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Aerodynamic Challenges and Innovations in Wing Designs for Supersonic Flight: A Comprehensive Review

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ABSTRACT

Supersonic flight has been of interest for decades due to the advantages it offers in speed and efficiency of transport, which are advantageous to both commercial and military aircraft. This paper covers a comprehensive review of various wing configurations for supersonic flight. We explore the aerodynamic and structural challenges associated with the various wing types. Supersonic flight offers significant benefits, but also poses complex engineering challenges including concerns with drag, stability, and sonic booms. This review examines the performance of straight, low-sweep, swept-back, delta, forward-swept, and oblique wings and highlights their respective advantages and limitations across different regimes. Straight and low-sweep wings excel at subsonic speeds, but struggle with high drag at supersonic velocities, while swept-back wings and delta wings offer superior performance at high speeds but come with trade-offs in lift and low-speed efficiency. Forward-swept wings provide potential for noise reduction and overall favorable supersonic flight characteristics, but face challenges like aeroelastic instability. Oblique wings, though promising in reducing drag and sonic booms, have significant structural challenges at high Mach numbers. Ongoing research in materials science and aerodynamic modeling continues to advance supersonic aircraft design. These studies and development efforts are paving the way for next-generation supersonic aircraft.

Keywords: Aerospace and Aeronautical Engineering; Computation and Theory; Supersonic Flight; Wing Design; Aerodynamics and Sonic Booms

INTRODUCTION

Supersonic flight has captivated scientists for decades and has been around since the Cold War era.[1,2] Nowadays, breaking through the sound barrier has become commonplace in our daily lives with aircraft that can cruise up to Mach 3.3. Supersonic flight, however, remains very challenging due to the high stress on an aircraft's structure,[3] high-temperatures on aircraft due to frictional heating at supersonic speeds,[4] reduced fuel efficiency, challenges with breaking the sound barrier,[5] reduced fuel efficiency due to high drag at supersonic speeds,[6] and more. Despite these challenges, supersonic flight is still of high interest for critical warfighting capabilities[7] and for passenger transport.[8] Research efforts in supersonic flight is therefore still a hot topic in aerodynamics research, and development of new generations of supersonic aircraft are still underway. For example, Boom Supersonic, a company in the United States, is developing a next generation supersonic passenger airliner.[8] Other companies working on supersonic passenger aircraft include Hermeus, who claim that their hypersonic MN 5.0 design enables 90-minute flights from New York to Paris.[9] Lockheed Martin had also been working to develop aircraft with low-boom characteristics prior to 2021.[10]

Perhaps the most iconic supersonic aircraft was the SR-71 Blackbird, a military spy plane developed by Lockheed Martin in 1964. It remains one of the only aircraft that could reach a high cruise speed of Mach 3.3.[11] The SR-71 Blackbird was manufactured to fly at high speeds and at high altitudes to avoid missiles and anti-aircraft fire. The plane used a common wing design called the delta wing,[12] which worked well at high speeds, but when flying at low speeds, the plane's aerodynamics would cause it to fall like a brick. The design of these supersonic aircraft essentially involves the design of two aircraft, one configuration for subsonic flight and another for supersonic flight.[13] The design of supersonic aircraft poses significant challenges due to the complex interplay between the aerodynamic properties of the wings, body, and engines. Each component must be optimized to handle extreme forces, high temperatures, and increased drag encountered at supersonic speeds.

Wing designs are a critical feature of an aircraft, especially supersonic aircraft, which determine the flight characteristics of the aircraft in the air.[14] The most common wing configurations currently in use are swept back wings[15] and the straight wing configurations,[16] which are typically used in commercial aircraft. However, commercial aircraft, aside from the concorde that was retired in 2003, are not known for flying past the speed of sound. There are a few factors that contribute to the lack of popularity of commercial supersonic flight, which include the high stresses required to break the sound barrier that typically require more expensive aircraft designs and materials, lower fuel efficiency at supersonic speeds, and the generation of loud sonic booms, which are sound waves that emanate from the aircraft. Supersonic flight for commercial airliners, however, is sought after because this would enable commercial aircraft to transport personnel over large distances much more quickly. In addition to commercial interest in supersonic flight, supersonic aircraft for military use is of high interest to enable military aircraft to fight, maneuver, and perform reconnaissance missions more rapidly and effectively. Due to the commercial interest and military interest of supersonic flight, research in the topic is ongoing.[17,18]

In addition to wing designs, the loud sonic boom emitted from supersonic aircraft limits the ability of these aircraft to be used primarily over open seas to prevent disturbing people on the ground. Active research in the area of defending acceptable sonic boom intensity is ongoing.[19] For example, Reigel and Sparrow (2022) recently covered the impact of secondary shockwaves finding that in certain atmospheric conditions, secondary shockwaves from supersonic flight could "bend" toward land even if an aircraft is flying overseas.[20] As a result of complex flight dynamics, practical engineering tradeoffs for aircraft designs, and practical implications for the use of supersonic flight as it pertains to on-ground populations, research on the influence of wing configurations supersonic flight has been an area of interest. This review covers the influence of wing designs on supersonic aircraft flight dynamics and their practical implementation. We cover various wing designs, including swept and straight wings, delta wings, forward swept wings, and oblique wings.

DISCUSSION

The Mach number, Ma is the ratio between an aircraft's velocity, u, to the speed of sound, c where $\mathrm{Ma} = u/c$. Subsonic flight occurs at $\mathrm{Ma} < 1$, and supersonic flight occurs when $\mathrm{Ma} > 1$, when the aircraft is traveling faster than the speed of sound. Flying faster than the speed of sound offers numerous advantages, with the most obvious being the dramatic reduction in travel time. Supersonic speeds allow aircraft to cover long distances much more quickly, significantly cutting down travel time between distant locations. There are challenges with supersonic flight, however. It has been widely reported that the two major challenges facing supersonic aircraft adoption are the noise emissions due to the sonic boom and environmental impacts due to fuel consumption and emissions from supersonic aircraft.[21,22] These factors pose challenges for aircraft designers. In addition, the flight dynamics and physics of flight at supersonic speeds are very different to subsonic flight.[23,24] One aspect of flight dynamics that changes dramatically at supersonic speeds is the aircraft center of pressure, which moves toward the back of the aircraft at supersonic speeds, greatly impacting the aircraft's stability.[25] Designing supersonic aircraft presents unique challenges, since they need to be capable of flying both stably at supersonic speeds and efficiently at subsonic speeds. Achieving this balance requires careful consideration of the wing structure and configuration, which is one of the most critical factors in the overall design. The wing needs to minimize drag and maintain stability at high Mach numbers, while also providing sufficient lift and maneuverability during takeoff, landing, and subsonic cruising This multiple purpose design makes supersonic aircraft development highly complex, particularly in optimizing performance across a wide range of flight conditions. Wing design and its impact on flight characteristics of supersonic aircraft is a key parameter in supersonic aircraft design.

Straight and Low-sweep Wings

Straight and low-sweep wings are commonly used on gliders and propeller aircraft due to their ability to produce relatively high amounts of lift at relatively low speeds. This high lift advantage at low speeds is crucial for aircraft that need slow, stable flight, such as gliders, which benefit from the enhanced lift-to-drag ratio at subsonic speeds. The straight-wing design produces less drag at low speeds, which improves fuel efficiency and flight stability for slow-moving aircraft. These straight and low-sweep wings, however, are less ideal for high-speed flight because they experience relatively high amounts of drag at high speeds. This is partly why high-speed aircraft, such as commercial jets and military planes, use swept-back wings, which are better suited for reducing drag at higher speeds, especially near the speed of sound. While straight wings are highly efficient for slow flight, their higher drag at faster speeds limits their use in high-speed aircraft. In contrast, the reduced lift of swept wings at low speeds is acceptable in high-speed aircraft, where the priority is minimizing drag and improving performance at higher Mach numbers. Another important factor in wing design is lift-to-drag ratio. When considering the lift-to-drag ratio of a wing, straight wings generally have relatively high lift-to-drag ratio at lower Mach numbers ($Ma < 0.8$).[26]

Despite the relatively high drag of straight and low-sweep wings at high speeds, numerous studies have been conducted on the use of these wings for high-speed aircraft and in particular, for supersonic aircraft. Martins et al. (2004) studied a concept for a supersonic business jet capable of flying at Mach 1.5 with a low-sweep wing design, finding that the low-sweep design decreased friction drag.[27] The study investigated the impact of wing geometry, including thickness, on drag and lift of the wing. Kishi et al. (2019) numerically investigate low-sweep wing designs in supersonic aircraft finding that forward camber and twist angle at the middle of the wing had the largest impact on drag reduction of the wing.[28] The study found that a thin leading edge with negative camber was optimal due to the generation of shock waves at the leading edge. Hoffman et al. (1955) investigated the impact of indentations on the drag of straight-wing aircraft at supersonic speeds.[29] The study showed that indentations significantly reduced drag, especially at Mach 1.10, making the aircraft more efficient at those speeds but also found that as the speed increased beyond Mach 1.3, the benefits of the indentations diminished. Jones (1991) proposes the concept of a supersonic aircraft that is made of a single straight wing capable of efficiently flying over a wide range of Mach numbers by simply adapting the the wing by steering it to different sweep angles.[30]

In summary, while straight and low-sweep wings offer significant advantages for low-speed, stable flight due to their high lift-to-drag ratios, they are less suitable for high-speed flight, particularly at supersonic speeds where drag increases significantly. However, ongoing research has explored adaptations to these wing designs, such as camber adjustments, twist angles, and surface modifications, that can reduce drag and improve performance in high-speed and supersonic applications demonstrating their potential use in specific contexts.

Swept-back Wing

Swept-back wings are commonly used on high-speed aircraft, such as commercial jets and military planes, due to their relatively low drag at higher speeds. This relatively low drag at high speeds is particularly important at transonic and supersonic speeds, where the airflow around the aircraft approaches or exceeds the speed of sound. When considering lift-to-drag ratio, backward swept wings trend to have relatively high lift-to-drag ratios at higher Mach numbers (Ma > 0.9), especially at supersonic speeds.[26] The backward sweep of the wing helps delay the onset of shockwaves at supersonic speeds, which improves the aircraft's aerodynamic efficiency at supersonic speeds. One downside, however, is that swept-back wings generally produce less lift at lower speeds, which is why they are not typically found on slower aircraft like gliders or propeller planes. Despite the reduced lift, swept-back wings offer better performance at higher Mach numbers, making them ideal for high-speed flight where minimizing drag is a priority. Another key factor in swept-wing design is the lift-to-drag ratio, which generally improves as the aircraft's speed increases, allowing for more efficient flight at transonic and supersonic speeds.[31]

The swept back wing configuration is known for its reduced drag at high speeds, which is why they are commonly used in high-speed transonic and supersonic aircraft.[32] This reduced drag is due to the fact that swept-back wings delay the formation of shock waves by increasing the effective Mach number at which the airflow over the wing reaches the speed of sound which improves aerodynamic efficiency during supersonic flight. This wing configuration also provides higher stability, better handling, and increased maneuverability at supersonic speeds.[33] It allows the aircraft to perform better at higher mach numbers and has a higher critical mach number. Swept-back wings also reduce wingtip vortices which further improves the aircraft's performance.[34]

Research in swept-back wing design in supersonic aircraft is an active area of investigation. Rahman et al. (2022) numerically investigated the use of swept wings in supersonic aircraft with sweep angles of 0 to 60 degrees and concluded that the optimal sweep angle of a swept wing is a complex parameter to determine that depends on the wing, aircraft control method, and aircraft body structure.[31] Kishi et al. (2019) numerically investigate swept wings designs in supersonic aircraft, and found that forward camber and twist angle at the middle of the wing had the largest impact on drag reduction, which are finding that are in line with low-sweep wings.[28] The study found that a small twist angle and small positive camber at the leading edge was optimal for the swept wing design. These findings align with similar findings in the study of low-sweep wings, showing that subtle geometric modifications can greatly impact wing performance. Further advances in computational fluid dynamics (CFD) have allowed researchers to simulate and refine wing shapes with greater precision. For example, Manshadi and Aghajanian (2018) explored the use of multi-objective optimization, which enables the development of wing designs that perform optimally across a range of flight conditions.[35] The researchers used a response surface method and genetic algorithm to optimize wing designs focusing on balancing trade-offs between drag reduction and maintaining sufficient lift at various speeds.

Shock control techniques on swept-back wings is another area of research that is being explored to manage the impact of shock waves on the wing surfaces at supersonic speeds. One challenge that has been widely documented in the literature for swept wing designs is crossflow instability, especially at supersonic speeds, which is an area of research under investigation.[36] Haas et al. (2021) studied the cross-flow stability of supersonic swept wings using Linear Stability Theory finding that cross-flow stability is reduced for an increasing wing sweep angle and larger thickness to chord ratios of the wing. Despite challenges with wing stability, modern control methods and techniques may be used to readily overcome stability challenges of swept wings, especially at supersonic speeds. Despite challenges with backward swept wings, they remain very popular for high-speed aircraft due to their ability to reduce drag and delay the formation of shock waves at transonic and supersonic speeds.

Delta Wings

One of the most common wing types found in supersonic aircraft are delta wings. Two supersonic airliners have flown, and these include the Concorde and Tupolev Tu-144, both of which had delta wings. The T-144 had limited service due to safety concerns, and the Concorde was discontinued in 2003 due to high operating costs and reliability concerns. Delta wings are also very common on military aircraft. The the Convair F-102 Delta Dagger, the SR-71 Blackbird, and the Eurofighter Typhoon are examples of military aircraft that use delta wings. The F-22 Raptor also uses a variation of a delta wing design that also incorporates trapezoidal wing structures. When considering lift-to-drag ratio, similar to the backward swept wings, delta wings trend to have relatively high lift-to-drag ratios at high Mach numbers, especially at supersonic speeds (Ma > 1.2).[26] These delta wings, however, suffer from very poor aerodynamic performance at low speeds.[37]

The aerodynamic performance of delta wings across transonic and supersonic speeds is complex and unintuitive. Many studies have been conductive from the 1960s and beyond to understand the physics of flows around delta wings.[38] Studies have determined that up to six different flow patterns over delta wings may be observed, which include the classical vortex, vortex with shock, separation bubble with shock, shock-induced separation, shock with no separation, and separation bubble with no shock.[39–41] Despite the complex physics governing aerodynamic characteristics of delta wings, there is a plethora of experimental and theoretical modeling of flight characteristics of these wings. Delta wings have proven to be particularly effective for supersonic flight due to their ability to reduce drag and maintain stability across a wide range of high-speed conditions.[26] The triangular shape of delta wings helps in managing shockwaves and controlling boundary layers, which minimizes wave drag and improves performance at high Mach numbers.[42] For instance, studies have shown that delta wings maintain a relatively high lift-to-drag ratio at supersonic speeds, aided by the formation of leading-edge vortices that provide significant lift as the angle of attack increases.[42] Research on the specific design parameters, including wing thickness, camber, and sweep angle have demonstrated that subtle changes to these parameters can dramatically modify performance and may be used as a means of performance optimization, as shown by the empirical and theoretical studies presented in the literature.[42] For future supersonic aircraft, delta wings continue to be an area of significant research focus due to their adaptability and proven performance across various supersonic regimes.

Forward Swept Wings

The forward-swept wing design is one of the most prominent examples of unconventional wing configurations. The forward swept wing configuration has been applied in numerous military aircraft, namely the Sukhoi Su-47 Berkut and the Grumman X-29. The forward swept wing concept has even been applied to commercial aircraft, like the Hansa HFB-320, for example. Researchers have discovered that forward swept wings may have several advantages over swept-back wings and other wing designs in supersonic flight. One of the main advantages of the forward swept wing is that the forward swept wing dramatically reduces the sonic boom when compared to traditional backward swept wings.[43] This reduces noise produced from an aircraft. In addition to reduced sonic boom, the forward swept wing offers similar drag and lift characteristics to the backward swept wing.[44] Other advantages of the forward swept wing have been reported. For example, Setoguchi and Kanazaki (2020) investigated forward swept wings for supersonic business jets and found that forward swept wings had superior stall characteristics compared to backward swept wings.[45] The improved stall performance of forward-swept wings is mainly due to the fact that the airflow stays attached to the outer sections of the wings at higher angles of attack, preventing early separation and maintaining better control during a stall.

Forward swept wings, however, do have drawbacks. These wings can experience aeroelastic divergence at high speeds, which impacts the stability of the aircraft and puts a lot of stress on the wings requiring more sophisticated controls to maintain aircraft stability and more sophisticated materials to hold up to the stresses on the wings.[46] In addition, increased drag on forward swept wings at high Mach numbers (Ma = 2) have been reported in experimental studies.[47] In summary, while forward-swept wings provide tangible benefits over swept-back wings, such as noise reduction and stall performance, their application is limited. Despite their limited application, they remain a compelling option for certain high-performance aircraft designs and are still actively under investigation. Research and development efforts for forward swept wings should continue due to the possibility for substantial reduction of sonic booms, which would make implementation of these aircraft overland easier.

Oblique Wings

The oblique wing is another unconventional wing design which has been tested in wind tunnels and theoretically studied. Only one aircraft has been built with an oblique wing, which is NASA's AD-1 experimental aircraft that was built in the 1970s. Studies on oblique wings have suggested that these wings may have improved lift-to-drag ratio when compared to other conventional wing types, but that may also suffer from structural and stability challenges.[48] Some studies have suggested that oblique wings reduce lift dependent wave drag by a factor of 4 and volume dependent wave drag by a factor of 16 in supersonic flight.[49] Some studies have found that the oblique wing may produce a sonic booms that are not capable of reaching the ground at Mach 1.1, enabling silent overland supersonic travel.[50] Wintzer et al. (2012) suggest that oblique wings may only be advantageous to more conventional wing designs with cruise Mach numbers are relatively low (Ma < 1.6).[51] While oblique wings offer promising aerodynamic advantages over other conventional wing types, including reduced drag and reduced sonic boom, they face significant challenges related to structural stability and performance at higher Mach numbers. Despite these hurdles, research on oblique wing aerodynamic performance is ongoing, and is even being investigated for use in commercial aircraft to explore the potential of oblique wings to improve efficiency and reduce environmental impact of transonic and supersonic flight.[52,53] As technology advances, oblique wings may find practical applications in next-generation aircraft designs. These wings should continue to be explored due to the substantial improvements in transonic and supersonic flight efficiency, and the potential to substantially reduce sonic booms.

CONCLUSION

Supersonic flight offers the advantage of rapid transport, which can dramatically improve transport efficiency. Supersonic flight, however, is not trivial and supersonic aircraft design is very challenging, governed by complex physics. This review of various wing configurations for supersonic flight reveals a complex interplay between aerodynamic efficiency, structural stability, and practical performance at varying speeds. Straight and low-sweep wings provide advantages at lower speeds but face significant drag at supersonic velocities, while swept-back wings offer better performance at higher Mach numbers but with limited lift at lower speeds. Delta wings are effective in reducing drag and maintaining stability at supersonic speeds but struggle with poor aerodynamics performance at low speeds. Forward-swept wings present advantages in reducing sonic booms and enhancing stall performance but suffer from aeroelastic instability and high drag at extreme speeds. Lastly, oblique wings, while promising in terms of reducing drag and sonic boom effects, face significant structural challenges. Despite these limitations, ongoing research into these wing designs, coupled with advancements in materials science and computational modeling, continues to push the boundaries of supersonic flight. These studies open exciting possibilities for the future of commercial aviation and bring the dream of a new era of supersonic travel closer to reality.

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