Optimization and Application of Busemann Biplane and Its Variants in Supersonic Flight

Shuyuan Zhang

Yizhong High School, Tianjin, 300000, China

shuyuan07@ldy.edu.rs

Abstract. The Busemann biplane is designed to reduce shock wave drag in supersonic flight. With advances in aerospace technology and increasing flight speeds, the potential applications of the Busemann biplane in hypersonic aircraft design have sparked widespread discussion. This paper investigates the aerodynamic characteristics of the Busemann biplane and its variants in supersonic and hypersonic flight, with a focus on the effects of adjusting geometric parameters and relative positioning between the wings on aerodynamic performance. The study demonstrates that the Busemann biplane can effectively reduce drag and improve the lift-to-drag ratio by eliminating shock waves. However, at an angle of attack of 0°, the lift coefficient of the Busemann biplane approaches zero, which poses certain limitations for practical applications. Through experiments analyzing different biplane configurations, it is concluded that increasing the staggered arrangement between the wings further reduces drag and improves the lift-to-drag ratio. This paper highlights the potential of the Busemann biplane in future aircraft design and suggests further optimization of its aerodynamic design to enhance actual flight performance.

Keywords: Busemann biplane, supersonic flight, aerodynamic optimization.

1. Introduction

With the continuous advancement of aerospace technology, supersonic and hypersonic flight have gradually become focal points of research in the aviation field. In supersonic flight, where the speed exceeds Mach 1.2, the compression effect of the air and the occurrence of shock waves lead to a significant increase in drag. In hypersonic flight, with speeds exceeding Mach 5.0, not only must air compression and shock wave effects be considered, but also the heat generated by friction between the air and the surface of the aircraft, as well as the chemical reaction issues. Reducing drag and increasing the lift-to-drag ratio in both supersonic and hypersonic flight are key challenges to improving flight efficiency and the overall performance of aircraft [1]. To address this challenge, the concept of the Busemann Biplane has been proposed, which significantly reduces drag by suppressing shock waves, making it a valuable aerodynamic structure for research.

The focus of this study is the aerodynamic characteristics of the Busemann Biplane and its variants. The research will explore methods to optimize aerodynamic performance by adjusting the geometric parameters and relative positions between the two wings, with an emphasis on how structural design can reduce drag and improve the lift-to-drag ratio. Additionally, this paper will explore the potential applications of the Busemann Biplane in future supersonic and hypersonic flight, proposing directions for further theoretical and experimental studies. Through analyzing experimental results of the Busemann Biplane and its improved versions, this study aims to verify its feasibility in efficient flight and provide references for future aircraft design.

2. Basic theory of Supersonic flight

2.1. Brief introduction of supersonic flight

The supersonic flight indicates the airspeed of aircraft is greater than 1.2M (Generally took 1225 kph) in the compressed flight. In the range over 1.2M, the properties of the air become different with the properties within the subsonic range. The most significant property this essay concerns, is the associated shock wave and drag force produced in the supersonic flight. The density of air does

change within supersonic range, the air becomes compressible. The shock wave is generated around the aircraft due to the violent change in pressure. The air is compressed rapidly, the speed of aircraft is over the speed of air to propagate the information. The airstream is concentrated on a specific point, as the pressure accumulates on this point, the high-speed shock wave is generated.

2.2. Difference between supersonic flight and hypersonic flight

Supersonic flight is defined within the range of airspeed from 1.2M to 5.0M, hypersonic flight is defined within the range of airspeed over 5.0M. The compressibility and shockwaves are the dominant air features that must be considered in supersonic range. The thermal and chemical reaction effects become more significant in hypersonic range, thus the hypersonic flight must consider more about these two effects. In the hypersonic range [2]. The thermal energy associated by the friction between the air and the aircraft surface leads to the limitation of aircraft design. For example, the aerospace material aluminum is not applicable for the aircrafts within the range of hypersonic and supersonic.

2.3. Advantages and disadvantages of Variable-sweep wings

Variable-sweep wings can adjust the sweep angle of wings. When the aircraft is within supersonic and hypersonic range, the aerodynamic characteristics on the wings do change significantly. Large sweep angle is effective in reducing the intensity of shock wave generated on the wing tip. As a result, the stability and aerodynamic efficiency can be improved by increasing the sweep angle within supersonic and hypersonic range. The disadvantage of variable-sweep wings is mainly about the mass of the system. The system of variable-sweep wings including the structure to stretch and contract the sweep angle of wings, this system definitely increases the complexity and mass of the lift system, the difficulty of the aircraft maintenance is increased.

Drag force: $F_D = \frac{1}{2} C_D \rho U^2 A$ and Lift force: $F_L = \frac{1}{2} C_L \rho U^2 A$ can be get. The drag coefficient (C_D) varies within a small range, the lift coefficient (C_L) can be simplified as directly proportional to the angle of sweep (α), which is shown in figure 1 [1].

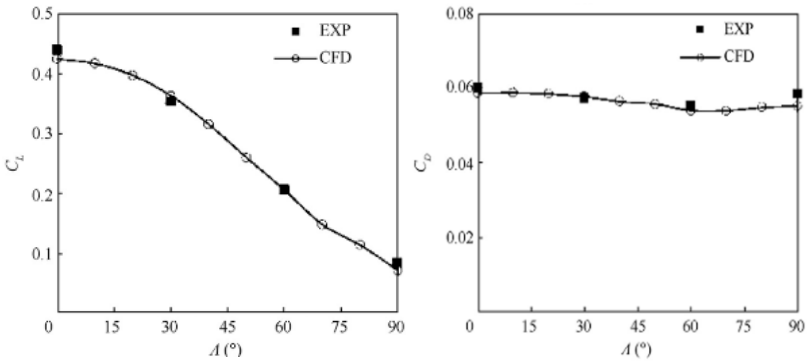


Figure 1. Drag force and Lift force [1]

2.4. Advantages and disadvantages of Waverider structure

Waverider is a type of design applied on supersonic aircrafts. Waverider is related to the theory of compression lift. Using the associated shock wave produced during the supersonic and hypersonic flights, the pressure under the lower surface of the wings increases significantly, the lift force on the aircraft is increased. The design of waverider increases the lift-drag ratio ($\frac{C_L}{C_D}$) of the aircraft, improving the efficiency of the flights.

The disadvantage of the waverider structure is that the most waverider-structured wings are designed for a certain limited range of airspeed. This limitation is corresponding to the limitation of improvement of speed for the aircraft. As the cruise airspeed of the aircraft is increased, the waverider lift system must be adjustable to adapt to different requirements of the aircraft.

The airstream flowing through the oblique shock increases the pressure, a high-pressure region is created below the lower surface of the aircraft. The oblique shock does not affect the airstream on the upper surface, thus a relatively low-pressure region is generated above the upper surface of the aircraft. The pressure difference is produced above and below the waverider aircrafts, so the pressure difference takes the most proportion of the formation of the generation of the lift force. The concept of the waverider airfoil is shown in the figure 2 below [2].

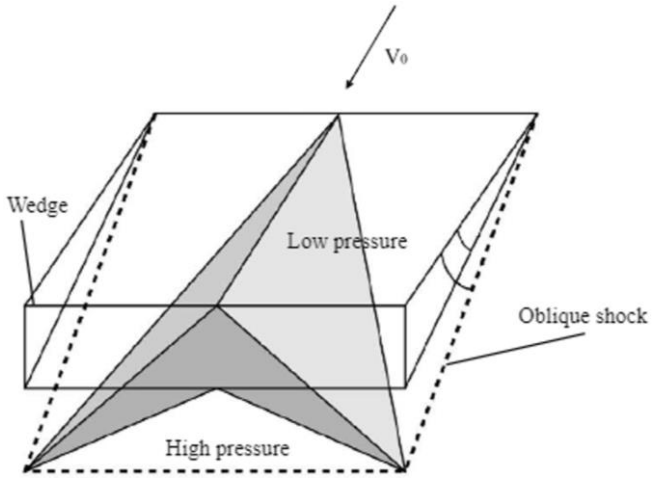


Figure 2. Concept of the waverider airfoil [2]

2.5. Brief introduction of Busemann Biplane

The basic structure of the Busemann Biplane can be simplified as the cross-section symmetrical biplane, the Busemann Biplane is known as its special property. At the attack angle of 0°, the drag coefficient is 0, and the lift coefficient is 0. At a depression or an elevation angle, both drag coefficient and lift coefficient increase which is shown in figure 3 [3].

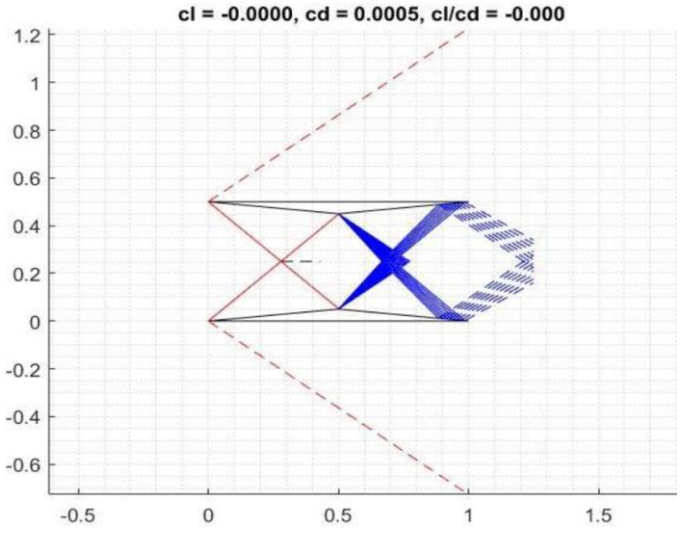


Figure 3. Busemann Biplane [3]

The conception of the Busemann Biplane is that by combining two airfoil components in the way illustrated in the graph above, and adjust their geometry parameters and relative locations such as the stagger, the waves generated by the aerodynamic components in the supersonic flight will cancel out each other [3].

3. Aerodynamic Optimization of Busemann Biplane

3.1. Motivation of experiment

The essay is trying to research on the Busemann Biplane and its variants, to discuss the feasibility of application of the Busemann Biplane. According to the previous research done by other researchers, the aerodynamic property of the Busemann Biplane can be alternated by adjusting the arrangement of the two planes, including the separation, stagger and shape of the wings. The author is doing the comparison between the variants of the Busemann Biplane, discussing the feasibility of application of the Busemann Biplane and its variants, and proposing the possible research on the Busemann Biplane in future.

3.2. Theory of experiment

The NACA Technical Report No. 1316 was trying to improve the performance of the Busemann Biplane by adjusting design parameters and rearranging the aerodynamic parts [4]. Moeckel concluded two categories: variable spacing biplanes and constant spacing biplanes. Variable spacing biplanes have shock waves generated on both the upper and lower wings that are eliminated by impacting on the inner corners and cancel each other. Constant spacing biplanes have the constant length of the shockwaves generated by the leading edges and keep in persistence throughout the spacing between the biplanes [4]. The calculating process was simplified to allow the early computer to be able to solve the integrations and derivations of aerodynamic coefficients [5].

Referring to the previous research done by other researchers, there are some theories of the Busemann Biplane and its variants listed below. There are five-point results given by the experiment of Moeckel [5]. (1) A biplane with the geometric shape of triangle for its cross section, generally has lower drag coefficient than the biplane with geometric shape of rhombus for the cross section, where the two types of biplanes have the same ratio of thickness. (2) The lift-drag ratio ($\frac{C_L}{C_D}$) varies with the angle of edge of each single wing of the biplane, where all the angles of edge varied simultaneously. (3) The maximum lift-drag ratio ($\frac{C_L}{C_D}$) is limited by the thickness of the lower airfoil, when the thickness of the upper airfoil keeps constant. The lift-drag ratio ($\frac{C_L}{C_D}$) of the biplane might be increased by increasing the thickness of the lower airfoil beyond the thickness of the upper airfoil at a low attack angle (α). (4) When edge angles of the biplane became less than the leading-edge angles, the lift-drag ratio might be slightly improved. Refer to the graph below. (5) The pressure center varies with the attack angle(α), and this variation is considered as greater for the non-symmetrical biplanes, rather than the symmetrical biplanes.

Several authors and research groups have researched on the improvement of performance of the Busemann Biplane [6]. (a) The cross-sectional area is changed by applying the flaps at both leading and trailing edges [7]. (b) Increasing the area of the throat region in exchange by staggering airfoil configurations, will lead to the slightly loss of efficiency, due to the reason of wave-cancellation [8]. (c) The unsymmetrical biplane with the upper surface is flat and the lower surface is triangular shaped, effectively reducing the shock wave generated. Additionally, the drag coefficient is decreased. The lift-drag ratio ($\frac{C_L}{C_D}$) has increased significantly [9]. (d) Increasing the ratio of throat-inlet minimizes the problem of hysteresis involved by airflow within the range of acceleration [10].

3.3. Experiment analysis

3.3.1 Effect of Staggered Airfoil Configurations on Drag Reduction

The author tried to do the research on the relationship of staggering airfoil configurations of the Busemann Biplane and its aerodynamic property, drag coefficient (C_D) to be precise.

The author refers to the result of an experiment held by Vijay Kumar Patidar, Rajesh Yadav, and Sudhir Joshi, whose result was published in 2016 [9]. By adjusting airfoil by a chord length at the

intervals of 0.1c backward per set longitudinally, they have researched for several various staggered configurations.

Their experiment result suggests that by adjusting the setup of the staggered configurations of the Busemann Biplane, is a method to maintain the effect of wave-cancellation phenomenon but sufficiently reduce the drag force produced. Correspondingly, the drag coefficient (C_D) is decreased under the same or similar conditions. Drag coefficient (C_D) and lift-drag ratio ($\frac{C_L}{C_D}$) variation for staggered configurations is shown in figure 4 [9].

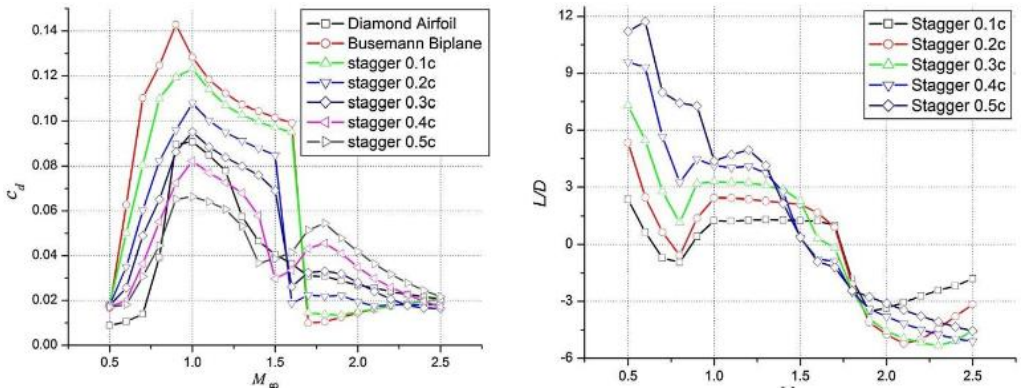


Figure 4. Drag coefficient (C_D) and lift-drag ratio ($\frac{C_L}{C_D}$) variation for staggered configurations [9]

The trend of variation of the drag coefficient (C_D) under different stagger configurations are similar. The trend of variation of the lift-drag ratio ($\frac{C_L}{C_D}$) under different stagger configurations are similar as well. As the stagger configuration of the Busemann Biplane increases, both the drag coefficient of the biplane and the lift-drag ratio ($\frac{C_L}{C_D}$) are decreased at the same speed generally. Thus the author concludes that the drag coefficient (C_D) and the lift-drag ratio ($\frac{C_L}{C_D}$) are positively corresponding to the staggering configurations.

The researchers obtained the conclusion that staggering the airfoil backward increases the area of the throat which causes the shock wave. Effective reducing the drag coefficient (C_D) without affecting the efficiency of wave- cancellation [11].

3.3.2 Analysis of Staggered Configurations on Drag Coefficient in Busemann Biplane

Referring to another research done by the researchers Boping Ma, Gang Wang, Jie Wu, and Zhengyin Ye, from Northwestern Polytechnical University, China, a similar qualitative conclusion to the experiment above can be obtained [12]. The Drag coefficient and L/D variation for staggered configurations is shown in figure 5.

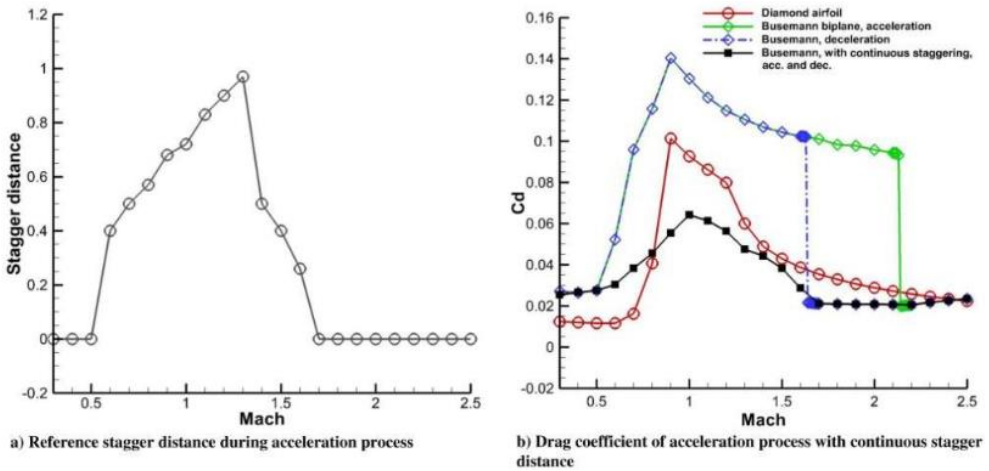


Figure 5. Drag coefficient and L/D variation for staggered configurations [12]

This experiment researched on the relationship between the stagger difference and the drag coefficient (C_D) as well. Obviously, the author can obtain the conclusion that increasing the stagger configurations is positively corresponding to the drag coefficient (C_D) of the Busemann Biplane.

3.4. Conclusion of the experiment

Both of the experiment A and B suggests that by increasing the stagger configurations of the Busemann Biplane improve the aerodynamic property especially on the drag coefficient (C_D), and results in the improvement of the lift-drag ratio ($\frac{C_L}{C_D}$). The author suggests that the improvement of the aerodynamic property will result in the application of the biplane especially for the supersonic and hypersonic flight. The total formation of the air drag force (F_D) is related to the combination of shock wave, effect of the compression of the air and the corrected drag coefficient (C_D). By reducing the drag coefficient and effect of the shock wave cannot ensure the comprehensive improvement of the aerodynamic property of the biplane. But the author believes to discuss on the feasibility of the application of the Busemann Biplane, the research can still concentrate on the reduction of the drag coefficient (C_D).

4. Discussion on the practicality of Busemann Biplane

4.1. Enhancing Lift through Shock Wave Cancellation and Nozzle Effect

The author believes that it is possible to apply the Busemann Biplane and its variants on the supersonic and hypersonic flights. The author admits that the performance of Busemann Biplane in the aerodynamic simulating softwares gave indicated the infeasibility of the practical application of Busemann Biplane due to the Busemann Biplane provides almost zero drag coefficient (C_D) but zero lift coefficient (C_L) in the computed simulating analysis. The author thinks the previous researches were mainly on adjusting parameters and rearranging the relative positions of two wings of Busemann Biplane. The author believes the further research on the Busemann Biplane can take the consideration of the structures of the biplane and the side effects of the biplane.

The author believes the further research can take the simulation of aerodynamic properties of the biplane. The author suggests using the method of canceling shock waves produced by two wings. By bending the biplane downward with a degree, the airflow passing through the biplane is ejected out with an angle of depression. This adjustment enables the biplane to act as a nozzle, due to the biplane now changing the direction of ejection airflow. According to the conservation equation of mass,

$$\rho_A V_A A_A = \rho_B V_B A_B \tag{1}$$

The cross-sectional area of the front of the biplane, must be much smaller than the cross sectional area of ejection airflow. As a result, most proportional of the airflow intake at the front of the biplane, must be eliminated as the airflow passes through the spacing between the biplanes. The ejected airflow provides the reaction force to the biplane structure. The horizontal component of the reaction force might be canceled by the drag force produced, but the vertical component of the reaction force exerting on the biplane is upward, the vertical component can be used as the lift force.

Additionally, the airflow passing through the biplane is decelerated sufficiently, the ejection airflow has lower speed than the external airflow in supersonic flight. The difference of pressure enabling the biplane to intake external airflow at the edge of the biplane when ejecting the airflow, this predicted phenomenon might provide the forward force to the biplane. The predictable disadvantage of this design is that the drag force is not negligible, the drag coefficient (C_D) cannot be maintained as zero. The upper and lower surfaces contacting the external airstream have a curvature, generate the drag force exerting on the upper and lower wing surfaces, and cannot be reduced.

4.2. Airflow Deceleration and Lift Generation

The author thinks that by using the method of the Busemann Biplane, another type of consideration is to decelerate the speed of airflow passing through the biplane. The author suggests that using symmetrical airfoils inner the biplane, to contribute a triple levels of divergence system of the airflow. This structure is trying to decelerate and diverge the airflow into the airfoils system. After the boundary of the shock wave region and the divergence region, the speed of airflow will be reduced to below 1M, the subsonic airflow region is produced. The subsonic region of the airflow will continuously be promoted to the bi-nonsymmetrical airfoils. According to the mass conservation equation of fluid,

$$\rho_A V_A A_A = \rho_B V_B A_{Ba} \tag{2}$$

The product of density of fluid, the velocity of fluid and the area of fluid is constant, where the mass of fluid intake per unit time is constant. The velocity of supersonic airflow is much higher than the velocity of subsonic airflow, so the cross-sectional area of intake of supersonic airflow must be much smaller than the cross-sectional area of subsonic airflow region.

Additionally, the most of airflow intake at the front of the region of the bi-nonsymmetrical airfoils, the airstream can be assumed as incompressible, using the Bernuolis's equation,

$$P + \frac{1}{2}\rho v^2 + \rho g h = constant \tag{3}$$

The pressure difference upper and below the bi-nonsymmetrical airfoils is produced, the lift force is produced. This airfoil system aims to reduce the air resistance in supersonic and hypersonic flights by reducing the speed of airflow. This airfoil system is actually more considered to set the Busemann Biplane airfoil as the aerodynamic components, and the components to provide lift force are the non-symmetrical airfoil system at the second half.

5. Conclusion

The current researches held by other individual researchers and research groups indicate a result that the Busemann Biplane and its variants, indeed reduce the drag force generated during the supersonic and hypersonic flights. But the problem the author concerns is the section of lift force of the biplane structure. At the angle of attack (α) of α=0°, the lift coefficient of the Busemann Biplane and its variants is generally zero. At the angle of attack (α) within the range α≠0°, the lift coefficient (C_L) is not zero, as the drag coefficient (C_D) is not zero. Both the of lift coefficient (C_L) and drag coefficient (C_D) are increasing as the angle of attack (α) approaches 90° or -90°. The Busemann Biplane and its variants behave more like any other common airfoil with an angle of attack α≠0°, the purpose of application of the biplane is unsatisfied as the specific property of the biplane structure. The author believes the introduction of the biplane structure into the practical application is still useful. By adjusting the parameters and adding other aerodynamic components into the biplane structure is possible to obtain an acceptable range of the lift-drag ratio ($\frac{C_L}{C_D}$). As the performance of the lift-drag ratio ($\frac{C_L}{C_D}$) is improved, the application of the biplane is feasible and predictable especially in the supersonic flights.

References

[1] Lifang Z, Liu L I U, Xueming S, et al. Mechanism analysis of hysteretic aerodynamic characteristics on variable-sweep wings. Chinese Journal of Aeronautics, 2023, 36 (5): 212-222.

[2] Broglia A. Preliminary design of waverider aircraft. Politesi.polimi.it, 2014.

[3] Eckert A B. Analysis of the Busemann Biplane Characteristics Using MATLAB and ANSYS Simulations. San José State University, 2021.

[4] Matsushima K, Kusunose K, Maruyama D, et al. Numerical design and assessment of a biplane as future supersonic transport—revisiting busemann's biplane. 25th International Congress of Aeronautical Sciences, ICAS Paper. 2006, 3 (1): 2006.

[5] Moeckel W E. Theoretical aerodynamic coefficients of two-dimensional supersonic biplanes. Ntrs.nasa.gov, 1947.

[6] Tai M, Son C, Oh S. The Analysis of Aerodynamic Characteristics for Busemann Biplane with Flap. Journal of computational fluids engineering, 2013, 18 (3): 42-50.

[7] Sánchez Aguado C. Numerical Investigation into the Performance of a Supersonic Busemann Biplane for Different Off-design Conditions. Universitat Politècnica de València, 2023.

[8] Yamashita H, Obayashi S, Kusunose K. Reduction of drag penalty by means of plain flaps in the boomless busemann biplane. International Journal of Emerging Multidisciplinary Fluid Sciences, 2009, 1 (2): 141-164.

[9] Patidar V K, Yadav R, Joshi S. Numerical investigation of the effect of stagger on the aerodynamic characteristics of a Busemann biplane. Aerospace Science and Technology, 2016, 55: 252-263.

[10] Zhai J, Zhang C A, Wang F M, et al. Design of a new supersonic biplane. Acta Astronautica, 2020, 175: 216-233.

[11] Maruyama D, Kusunose K, Matsushima K, et al. Aerodynamic analysis and design of Busemann biplane: towards efficient supersonic flight. Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering, 2012, 226 (2): 217-238.

[12] Ma B, Wang G, Wu J, et al. Avoiding choked flow and flow hysteresis of busemann biplane by stagger approach. Journal of Aircraft, 2020, 57 (3): 440-455.