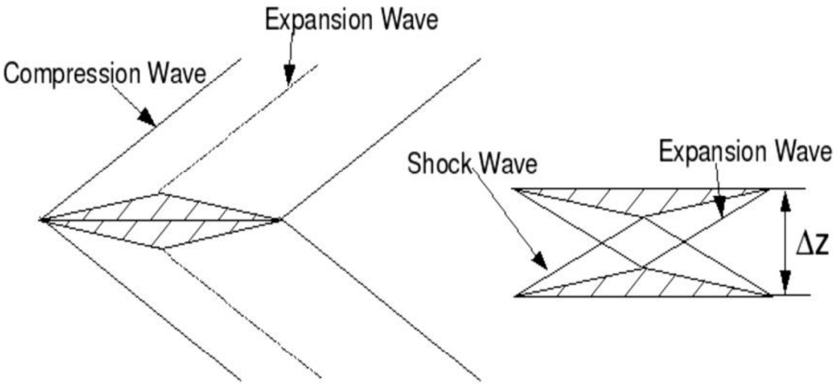
CHAPTER 2

LITERATURE REVIEW

Speed is of utmost importance for an aircraft as it can save precious time in this fast paced world. Only few transport aircrafts have managed successful service at supersonic speeds like the Concorde and T-144, since the first successful human flight by Wright brothers in 1903. Although many military aircraft and missiles fly routinely at supersonic speeds, the supersonic speeds for transport aircrafts have not been feasible due structural and economic requirements for such aircrafts. There are many reasons that prevent the transport aircrafts from flying at supersonic speeds. The most important factor is the sonic boom, the sound generated due to the shock waves induced on the aircraft, when flying at supersonic speed. The flying of supersonic transport aircrafts over residential areas is prohibited in many countries, because of the sonic boom, and this restricts the operational flexibility for the supersonic transport. Another factor that affects the commercial operations of supersonic transport aircrafts is the large amount of drag at supersonic speeds. A substantial quantity of fuel is needed to overcome this drag which makes the cost of flying very high and thus economically less viable.

Both these problems were fully understood by researchers well before mid-Nineteenth century. Many researchers tried to address the problems but due to lack of technological advancements at those times could not lead to fruitful solutions. One of the most interesting solutions provided in this regard was the concept of supersonic biplane which eliminates the wave drag and sonic boom completely at design Mach number at least theoretically. Recently many research organizations are working on this concept to minimize the intensity of sonic boom so that the supersonic transport will be the reality for the future. Some of the important findings available in the open literature are discussed below.

. The Busemann biplane is formed by splitting a diamond airfoil along the chord and placing them one over other such that area between the elements resembles a convergent-divergent nozzle as shown in Fig.2.1. He proposed that the wave drag generated by the shock waves is eliminated by the shock interaction between the biplane configuration by suitably placing the biplane elements in such a way that the shock wave induced by the upper and lower element interact with each other and reduces the strength of the reflected shock. Further the reflected shocks interact with the expansion fan at point of maximum thickness and the wave drag is eliminated. The shock-shock interactions in supersonic biplane at design Mach number is shown in Fig. 2.1.



Diamond airfoil Busemann biplane configuration

Fig. 2.1: Wave cancellation Effect in Busemann biplane. [4]

M J Lighthill [5] in 1944 further studied the Busemann biplane concept and found that the biplane configuration has many advantages with disadvantages as well. He concluded that due to greater surface area because of internal convergent divergent section, the component of frictional drag is more for the biplane but the overall drag is decreased at supersonic speeds.

W E Moeckel [6] in 1947 performed a detailed parametric study of the spacing between the biplane elements and effect of the leading edge and trailing edge angles of the two airfoils under lifting conditions. He proposed that the unsymmetrical biplanes have a higher aerodynamic efficiency than the symmetrical biplanes as the overall lift for the combination is increased at higher angles of attack while the drag coefficient can be minimized due to the shock cancellation and shock reflection between the elements.

A Ferri [7] in 1947 conducted the wind tunnel testing for the Busemann biplane under lifting and non-lifting conditions. He measured the aerodynamic forces and studied the viscous effects. He observed the undesirable phenomena of "chocking" and "hysteresis" that occur in a biplane configuration at off-design conditions. Ferri also concluded that biplanes have better aerodynamic efficiency than the monoplanes.

R M Licher [8] in 1955 proposed an unsymmetrical biplane configuration for which the wave drag reduced to 2/3rd of that for a single flat plate under the identical lifting conditions. He also found that the wave drag is eliminated due to the favorable interaction of the waves between the biplane elements as shown in Fig. 2.2. **Tan H S** [17] in 1960 studied the Licher biplane concept for a finite wing, and he concluded that the drag is further reduced in three dimensions and this further increases the aerodynamic efficiency of the biplane.

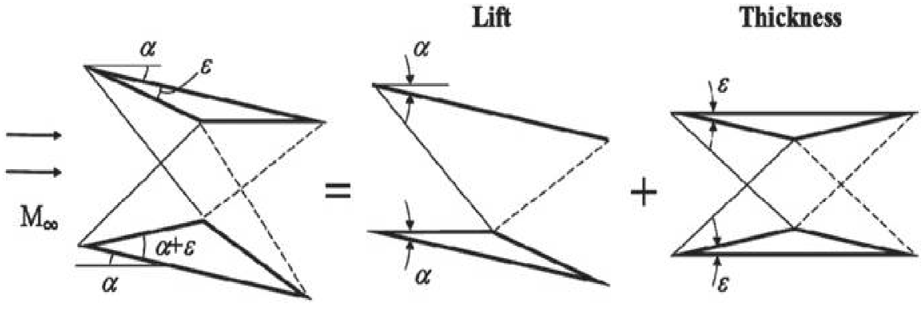


Fig. 2.2: Licher biplanes with lift and thickness components. [16]

After the studies by Licher in 1955 and Tan HS in 1970, no further work on supersonic biplanes was reported in the open the literature. This is primarily because of the non-availability of the advanced materials and resources for the manufacturing of biplane wings that could withstand the stresses at supersonic speeds. Also due to the cold war the focus was more on development of military planes wherein drag reduction and hence cost is not of utmost importance. Recently scientists at Tohoku University in Japan have focused on the design and development of supersonic transport jet with biplanes. Initial work on supersonic biplanes at Tohoku University was reported by Kusunose et al. in 2004 [9]. He presented the idea that the supersonic biplane can successfully reduce the wave drag at supersonic speed for successful commercial flights.

KUSUNOSE et al. in 2006 [10] studied the Busemann biplane using Computational Fluid Dynamics under lifting and non-lifting condition. As the Busemann biplane produces zero-lift at design Mach number of 1.7 and $\alpha = 0°$, hence they modified the Busemann biplane such that it could generate positive lift along with successfully reducing the wave drag, using the shock cancellation and reflection effect between the element. The modified design by the Kusunose et al. is as shown in Figure 2.3. The modified upper and lower elements combination increases the lift coefficient for the Busemann from 0 to 0.024.

Maruyama et al. [11] in 2006 at Tohoku University Japan carried the work done by Kusunose et al. They applied the inverse design method to come up with a biplane configuration that produced a low value of the wave drag for desired value of the lift coefficient ($C_L > 0.10$), at a designed $M_\infty = 1.7$. They found that for thickness to chord ratio of 0.102 the biplane configuration has lower wave drag compared to the Busemann and the Licher biplanes. The biplane configurations proposed by Maruyama et al. also generated a positive lift coefficient ($C_L > 0.07$) at zero incidences. They also found that for lift coefficient greater than 0.14, the wave drag was lower than that for a single flat plate.

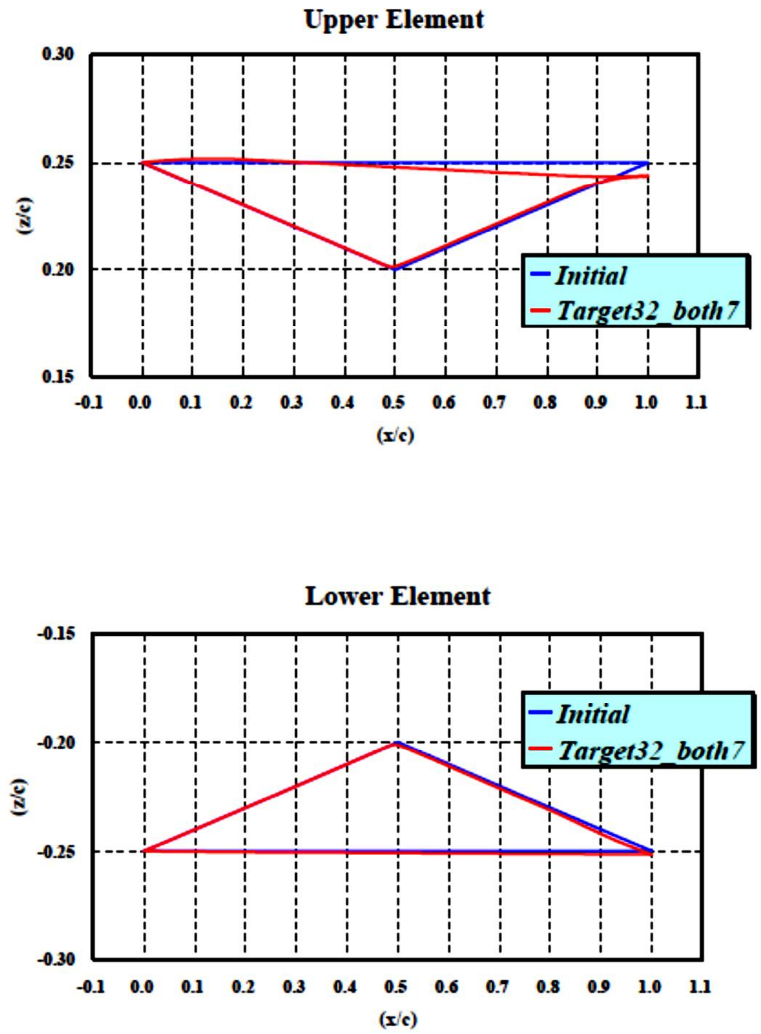


Fig. 2.3: Modified elements of Busemann biplane proposed by Kusunose et al. [4]

Matsushima et al. [12] in 2006 continued the studied on biplanes proposed by the Kusunose and Maruyama using modern computational fluid dynamics techniques and they observed that in biplane configurations, chocking occurs for the wide range of Mach numbers, i.e. for $0.5 \leq M_\infty \leq 1.64$. They also performed simulations for the accelerating case wherein the freestream Mach number was ramped from 0 to M_∞ =2.6. They introduced a mechanism of controlling the throat to inlet area ratio as shown in Fig. 2.4, which acts as a means to reduce the drag of the biplane at lower freestream Mach numbers.

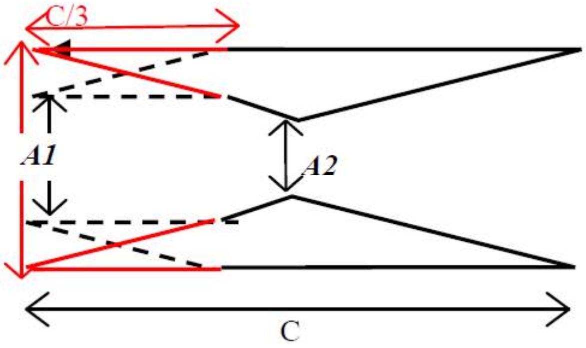
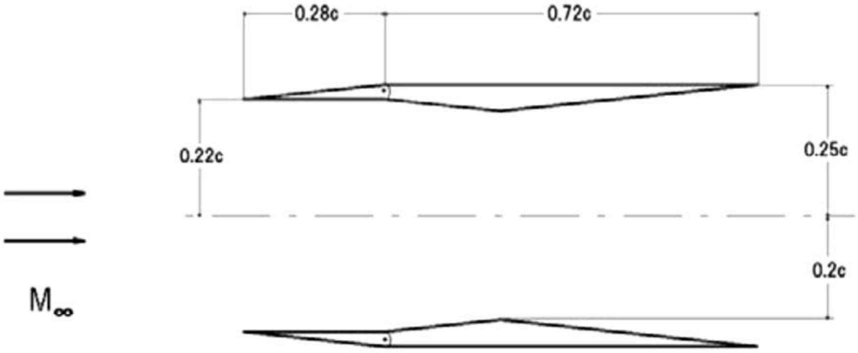


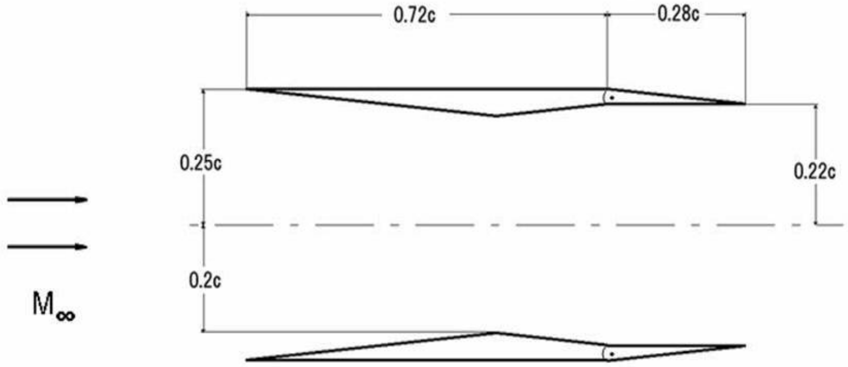
Fig. 2.4: Busemann Biplane with Control Devices [7]

Yamashita et al. [13] in 2007 studied the phenomena of flow choking that occur in the Busemann biplane at the off design conditions. They introduced the use of leading edge and trailing edge flaps to control the throat to the inlet area ratio of a Busemann biplane as shown in Fig. 2.5. The deflection of leading edge flap increases the throat to inlet area ratio of the biplane and thus controls the Mach number required for the start of the biplane. The use of trailing edge flap controls the rear streamline pattern and thus reducing the drag at subsonic speeds. They suggested that the leading edge and the trailing edge flap systems were useful in avoiding the flow choking at subsonic and supersonic speeds. Furthermore they established that the intensity of the sound barrier can be decreased, as compared to the Busemann biplane, by utilizing a leading edge flap.

Maruyama et al. [14] in 2007 studied the off-design performance of the Busemann biplane, starting at low subsonic Mach number. He proposed the use of variable leading edge and trailing edge flap systems for various Mach numbers from take-off to cruise as shown in Figure 2.6. By utilizing the different combinations of leading and trailing edge deflections the chocking Mach number drops to 1.56. Hence in actual flight the chocking is avoided for the off design condition and the biplane can be reconfigured to original Busemann biplane when the biplane accelerates to the design Mach number of 1.7. In this way the biplane is able to accelerate to the design Mach number without suffering from the high value of the wave drag at lower Mach numbers.



(a) Leading-edge flaps



(b) Trailing-edge flaps

Fig. 2.5: Busemann biplane with leading edge and trailing edge flaps [13]

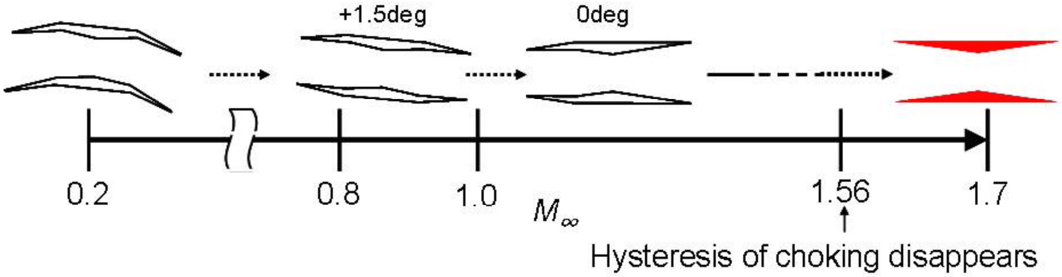


Fig. 2.6: Variable biplane configuration for complete flight regime [14]

Yonezawa et al. [16] also in 2007 investigated the aerodynamics of a three dimensional biplane configuration with different wing planform shapes with a focus on the effect of the tapered ratio and winglets on the aerodynamic drag of the biplane. They concluded that near the tip of the rectangular wing the local drag coefficient is increased due to the formation of a Mach cone which disturbs the favorable shock wave interaction. By the use of winglets this effect can reduced and the drag coefficient can be decreased to values similar to the Busemann biplane configuration. They also found that, in the case of a Carpet biplane wing, a polar shock wave is formed in the compression area and the Mach cone appear at the wing root. They concluded that although the wing with winglets is the best in terms of total drag reduction that the winglets increases the viscous drag and a strong structural configuration is required due to the large forces on the winglets at the tip of the wings.

Maruyama et al. [17] in 2008 investigated the aerodynamics of a three dimensional supersonic biplane through numerical solution of Euler equations. They found that the Mach cones affect a large area on the three dimensional wing and produces a large wave drag. Among the tapered wings they investigated it was found that wing with a taper ratio 0.25 and aspect ratio of 5.12 gives the lowest drag coefficient with value equal to of a two dimensional single flat plate configuration. They also investigated the use of hinged flaps and slats in 3D to countermeasure the high value the drag coefficient at lower Mach numbers, and the flow chocking was observed to disappear at $M_\infty = 1.51$ with the use of these flaps and slats.

Kashitani et al. [18] in 2008 performed flow visualization experiments in a low speed smoke tunnel to study the flow behavior around a biplane configuration with the flaps and slats. They estimated the lifting capability of the biplane by utilizing the streamline pattern and concluded that at low angles of attack, the flow does not separate from the surface, but with increasing angles of attack, the flow starts to separate form the leading edge, and the size of the separation zone can be decreased by utilizing the concept of leading edge and trailing flaps. They alos found that the lift curve slopes were identical in both the cases, with and without flaps and slats. The lift coefficients increased with the trailing edge flap deflection angle while increasing in leading edge flap deflection angle increased the stalling angle for the biplane configuration. The overall effects of the flaps and slats on biplane configurations were found to be similar to the conventional monoplane.

M Yonezawa and S Obayashi [19] in 2009 studied the effect of planform shape on the aerodynamics of a three dimensional biplane. As the three-dimensionality disturbs the shock interaction between the biplane elements, wave drag for the combination is increased. They studied the drag characteristics and shock wave interaction under the zero lift condition by using the different sweepback angles and the taper ratio of the biplane wing. They concluded that a biplanes having sweep back angle 10° with taper ratio of 0.4 and also those having sweep back angle 20° with taper ratio of 0.2 have the lowest drags. Lower wave drags were observed for all configurations with the adequate taper ratio with low sweep back angle such that the combination makes the vortex line perpendicular to the freestream.

Y Utsuma and S Obayashi [20] investigated the use of supersonic area rule for Busemann biplanes in 2010. They proposed that the sonic boom can be minimized by using the wider fuselage at the wing attachment point for the supersonic aircrafts. This requires a reduction in the wing area so as to compensate the area covered by the wider fuselage. Finally they proposed a supersonic biplane configuration for practical applications of takeoff, climb and landing requirements.

H Yamashita and S Obayashi [21] in 2010 studied the effect of seasonal atmospheric gradients on the variation of sonic booms. They concluded that in the winter the sonic boom overpressure is decreased but in the summer the overpressure is increased. They also found that the overpressure is increased at low altitude regions, throughout the year. They also found that the mountain regions around Himalayas and Rocky showed a decrease in overpressure.

Utsumi et al. [22] in 2010 used the method of characteristics for the multidisciplinary design optimization of three dimensional supersonic biplanes. They concluded that a small thickness-to-chord ratio and large dihedral angle decreases the wave drag but increases the wing weight. The aerodynamic performance of the optimized biplanes was found to be similar to that of a delta wing or an arrow wing.

Kawazoe et al. [23] in 2010 carried out the study of a silent biplane configuration through a low speed wind tunnel experiments under static and pitching attitude conditions. They found that the wings with front side taper, rear side taper and both side taper have the same performance parameters, similar to a general thin wing. But the front side tapered wing at angles of attack is higher than eight degree, was different from the others because of the generation of leading edge vortex on the upper wing.

Matsushima et al. [24] in 2010 studied the characteristics of three dimensional Busemann type biplanes using Computational Fluid Dynamics. They selected a tapered wing with aspect ratio 5.12 and taper ratio of 0.25 and concluded that for the wing fuselage configuration, the performance of the biplane configuration is better than the isolated wing if the biplane wing is located in the expansion wave regions.

D Maruyama et al. [25] in 2011 discussed the effect on three dimensionality of the biplane and concluded that if the biplane wings are located on the body whose expansions waves affect the area of the wing then the proposed designs are able to achieve C_L of 0.131 and the L/D ratio of 20.8 at $\alpha = 1.19°$ in inviscid fluid. The performance of such a three dimensional wing is similar to the two dimensional wing. This combination also reduces the wave drag at the off-design condition by utilizing the concept of hinged slats and flaps in between the wing root to wing tip.

Hu [26, 27] in 2011 studied the biplane configuration at design and off-design. They optimized the Busemann biplane via adjoint based optimization technique and proposed the modification in the geometry of the Busemann biplane that successfully reduces the wave drag at off-design condition i.e. Mach number ranging from 1.1 to 1.7.

H Yamashita et al. [28] in 2013 studied the effect of winglets of a boomless tapered supersonic biplane during the starting process, experimentally as well as through computational fluid dynamics. They found that the tapered biplane wing without winglets expands the low pressure flow from the wing root with increase in Mach number while the tapered wing with winglets decreases the pressure and the start Mach number is 0.05 higher than the wing without winglets. Yamashita et al.[29] further tested the start and unstarts characteristics of the finite rectangular biplane wing for different aspect ratio in the wind tunnel for the Mach number in the range of 0.3 to 2.3. They found that the start/unstart characteristics differs from that of a two dimensional Busemann biplane. The wing with low aspect ratio comes to the start state at lower Mach numbers.

Based on the literature survey, it has been observed that among the variety of design requirement, reducing drag and intensity of sonic boom on supersonic biplane is the most crucial one. The major problem with the supersonic transport aircraft is the shock waves and the intensity of the sound produce by the shock waves. The effect of the shock waves in supersonic flight cannot be neglected but can be minimized. It has been a long cherished dream of aerospace engineers worldwide to develop a supersonic transport aircraft which necessitates to design a supersonic aircraft wherein the effects of shock waves i.e. the intensity of the sonic boom is minimized.

Based on the extensive literature survey on the aerodynamics of supersonic biplanes for efficient low boom, low wave drag supersonic transport aircraft the following conclusion can be drawn.

- Busemann biplane configuration has less wave drag due to less volume than the standard diamond airfoil.
- A Licher's unsymmetrical biplane configuration could achieve lower wave drag than two dimensional diamond airfoil at C_L greater than 0.14.
- The aerodynamic performance for the three dimensional wing can be improved by using the tapered planform.
- Biplane with flaps and slats reduce the effect of flow choking in acceleration and deceleration stages at off-design condition.
- Biplane with winglets improves the aerodynamic performance in three dimensions.
- Finally for wing fuselage combinations, the performance of the biplane wing is improved when the biplane wings are located in the expansion wave regions of the fuselage. Such wing body configuration has C_L of 0.131 and L/D of 20.8 at an angle of attack of 1.19° in the inviscid flow.

It is clear from the review of above findings that very less work has been done on drag reduction in supersonic in transport aircrafts using supersonic biplanes. Also most of these researches have been done very recently and yet to be time tested. As the aerospace community continues to strive hard for making successful supersonic transport flight, more research efforts are needed to come up with newer ideas and comprehensive solution to the supersonic transport problem. The newer ideas should also be able to withstand the test of practicality and sustainability. Keeping these two factors in mind, an effort has been made to test the idea of staggered biplane in the stagger can be varied so as to produce minimum wave drag at all Mach numbers in the operational range from take-off to cruise. Also the configurations examined in the open literature are all having a sharp leading and trailing edges which give perfect wave cancellation effects. However, due to manufacturing difficulties and also due to structural limitations, the sharp edged supersonic biplanes are not feasible and hence the effect of leading edge and trailing edge radii on the wave cancellation phenomena needs to be studied.

Thus this research focuses on the comprehensive study of the aerodynamics of staggered supersonic biplanes with sharp and rounded leading edges at both lifting and non-lifting angles of attack. The investigation has been carried out through a range of Mach numbers between 0.5 and 2.5 to cover the entire range of flight.