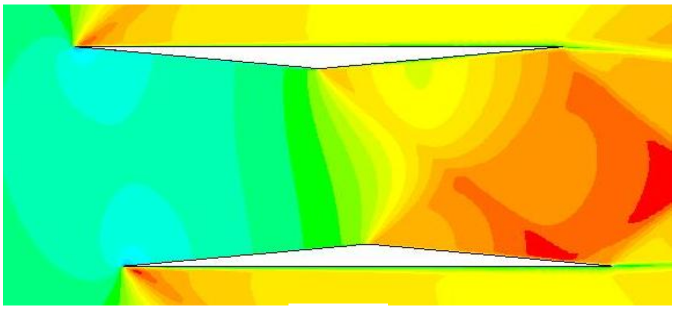


M_∞ = 0.7

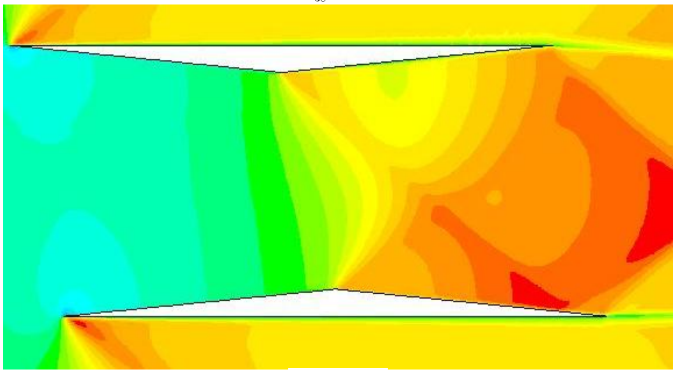


M_∞ = 0.9

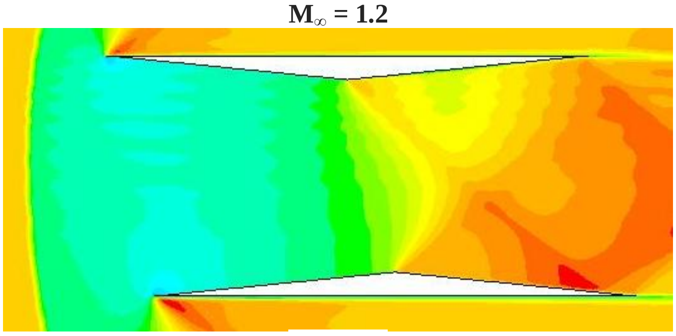
Figure 11(a). Mach number contour of Stagger configuration x = 0.1c ($0.5 \leq M_\infty \leq 0.9$).



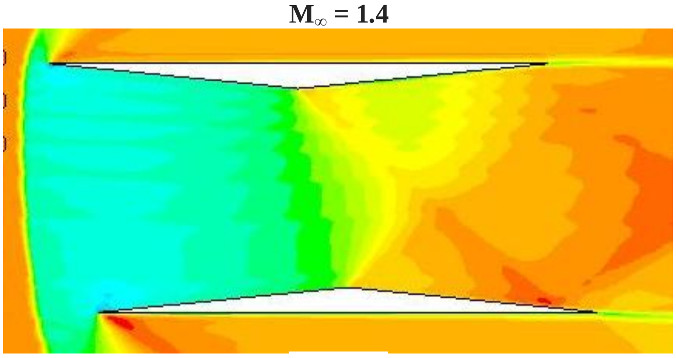
M_∞ = 1.0



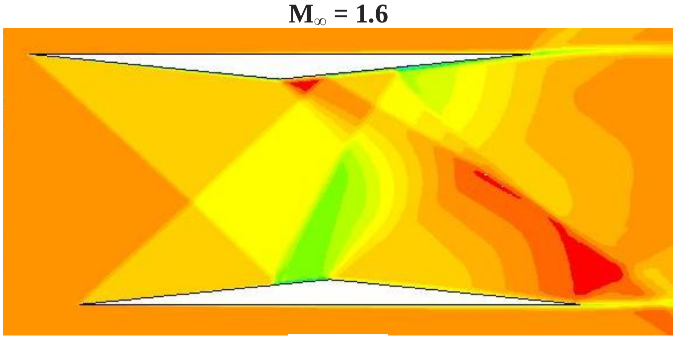
M_∞ = 1.2



M_∞ = 1.4

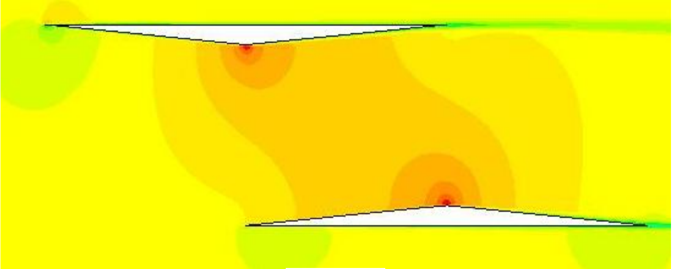


M_∞ = 1.6

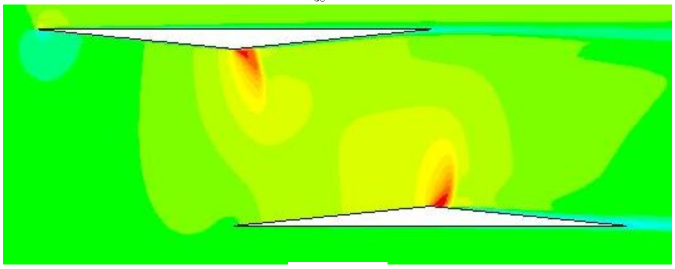


M_∞ = 1.7

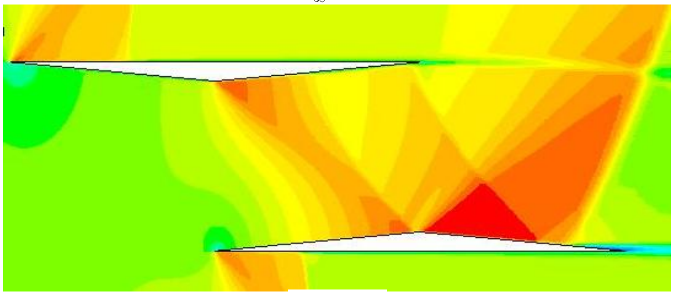
Figure 11 (b). Mach number contour of Stagger configuration x = 0.1c ($1.0 \leq M_\infty \leq 1.7$).



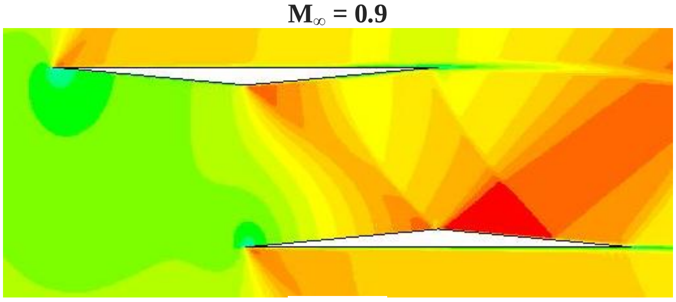
$M_{\infty} = 0.5$



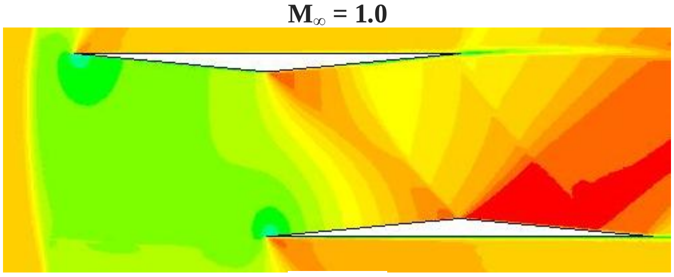
$M_{\infty} = 0.7$



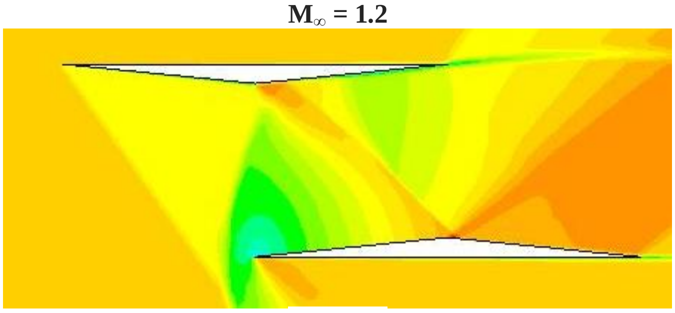
$M_{\infty} = 0.9$



$M_{\infty} = 1.0$

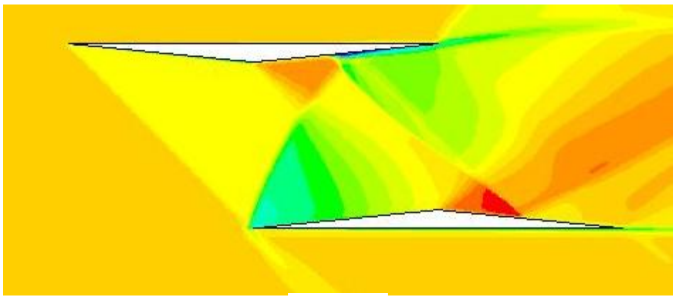


$M_{\infty} = 1.2$

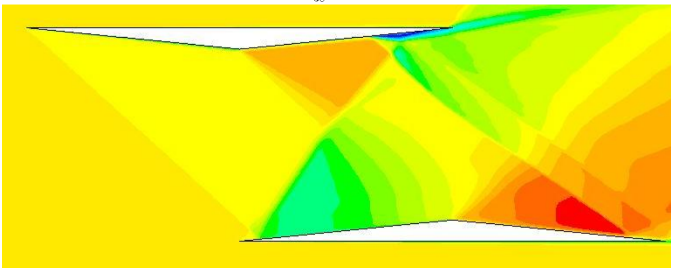


$M_{\infty} = 1.4$

Figure 12(a). Mach number contour of Stagger configuration x = 0.5c ($0.5 \leq M_{\infty} \leq 1.4$).



$M_{\infty} = 1.6$



$M_{\infty} = 1.7$

Figure 12(b). Mach number contour of Stagger configuration x = 0.5c ($1.6 \leq M_{\infty} \leq 1.7$).

I. Conclusion

The performance of the Busemann biplane is desirable at designed Mach number but undesirable at off design condition, the performance is poor due to flow chocking. CFD results showed that the chocking occurs over the wide range of free stream Mach numbers from 0.5 to 1.6. After carefully analysis and consideration, it is observed that the flow chocking can be reduced by using stagger configuration. The stagger configuration of the two elements allows for the drag reduction and wave cancellation effect that occurs between the two airfoils elements. These analysis shows that the biplane configuration can eliminate shock waves significantly at off design conditions and will be strong candidate in the development of the nearly boomless supersonic transport aircraft.

In actual flight, the flow chocking and the hysteresis is avoided over a wide range of free stream Mach numbers. The supersonic biplane can use the different stagger configuration from take-off and then reconfigure back to the form of a traditional Busemann biplane while flying at design Mach number, by use of this configuration supersonic biplane can be accelerate to the design Mach number without suffering the disadvantage of high wave drag.

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