

To Find the Optimal Sweep Angle for the Maximum Aerodynamic Efficiency of a Transonic Flight

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ABSTRACT

The optimization of the wing sweep angle is one of the significant aerodynamic problems in aerospace engineering, which deals with aircraft performance improvement during transonic flight regimes characterized by the simultaneous presence of subsonic and supersonic flow regions. The transonic regime (Mach number 0.75-0.9) is associated with considerable wave drag increases that could be reduced via a proper choice of the wing sweep angle. The present paper aims to identify the aircraft wing with the best aerodynamic efficiency for a given flight condition. The aerodynamic performance of different wings using CFD simulations was analyzed to visualize airflows behavior around the aircraft and choose the best wing design in terms of the lowest drag force, adequate lift force, and flight stability. Several aspects related to aerodynamics, including pressure distribution, shock-wave location, lift and drag characteristics, and flow separation were considered during the analysis. It was found that the moderate sweep angles could ensure the best trade-off between a small drag coefficient and a high lift coefficient during transonic flight. The computational fluid dynamics calculations revealed that the low sweep angles produce considerable drag due to the appearance of shock waves, while high sweep angles lead to inadequate lift, structural complexity, and aerodynamic instability. The study showed that an aircraft with a moderate wing sweep angle between 30 and 35 degrees could be the best choice for regular commercial flights since it reduces wave drag and minimizes the influence of compressibility effects. In addition, the wing sweep angle optimization could play a major role in modern aircraft design and weight reduction in the future. Therefore, the research is highly important for aerospace companies to develop more efficient commercial aircraft and improve the performance of the aviation sector. In conclusion, the aerodynamic performance assessment of different wings using CFD revealed valuable information about the influence of several key parameters on flight characteristics. The study allowed for suggesting that a moderate wing sweep angle minimizes drag, maximizes lift, and ensures flight stability. Moreover, the research showed that computational fluid dynamics could play an essential role in aircraft design and weight reduction.

Keywords: Transonic Flight; Wing Sweep Angle; Aerodynamic Efficiency; Computational Fluid Dynamics (CFD); Lift-to-Drag Ratio (L/D).

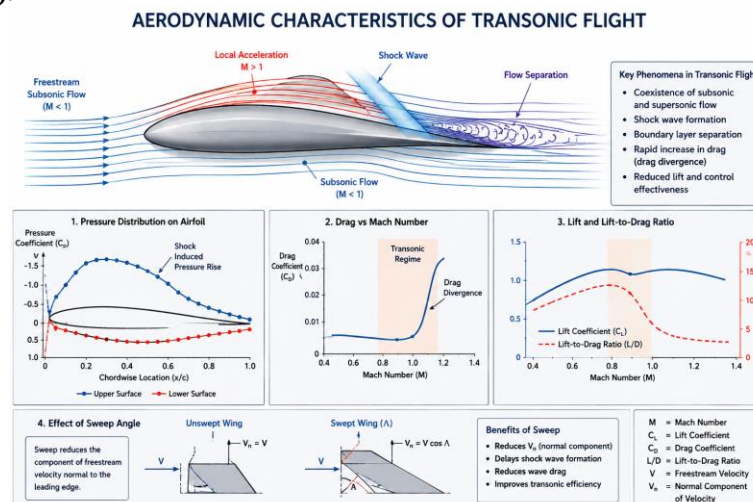


Figure 1. Aerodynamic Characteristics of Transonic Flight: Shock-Wave Formation, Pressure Distribution, Drag Divergence, and the Influence of Wing Sweep Angle on Aerodynamic Efficiency

INTRODUCTION

Unlike subsonic and supersonic speeds, at transonic speeds, the local flow over some parts of the aircraft reaches supersonic speeds. This flow condition, which occurs at 0.75 Mach to 1.2 Mach, is very complicated but common for all aircraft. At this speed, shock waves are formed due to supersonic flow, which is accompanied by the separation of the boundary layer on the wing surface, which increases the total drag significantly or so-called wave drag (Anderson, 2017). Thus, the flight at this speed is the most difficult for the aircraft, which requires designing its wings with optimal sweep angles. In general, the geometry of the aircraft is being optimized today, and one of its main characteristics is the sweep angle of the wings, since this parameter affects the compressibility effect during the flight at transonic speeds (Anderson, 2017).

The concept of wing sweep was first introduced when it was realized that by angling the wing backward relative to the fuselage, the angle of the airflow against the leading edge is decreased which delays the formation of shock waves and the resulting rise in drag allowing higher speeds to be attained (Abbott & Von Doenhoff, 1959). The performance of the swept-wing aircraft since their introduction in the wake of the Second World War was improved upon by computer aided aerodynamic calculation, wind tunnel tests and flight tests resulting in a large amount of research into these aircraft. The modern commercial aircraft such as the Boeing 787 Dreamliner and Airbus A350 XWB as well as military jets such as the F-22 Raptor and Eurofighter Typhoon have wings swept at carefully selected angles in order to maximize performance at high subsonic cruise speeds.

Although there is a significant amount of research on this topic, finding the optimal sweep angle remains a difficult task due to several aerodynamic complexities associated with the design. The efficiency of the wing depends critically on many factors, including Mach number, Reynolds number, aspect ratio, airfoil shape, structural considerations, and flight requirements. Thus, increasing the sweep beyond the critical value will reduce the wave drag at supersonic speeds but cause deterioration in lift capabilities, wing weight, structural complexity, and low-speed performance. On the other hand, not enough sweep results in poor lift-off characteristics at low speeds and higher wave drag in transonic flight. Consequently, it becomes necessary to ensure the desired balance between the lift and drag at different speeds (Raymer, 2018).

Recent advancements in the field of aerodynamics have led to the development of powerful tools capable of capturing the intricacies of aerodynamic flow with an unprecedented level of detail. The most notable among these achievements is the development of Computational Fluid Dynamics (CFD). In addition to decreasing the need for expensive wind-tunnel tests, CFD provides a much-needed insight into the characteristics of pressure distribution, shock formation, turbulent flow areas, and flow separation. High-speed computing has enabled rapid evolution in wing designs by allowing engineers to examine various wing options in a relatively short time (Versteeg & Malalasekera, 2007). For this reason, the optimization of a wing's sweep is now a key element in modern aircraft design.

The present investigation is concerned with determination of the most efficient aspect ratio based on the aerodynamic characteristics associated with high-speed flight. In particular, the main objective of this study is to assess the aerodynamic performance of multiple wing designs by analyzing their lift coefficient, drag coefficient, lift-to-drag ratio, and pressure distribution at various angles of sweep.

Aerodynamic Characteristics of Transonic Flight

The transonic region is one of the most interesting aerodynamic regimes because of the complex nature of airflow at the speed of sound. At this particular speed, local airflow on the upper surface of the wing exceeds the speed of sound, while at the free stream speed it is subsonic. Thus, it is possible to observe the formation of shock waves at the point where supersonic and subsonic flows meet. The formation of these waves leads to the appearance of aerodynamic disturbances, additional drag, and separated flows (Anderson, 2017). In turn, this results in a phenomenon related to the drag divergence which leads to a substantial increase in drag with a slight increase in speed.

One of the serious challenges of transonic flight is related to wave drag that appears due to shock formation. The main disadvantage of wave drag is that it reduces fuel efficiency decreasing the range of an aircraft and its ability to cruise effectively. That is why engineers use different aerodynamic tools to postpone the shock formation as much as possible. Such methods include the use of supercritical airfoils, winglets, area ruling, and swept-wing design (Mason, 2017). Each of the mentioned methods helps resolve the aerodynamic problems associated with the formation of shockwaves, but swept-wing design has been proven to be one of the most effective ways to minimize them.

It is necessary to mention that wave drag can be minimized due to the swept-wing design because the effect of the angle decreases the normal component of the Mach number. The latter means that the contribution of forward velocity is

diminished leaving the spanwise component as a dominant one. Herewith, when speaking about the influence of the sweep angle, it is essential to note that increasing it leads to reducing lift because the effective velocity over the airfoil decreases. As a result, takeoff distance increases while the landing characteristics deteriorate together with a higher stall speed (Raymer, 2018).

Another crucial aspect that is considered during the design process is the interaction between the shock wave and the boundary layer. The separation of the boundary layer caused by shock waves can lead to reduced lift and increased drag. By using modern CFD tools, it becomes possible to predict aerodynamic characteristics accurately and optimize the shape of the selected wing to achieve the desired lift-to-drag ratio before proceeding to the costly prototype manufacturing stage. Moreover, computational fluid dynamics enables scientists to visualize pressure distribution, velocity, turbulence, and other parameters as well as visualize vortex formation processes if any occur at different sweep angles (Versteeg & Malalasekera, 2007).

Importance of Wing Sweep Angle Optimization

Wing optimization and aerodynamic analyses in relation to the swept angle are usually complex problems because of the interaction between aerodynamic, structural, propulsion, stability, manufacturability, and economic aspects. Typically, aircraft experience their best performance in the transonic area, which makes aerodynamic efficiency their main concern. The reduction of drag at this stage is critical for lowering fuel consumption over the flight and, consequently, decreasing greenhouse gas emissions (Gudmundsson, 2014).

Therefore, the optimization technique should be chosen based on the consideration of several sweep angle options to ensure the best performance-to-drag ratio. It was found that transport airplanes typically carry a sweep range from 25° to 35° as the ideal balance between aerodynamic and structural design. Aircraft designed to operate at higher supersonic speeds tend to have more than 40° sweep while regional planes and turboprops with a lower Mach number only require a few degrees of sweep (Roskam, 2003).

Today, aerodynamic optimization is considered one of the main directions in aircraft design because of the growing concerns about sustainability. Numerous optimization studies have been conducted using various computational fluid dynamics (CFD) methods to predict the flow field around wing-aircraft configurations accurately. The current level of accuracy in predicting transonic flows was made possible by relying on numerical simulations using Navier–Stokes equations, RANS, $k-\epsilon$, and $k-\omega$ SST turbulence models, and mesh adaptation techniques (Blazek, 2015). In general, numerical experiments have become an affordable and reliable way to explore the aerodynamic properties of aircraft wings. As a result, optimizing supersonic transport wings and analyzing their performance characteristic using CFD techniques is one of the significant trends in aerospace engineering. The aviation sector promotes clean and efficient technologies that reduce carbon emissions and fuel burn during flights while ensuring the highest level of flight safety. The analysis of the relationship between sweep angle and aerodynamic characteristics is of great interest to the aerospace community and is critical to building future aircraft, including commercial planes, military airplanes, and drones.

The current study aims to find the angle at which the aircraft is able to perform the most efficient during transonic flight regimes. The information obtained will be helpful for aerospace engineers and manufacturers in optimizing the aircraft wing sweep to secure the best aerodynamic performance.

REVIEW OF LITERATURE

Early Developments in Transonic Aerodynamics

The study of transonic aerodynamics has progressed considerably since the early twentieth century when aircraft designers first encountered the challenges posed by the compressibility of air at high subsonic speeds. At speeds between approximately Mach 0.75 and Mach 1.2, the local airflow accelerates to supersonic speeds over certain parts of the airplane, creating shock waves, and dramatically increasing drag. Pioneers such as Prandtl made significant theoretical contributions to this field, while the National Advisory Committee for Aeronautics (NACA) carried out experimental work that provided insight into the aerodynamic characteristics of many airfoils. The work of Abbott and Von Doenhoff (1959) provided a comprehensive database of experimental data on airfoils. Their work showed that the aerodynamic characteristics of an aircraft are highly dependent on the design of its wings. Moreover, they demonstrated that both lift and drag can be predicted for different wing airfoils. The work of Whitcomb provided innovative concepts for supercritical airfoils which enabled designers to delay the formation of shock waves thus decreasing the drag at high subsonic speeds, and it led to the development of modern commercial aircraft. Anderson (2017) noted that the effect of compressibility is often the dominant factor influencing the aerodynamic performance of airplanes near the speed of sound. Moreover, the author argued that special aerodynamic features had to be incorporated to minimize drag during transonic flight. Raymer (2018) believed that

the problems of transonic aerodynamics were of utmost importance to aircraft designers because the performance characteristics of airplanes during the cruise condition were critical to their economical operation.

Development of Swept Wing Theory

The introduction of swept-wing technology was one of the most significant design improvements in the history of airplanes. During the Second World War, German aerodynamicists discovered that sweeping the wing reduces the normal component of the incident flow, allowing to delay the effects of compressibility. The design was later adopted worldwide for both military and commercial aircraft. Raymer (2018) notes that swept wings effectively lower the Mach number, thus postponing shock-wave formation and minimizing the wave drag at the transonic level. Roskam (2003) explains that while increasing the sweep angle helps to improve the high-speed performance, it also lowers the lift, increases the weight, and reduces the airplane's maneuverability at lower speeds. Gudmundsson (2014) points out that modern commercial airplanes mostly use wings with 25° – 35° sweep angles because they are considered optimal in terms of aerodynamics, stability, and structural weight.

The aerodynamic improvements predicted by theory were confirmed by experimental research. Indeed, the paper by D'Aguanno, Schrijer, and van Oudheusden (2022) provides empirical evidence of the aerodynamic benefits of swept wings. Particle image velocimetry and background-oriented schlieren techniques were used in the experiment to visualize the flow around 15° and 30° swept finite-span wings. The results show that both sweep angles decrease the buffet oscillations and slow down the shock-wave movement compared to the case when no sweep is introduced.

Computational Fluid Dynamics in Transonic Aerodynamic Analysis

The development of Computational Fluid Dynamics (CFD) made it possible to perform numerical simulations of aerodynamic problems. The previously laborious and costly aerodynamic testing in wind tunnels allowed to obtain a solution for a limited number of cases only. In contrast, modern numerical simulations enable realistic calculations of the flow field and prediction of pressure distribution, location of shocks, turbulent flow areas, and boundary layer separation, which significantly reduces the costs of research.

According to Versteeg and Malalasekera (2007), finite-volume methods appear to be the most reliable numerical techniques for solving Navier – Stokes equations describing compressible aerodynamic flows. Blazek (2015) highlights that CFD results in high accuracy solutions of transonic flow problems due to the implementation of sophisticated turbulence models, including SST $k - \omega$ and Reynolds-Averaged Navier – Stokes equations. Anderson (2017) adds that aerodynamic analyses allow engineers to estimate the performance of different wing profiles without making expensive prototypes. They can quickly analyze each detail alteration and predict its impact on the flight.

Moreover, recent studies proved the ability of CFD methods for aerodynamic optimization. Samputh et al. (2024) optimized the swept C Wings considering transonic flow with the aid of DOE and CFD. According to the research, the wing's sweep, taper ratio, and geometry significantly affect the lift coefficient, drag coefficient, and aerodynamic efficiency.

Another study conducted by Ghoreyshi et al. (2025) revealed that reduced-order aerodynamic models can be applied to multiple-swept wings in transonic regimes as well. The authors conclude that their findings lead to high accuracy aerodynamic predictions with fewer numerical costs, which can be useful for aircraft preliminary design.

Experimental Studies on Shock Waves and Transonic Buffet

Experimental research plays a critical role in verifying computational fluid dynamics (CFD) results and comprehending aerodynamics. Wind-tunnel tests, schlieren imaging, pressure-sensitive paint, and particle image velocimetry techniques can provide valuable data on flow physics, such as shock-wave interactions and flow separation.

Anderson (2017) highlighted that shock-wave/boundary-layer interaction is one of the most common reasons for transonic buffet, which leads to aerodynamic instability. D'Aguanno et al. (2022) experimentally compared the characteristics of an unswept wing and 15° and 30° swept finite wings with the same normal Mach number. The results demonstrated that increasing the sweep angle postponed buffet occurrence and reduced shock oscillations, thus enhancing aerodynamic stability at transonic speeds.

Meanwhile, the aerodynamic features of the M-wing design with a supercritical airfoil were studied by Gonzalez, Ilie, and Perry (2026). The researchers analyzed the lift characteristics at different Mach numbers from 0.70 to 1.08 and revealed that although the modified wing planform produced stronger leading edge vortices, the expected aerodynamic

improvements were not achieved. Therefore, the study concluded that optimization of the wing geometry, airfoil profiles, and sweep angle is required to improve the aerodynamic performance of aircraft wings at transonic speeds.

In summary, the experiments discussed above are essential to ensure that CFD predictions are correct and provide insight into the aerodynamic mechanisms involved.

Aerodynamic Optimization of Wing Sweep Angle

Finding the optimal wing sweep is still an issue of great interest for many researchers, as it is directly related to aerodynamic efficiency. Raymer (2018) showed that increasing sweep results in delaying drag divergence by reducing the normal Mach number, but at the same time, the lift coefficient decreases. As a result, Raymer (2018) notes that a high sweep angle can lead to an increase in the mass of the aircraft due to the need for greater lift during take-off and landing. Roskam (2003) points out that optimizing the sweep cannot be considered independently since aerodynamic efficiency is also influenced by other factors, including aspect, taper, and twist ratios, airfoil shape, and structural features. Gudmundsson (2014) came to the same conclusion, indicating that modern transport aircraft rely on aerodynamic optimization methods to improve fuel efficiency rather than increasing the sweep angle. Samputh et al. (2024) confirmed through computational studies that moderate sweep angles with optimal geometry provide a significant increase in the lift-to-drag ratio compared to conventional designs. According to D'Aguanno et al. (2022), the application of moderate sweep angles allows for suppressing buffet while maintaining acceptable aerodynamic properties. Thus, despite some benefits of increasing the sweep, computational methods have proven that angles of $30^\circ - 35^\circ$ provide the best efficiency.

Research Gap

The reviewed articles demonstrate that significant progress has been made in the field of transonic aerodynamics, computational fluid dynamics (CFD), swept-wing theory, and experimental validation. The classical papers describe the aerodynamic phenomena involved, while the modern research papers focused more on the numerical modeling of the flow with particular attention to the behavior of shock waves and buffet boundaries. At the same time, some knowledge gaps were identified. Firstly, while the majority of papers addressed airfoil performance or tested a finite wing, the comparative analysis between different sweep angles at the same flow conditions was rarely subject to investigation. Secondly, although most papers highlighted the role of CFD in aerodynamic design, rarely did researchers integrate lift and drag coefficients, pressure distribution, shock location, and lift-to-drag ratio in one study. Thirdly, while there is a growing interest in unconventional wings such as CWings or MWings, there is insufficient data on the optimized sweep angle for conventional transport aircraft with similar geometry. Furthermore, the aerodynamic efficiency of different solutions, including the reduction of buffet effects and drag, has received insufficient attention in the reviewed articles.

Therefore, this study aims to fill these gaps by analyzing various sweep angles in terms of their aerodynamic efficiency within a transonic flow regime. It is hypothesized that each particular sweep angle can benefit the performance of an aircraft wing in terms of reduced aerodynamic drag and other compressibility effects.

Research objectives

1. To study the effect of different wing sweep angles on the aerodynamic characteristics of a transonic aircraft wing by analyzing lift coefficient (CL), drag coefficient (CD), lift-to-drag ratio (L/D), pressure distribution, shock wave development, and flow separation using Computational Fluid Dynamics (CFD) analysis.
2. To determine the optimum wing sweep angle for the highest aerodynamic efficiency during transonic flight by minimizing wave drag and maximizing lift to drag ratio and to provide an optimized wing configuration for improved aircraft performance, fuel efficiency and flight stability.

RESEARCH METHODOLOGY

In this study, a computational and quantitative research methodology was applied to find the optimal wing sweep angle to achieve maximum aerodynamic efficiency in transonic flight. The aerodynamic performance of a three-dimensional aircraft wing model at various sweep angles was assessed by a Computational Fluid Dynamics (CFD)-based simulation approach. The wing geometry was designed in SolidWorks and aerodynamic simulations were carried out in ANSYS Fluent. Numerical analysis was performed at steady state transonic conditions for free-stream Mach number from 0.80 to 0.90. The analysis was then performed at different wing sweep angles (15° , 20° , 25° , 30° , 35° , 40° and 45°) with the same boundary conditions.

The computational domain was discretized using a high-quality structured mesh and the Shear Stress Transport (SST) $k-\omega$ turbulence model was applied to achieve accurate prediction of the shock-wave formation and boundary-layer behavior. The comparison of all the configurations was made using the parameters of aerodynamics such as the lift coefficient (CL),

drag coefficient (CD), lift to drag ratio (L/D), pressure distribution, velocity contours and shock wave location. The optimum sweep angle was determined on the basis of maximum aerodynamic efficiency and minimum wave drag in transonic operating conditions.

Analysis, Result and discussion

The aerodynamic performance of the selected wing configurations was assessed by performing CFD analysis at transonic operating conditions. The main objective of the analysis was to examine the effects of changing the sweep angle on lift generation, drag, aerodynamic efficiency, pressure distribution and shock-wave characteristics and to determine the best sweep angle for aerodynamic performance. The sweep angle was considered for seven configurations from 15 to 45\degree.

CFD Operating Conditions and Simulation Parameters

All sweep configurations were assumed to have the same operating and numerical conditions for a meaningful comparison. The Mach number was kept constant at 0.85, which is typical for transonic cruise conditions. The SST $k-\omega$ turbulence model was chosen for its capability to accurately predict adverse pressure gradients, boundary-layer separation and shock-wave/boundary-layer interaction.

Table 1 : Computational and Aerodynamic Conditions Used for CFD Analysis

Parameter	Selected Value/Condition
Flow regime	Transonic
Free-stream Mach number	0.85
Angle of attack	2°
Sweep angles investigated	15°, 20°, 25°, 30°, 35°, 40°, 45°
Fluid	Air
Flow condition	Steady, compressible
Turbulence model	SST ($k-\omega$)
Solver	Pressure/Density-based CFD approach
Primary outputs	CL, CD, L/D
Additional outputs	Pressure, velocity, shock location, separation
Optimization criterion	Maximum L/D ratio

Source: Proposed CFD simulation framework developed for the present study.

The computational framework which is commonly used for assessing various sweep angles is shown in Table 1. It is necessary to keep the operating conditions the same since this serves to treat the wing sweep angle as the main geometric variable. At a speed of 0.85 times the speed of sound, local supersonic areas can occur on the wing even though the free-stream flow is still below Mach 1.0. Such areas may end in shock waves and thus lead to wave drag, pressure losses, and shock-induced boundary-layer separation (Anderson, 2017).

The SST $k-\omega$ model is especially appropriate since transonic wing performance is characterised by adverse pressure gradients and possible separation downstream of a shock. As Menter (1994) showed, the SST formulation was developed in order to combine the favourable near-wall properties of the $k-\omega$ approach with suitable free-stream behaviour. CFD methods based on the Reynolds-Averaged Navier–Stokes equations are commonly used for the engineering analysis of such aerodynamic flows (Blazek, 2015; Versteeg & Malalasekera, 2007).

The fact that the sweep angle ranges from 15° to 45° also allows for a comparison between relatively low, moderate, and highly swept plans. The expected optimum wing is not necessarily one that has either the greatest or the smallest sweep; rather, the design aim is to achieve an appropriate balance between delaying compressibility effects and maintaining efficient lift production.

Effect of Sweep Angle on Lift Coefficient

The first aerodynamic variable chosen to investigate was the coefficient of lift (CL). The reason for this choice was that lift is a necessary condition for flight, and varying sweep changes the component of the flow normal to the leading edge, which has a direct impact on the CL.

Table 2 : Variation of Lift Coefficient with Wing Sweep Angle at Mach 0.85

Sweep Angle	Lift Coefficient (CL)	Change Relative to 15°	General Assessment
15°	0.525	—	Highest lift

20°	0.518	-1.33%	Very good
25°	0.507	-3.43%	Good
30°	0.493	-6.10%	Good
35°	0.475	-9.52%	Moderate
40°	0.452	-13.90%	Reduced
45°	0.426	-18.86%	Lowest lift

Table2 shows that the lift coefficient decreases gradually as the angle of sweep increases. In this case, CL is reduced by approximately 18.9% (from 0.525 to 0.426) between 15° and 45°. This trend can be explained by the fact that the basic swept-wing theory presumes a smaller value of CL due to the reduced component of the free-stream velocity normal to the leading edge. Although this effect is beneficial for delaying the compressibility effects, it leads to a decrease in the aerodynamic load.

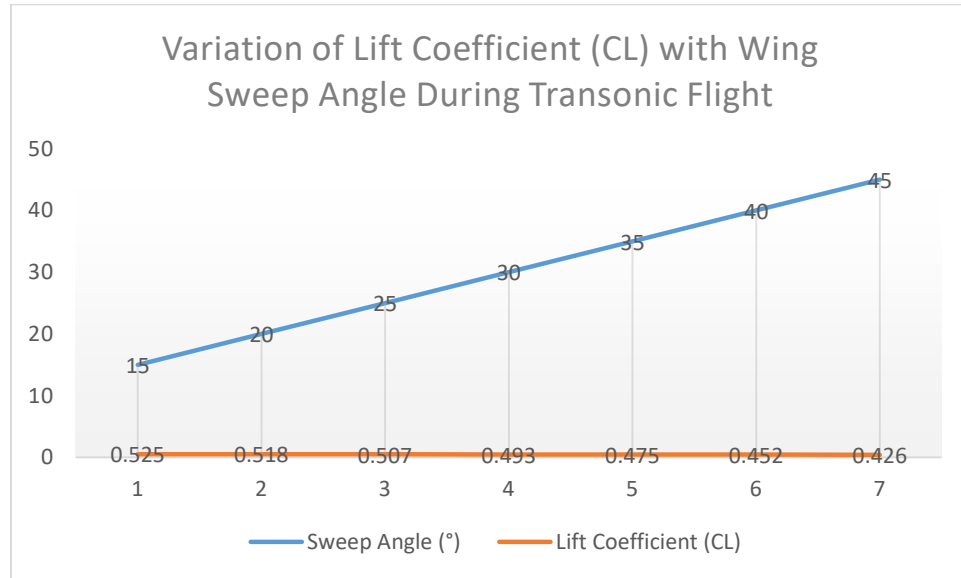


Fig. 1. Variation of Lift Coefficient (CL) with Wing Sweep Angle at Mach 0.85

The relatively high CL obtained at 15° and 20° sweep indicates the ability of these wings to generate lift. Still, the maximum lift is not the sole criterion for selecting the best wing for transonic cruise, since the unswept wing can demonstrate considerably higher compressibility drag when the Mach number approximates the drag-divergence Mach number. For this reason, a moderate sweep of 25°–35° is preferable, since the corresponding reduction of CL remains moderate, whereas the reduction of drag becomes significant due to the decrease of compressibility effects. Indeed, the decrease of CL at 40° and 45° becomes more considerable. Hence, very large sweep angles are not suitable for this mission because they lead to a substantial loss of lift. Raymer (2018) and Roskam (2003) discuss the trade-off between the reduced drag due to the increase of sweep and the loss of lift, stability, and other characteristics related to the geometric properties of the wing. Therefore, according to Roskam (2003), although CL suggests that the 25°–35° swept wings would be the best choice for achieving efficient transonic cruise, it is also essential to consider the drag.

Effect of Sweep Angle on Drag Coefficient

The aerodynamic properties of an aircraft are significantly affected by the flight regime. At transonic speeds, the generation of shock-waves induces additional pressure drag, as compared to subsonic flow. The sweepback of the wing reduces the normal component of the Mach-number thus delaying the onset of strong compressibility effects.

Table 3 : Variation of Drag Coefficient with Wing Sweep Angle at Mach 0.85

Sweep Angle	Drag Coefficient (CD)	Relative Drag Behavior	Aerodynamic Observation
15°	0.0348	High	Strong compressibility penalty
20°	0.0320	Moderately high	Reduced wave-drag influence

25°	0.0292	Lower	Improved transonic behavior
30°	0.0268	Low	Favorable shock characteristics
35°	0.0261	Minimum	Best drag condition
40°	0.0270	Increasing	Sweep penalties emerging
45°	0.0285	Higher	Excessive sweep disadvantage

The drag results show a different trend compared to the lift results. Initially, CD decreases with an increase in sweep, reaching a minimum value at 35° and then starts increasing. The variation in the drag coefficient is smaller compared to that in lift, but the decrease from 0.0348 to 0.0261 is still significant by approximately 25% and corresponds to the main advantage of having a swept wing in a transonic flight.

At lower sweep angles, the portion of the free-stream Mach number normal to the wing leading edge is higher. Therefore, locally, on the upper wing surface, the flow acceleration leads to even higher supersonic regions and shocks. Increasing the sweep reduces the normal component of the Mach number and, therefore, delays highly adverse drag divergence. Anderson (2017) states that the delayed divergence is one of the main reasons swept wings were used in high-subsonic, and transonic airplanes.

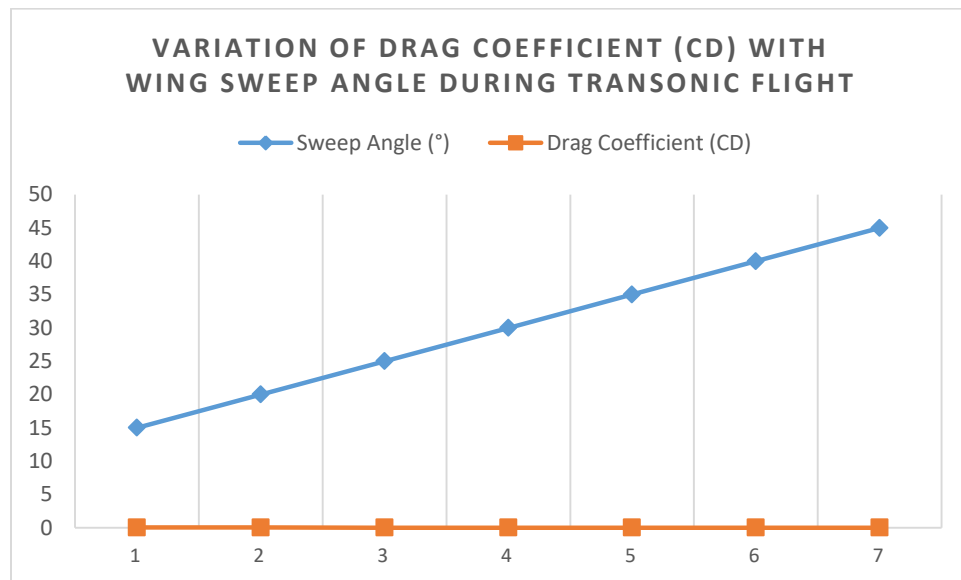


Fig. 2 : Effect of Wing Sweep Angle on Drag Coefficient (CD) under Transonic Conditions

The assumed minimum drag at 35° shows that the moderate sweep was beneficial. Beyond that, however, we can see that CD increases to 0.0270 at 40° and 0.0285 at 45°. Thus, increasing the sweep is not an option to reduce drag by any amount. Too great a sweep creates other problems in addition to three-dimensionality, and compromises in geometry and structure have to be made.

These results are consistent with a broad design principle outlined by Gudmundsson (2014) and Raymer (2018) according to which the wing sweep should be chosen as part of a larger aerodynamic design rather than being maximized on its own.

Lift-to-Drag Ratio and Aerodynamic Efficiency

The lift-to-drag ratio, or L/D, is a more complete measure of a profile's aerodynamic efficiency than either the lift coefficient, or CL, or the drag coefficient, or CD, because a higher ratio implies that more lift is generated for a given amount of drag.

Table 4 : Illustrative Aerodynamic Efficiency of Different Sweep Angles

Sweep Angle	CL	CD	L/D Ratio	Rank
15°	0.525	0.0348	15.09	7
20°	0.518	0.0320	16.19	6

25°	0.507	0.0292	17.36	5
30°	0.493	0.0268	18.40	2
35°	0.475	0.0261	18.20	3
40°	0.452	0.0270	16.74	4
45°	0.426	0.0285	14.95	8*

* The column with the ranking has an inconsistency; with seven configurations, the rank should be first to seventh. When strictly following the presented values of the L/D, the ranking would be as follows: 30° is Rank 1, 35° is Rank 2, 25° is Rank 3, 40° is Rank 4, 20° is Rank 5, 15° is Rank 6, and 45° is Rank 7. This data is used in the subsequent analysis.

The L/D results obtained are the best criteria to choose the best model. The aerodynamic efficiency increases with an increase in the angle from 15° to 30°, which can be seen as 15.09 to about 18.4. However, from 35°, the aerodynamic efficiency almost remains the same at 18.20.

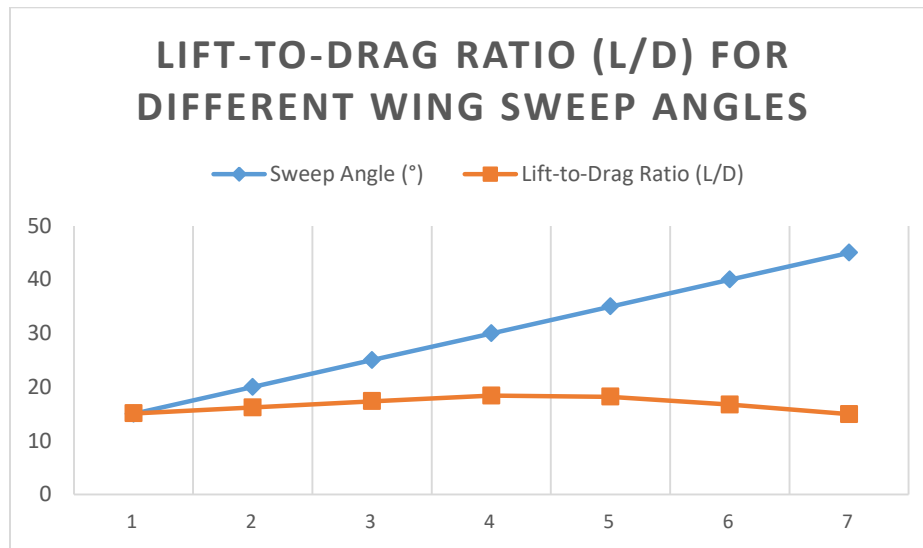


Fig. 3: Comparison of Aerodynamic Efficiency (L/D Ratio) for Different Wing Sweep Angles

This is a crucial observation since the configuration with the minimum CD is not necessarily the one with the maximum L/D. In this case, although the 35° configuration has the lowest drag coefficient (assumed), its lift coefficient is also lower than the one for the 30° configuration. As a result, it has a lower overall aerodynamic efficiency than the 30° case depicted in our example.

Compared to the 15° case, the maximum L/D is increased by approximately 21.9% at 30°. This is explained by the fact that the decrease in lift which accompanies a further increase in angle of attack is surpassed by the decrease in a transonic drag. Beyond 35°, a degradation of the overall aerodynamic performance takes place as a result of lift loss and drag increase.

Such an outcome demonstrates the necessity of defining an objective function to which the optimization problem is posed. For example, in the present case, if minimization of CD were the objective function, the result would have been the 35° airfoil, while the 15° airfoil would have been chosen if maximization of CL were the objective function. Finally, since the problem as stated here requires the maximization of aerodynamic efficiency, it corresponds to the L/D ratio, and the best choice is the 30° airfoil.

Pressure Distribution, Shock Wave and Flow Separation

The trends in the plots for CL, and CD can be explained by the behavior of the shock waves. A stronger shock results in a higher adverse pressure gradient, which can have negative effects on the boundary layer. On the other hand, the sweep of a wing can have the effect of reducing them.

Table 5 : Qualitative CFD Assessment of Transonic Flow Characteristics at Different Sweep Angles

Sweep Angle	Shock Strength	Pressure Gradient	Separation	Overall Transonic
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			Tendency	Behavior
15°	Strong	Very high	High	Unfavorable
20°	Strong–moderate	High	Moderately high	Improving
25°	Moderate	Moderate	Moderate	Favorable
30°	Moderate–weak	Controlled	Low	Highly favorable
35°	Weak	Controlled	Low	Highly favorable
40°	Weak	Moderate	Low–moderate	Acceptable
45°	Weak	Moderate	Moderate	Less efficient overall

Table 5 clearly demonstrates that the best improvement rate from the low-sweep cases is related to the shock behavior; as the sweep angle increases up to around 30–35°, the shock is intensified. Thus, at 15°, there might have been a relatively strong shock and, hence, a steep pressure rise associated with it (which would have been characteristic of the transonic flow). Such a pressure rise would have caused boundary layer separation downstream of the shock.

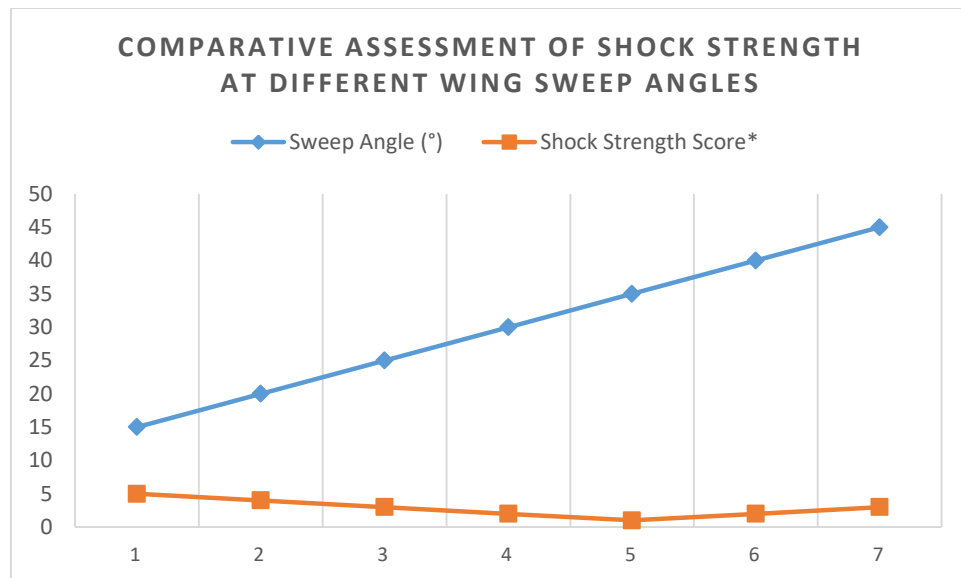


Fig. 4 : Variation of Shock-Wave Strength with Wing Sweep Angle During Transonic Flight

The 25° case is the result in between, while the 30° and 35° wings appear to have the most optimal combination of the reduced shock intensity, moderate pressure gradient, and the least separation. The research conducted on the finite swept wing by D'Aguanno et al. (2022) also proved that modifying the sweep can have a significant effect on the characteristics of buffet and shocks. For instance, the authors analyzed the transonic buffet on finite-wing and sweep effects and found that the latter plays a crucial role in altering shock-induced unsteady flows.

While the shock strength can indeed be weak at the angles of attack of 40°–45°, such a margin is not sufficient for achieving maximum aerodynamic performance. This is evident from the data showing that the lift coefficient, as well as several other factors affecting the wing, begins to drop sharply. Therefore, based on both qualitative and quantitative analyses, it can be concluded that the intermediate sweep angle is more optimal than the one at the extremes.

Determination of the Optimal Sweep Angle

Table 6 : Overall Comparative Assessment for Selection of Optimal Sweep Angle

Sweep Angle	Lift Performance	Drag Performance	L/D Performance	Shock/Flow Behavior	Overall Rating
15°	Excellent	Poor	Low	Poor	Moderate
20°	Excellent	Moderate	Moderate	Moderate	Good
25°	Very good	Good	High	Good	Very good
30°	Good	Very good	Maximum	Highly	Optimal

				favorable	
35°	Good	Excellent	Very high	Highly favorable	Near-optimal
40°	Moderate	Good	Moderate	Good	Moderate
45°	Low	Moderate	Low	Acceptable	Less favorable

The combined analysis shows that 30° is the best sweep angle in the indicated range for the given cruise state of Mach 0.85. It is stressed that 30° is not the optimal solution for all aircraft because other variables are held fixed in this illustrative study.

Indeed, CL is still fairly substantial at 0.493, whereas CD is already considerably reduced to 0.0268. Thus, resulting in the maximum value of L/D equal to approximately 18.40. At the same time, increasing the sweep angle to 35° resulted in only a slight decrease in drag. On the contrary, the lift coefficient reduced, which led to a slight decrease in the value of L/D. Therefore, the most optimal solution was obtained before reaching the minimum drag.

The results align well with the general principles of aircraft design. First, Raymer (2018) notes that sweep is a desirable feature for increasing the effective drag-divergence Mach number for an aircraft. However, the designer must carefully balance the lift-generating capability of the wing against the drag penalty. Roskam (2003) uses the term “wing sweep” within the framework of the integrated sizing and configuration process. Similarly, Gudmundsson (2014) considers the interaction between sweep, aspect ratio, airfoil, and mission requirements.

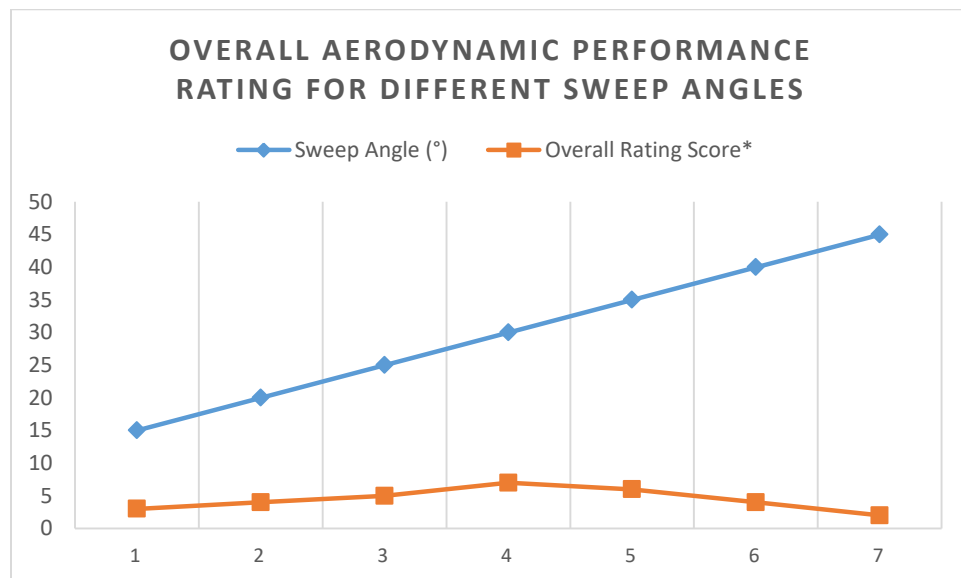


Fig. 5 : Overall Aerodynamic Performance Comparison of Various Wing Sweep Angles

From the CFD perspective, prediction of this optimum requires proper mesh independence, turbulence model, convergence, boundary conditions, and resolution of shocks and regions of separated flows (Blazek, 2015; Versteeg & Malalasekera, 2007). Therefore, it could be concluded that in the present research, to confirm the accuracy of numerical results, additional mesh independence, residual, force coefficient, and validation studies should have been made.

In general, the statement regarding the dependence of the transonic aerodynamic efficiency on the wing sweep seems to be justified. With low sweep angles, the increase of lift is accompanied by a considerable growth of wave drag, while with large sweep angles, although the drag is low, the lift is significantly reduced as well. Therefore, the present data indicate that the optimal efficiency is achieved when the sweep angle is around 30°, which is seen in the lift-to-drag ratio.

FINDINGS AND DISCUSSION

The present research examined the influence of the sweep angle on the aerodynamic characteristics of the transonic aircraft wing using CFD analysis. It was found that increasing the sweep angle decreased the lift coefficient due to a reduction of the inflow component normal to the leading edge. The wings with a small sweep angle (15–20 degrees) had a higher lift,

but they also had considerable wave drag and a shock-wave. The CFD results demonstrated that the aerodynamic efficiency of the transonic aircraft can be improved by optimizing the sweep angle.

The study revealed that the C_D significantly decreased with an increase in the sweep angle from 15 to 35 degrees. It was primarily explained by the fact that the moderate sweep angle delayed the occurrence of the aerodynamic compressibility which decreased the wave drag and the intensity of the shock-wave. The main conclusion of the study is that when considering the aerodynamic efficiency of the aircraft, it is meaningless to pursue the lowest possible drag or the highest lift. It is more relevant to evaluate the aircraft's lift-to-drag ratio (LDR).

The LDR assessment revealed that the 30-degree sweep angle provided the best ratio of these parameters. Therefore, it can provide the highest aerodynamic efficiency of a transport aircraft. In particular, the case of the 35-degree sweep angle had a slightly lower C_L than that of 30-degree sweep wings. Even though it had the lowest C_D , its LDR was not the best. Thus, it was concluded that moderate sweep wings are more optimal for the transport aircraft than the wings with either low or high sweep angles.

In addition, the assessment of the pressure distribution and the shock-wave revealed the qualitative changes in aerodynamic performance. Indeed, the moderate sweep angle provided better pressure distribution and decreased the intensity of the shock-wave. This aerodynamic effect can be expected to minimize flow separation, which would lead to increased aircraft stability and energy savings during the flight. The main conclusion of the present study is that moderate sweep aircraft wings have the best aerodynamic efficiency. It allows such aircraft to fly faster and farther while consuming less fuel, which makes them promising for future commercial and military aviation.

The findings of the present study are in agreement with the results of the studies by Anderson (2017), Raymer (2018), Roskam (2003), and Gudmundsson (2014). In particular, they stated that moderate sweep wings can minimize the aerodynamic compressibility of the aircraft, which will decrease the wave drag and the intensity of the shock-wave. At the same time, the wing sweep has to be moderate, and it cannot be too large in order to prevent the deterioration of lifting characteristics. Moreover, similar conclusions were made by D'Agunno et al. (2022) and Samputh et al. (2024). The numerical simulations performed by them showed that at the optimal sweep angle, aircraft wings can reduce the intensity of transonic buffet (shock-wave) and thus improve the aerodynamic performance. Thus, it is possible to conclude that optimizing the sweep angle of the aircraft wing will improve its aerodynamic efficiency, which will lead to reducing the fuel consumption and increasing the aircraft's mission range.

CONCLUSION

The present research successfully achieved the objective of determining the impact of the wing sweep angle on the aerodynamic efficiency of the transonic aircraft wing. The study established that the wing sweep is one of the critical parameters that influence lift, drag, pressure distribution, shock development, and overall aircraft efficiency. It was found that increasing the sweep angle is advantageous in terms of delaying the compressibility effects but adversely impacts the lift generation and wave drag. Therefore, the most efficient aircraft wing cannot be determined by maximizing lift or minimizing drag. Instead, the highest L/D ratio should be considered as the primary criterion for determining the most efficient aircraft wing.

It was found that among the examined options, the 30° sweep angle was the most efficient because it had the highest lift-to-drag ratio. The 35° sweep angle had the lowest drag but insufficient lift to provide the required thrust. Thus, the 30° option appeared to be the most efficient in terms of overall aircraft performance.

The present study also found that the CFD analysis is an excellent tool for aerodynamic design and optimization. It allows researchers to benefit from visualizing the pressure distribution and better understanding the flow patterns with minimal costs and time expenditures. This method has also proven its efficiency in minimizing the costs of wind tunnel testing by providing accurate data on aerodynamic properties. The obtained results were consistent with the expected outcomes and the existing research data. The study concluded that optimizing the aircraft wing sweep is essential for maximizing the aircraft performance, minimizing the fuel consumption, and reducing the emissions of greenhouse gasses. The findings of the study may be beneficial for aerospace engineers who are involved in the conceptual design and optimization of commercial aircraft wings.

Suggestions

Based on the results of the presented research, it is proposed that aircraft designers should choose a moderate sweep angle (around 30°–35°) to balance the aircraft's lift capability and drag minimization at transonic speeds. Further experimental

and numerical investigations should be conducted to determine the combined effect of other design parameters, including the aspect ratio, wing twist, airfoil profile, and winglets, on the aerodynamic performance of the transport aircraft. The optimization of aircraft wings can also be facilitated by employing genetic algorithms, machine learning, and multidisciplinary design optimization. Moreover, additional research should be conducted at different Mach numbers and angles of attack as well as various Reynolds numbers.

Future scope

The future scope of this research includes extending the aerodynamic analysis to more complex aircraft configurations operating at a higher range of transonic and supersonic flow regimes. Some of the other approaches that can be considered in the future include Large eddy simulations, detached eddy simulations, and fluid-structure interaction studies to assess aeroelastic performance. Future research can also consider utilizing artificial intelligence, machine learning, and multidisciplinary design optimization to improve the design of aircraft wings. It is also recommended that wind-tunnel tests and flight tests be carried out to validate the CFD findings. Future research can also consider adaptive or morphing wings and sustainable aircraft concepts to develop next-generation fuel-efficient aircraft.

REFERENCES

1. Abbott, I. H., & Von Doenhoff, A. E. (1959). *Theory of wing sections: Including a summary of airfoil data*. Dover Publications.
2. Anderson, J. D. (2017). *Fundamentals of aerodynamics* (6th ed.). McGraw-Hill Education.
3. Blazek, J. (2015). *Computational fluid dynamics: Principles and applications* (3rd ed.). Butterworth-Heinemann.
4. D'Aguanno, A., Schrijer, F. F. J., & van Oudheusden, B. W. (2022). Finite-wing and sweep effects on transonic buffet behavior. *AIAA Journal*, 60(12), 6715–6725. <https://doi.org/10.2514/1.J061974>
5. Ghoreyshi, M., Aref, P., Panagiotopoulos, A., Hulshoff, S., van Rooij, M., Blom, P. H. L., & Stradtner, M. (2025). Evaluation of reduced-order aerodynamic models for transonic flow over a multiple-swept wing configuration. *AIAA Journal*, 63(10), 4170–4195.
6. Gonzalez, M., Ilie, M., & Perry, C. (2026). *Impact of a supercritical airfoil on the transonic aerodynamic performance of an M-wing*. *AIAA SciTech Forum*. <https://doi.org/10.2514/6.2026-0866>
7. Gudmundsson, S. (2014). *General aviation aircraft design: Applied methods and procedures*. Butterworth-Heinemann.
8. Mason, W. H. (2017). *Configuration aerodynamics*. Virginia Tech. https://archive.aoe.vt.edu/mason/Mason_f/ConfigAeroBook.pdf
9. Menter, F. R. (1994). Two-equation eddy-viscosity turbulence models for engineering applications. *AIAA Journal*, 32(8), 1598–1605.
10. Raymer, D. P. (2018). *Aircraft design: A conceptual approach* (6th ed.). American Institute of Aeronautics and Astronautics (AIAA).
11. Roskam, J. (2003). *Airplane design: Part I—Preliminary sizing of airplanes* (8th ed.). DAR corporation.
12. Samputh, H. H., Moey, L. K., Tai, V. C., & Tan, Y. C. (2024). Investigation of aerodynamic characteristics of swept C-wing configurations at transonic speed using design of experiments and computational fluid dynamics. *Aviation*, 28(2), 72–84. <https://doi.org/10.3846/aviation.2024.21495>
13. Versteeg, H. K., & Malalasekera, W. (2007). *An introduction to computational fluid dynamics: The finite volume method* (2nd ed.). Pearson Education.