



EVALUATING THE IMPACT OF SUPERCRITICAL AND SYMMETRICAL AIRFOIL OPTIMIZATION ON TRANSONIC AERODYNAMIC EFFICIENCY

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ABSTRACT

The transonic flight regime, which ranges between Mach 0.8 and 1.2, introduces significant aerodynamic hurdles due to shock-wave formation, rapid increase in drag, and boundary layer flow separation. Consequently, airfoil optimization has become a vital area of research. Despite the vast amount of literature on both symmetrical and supercritical airfoils, there is little research focusing on comparing the extent to which optimization enhances the aerodynamic performance of both geometries in transonic conditions. This research aims to address this gap by evaluating the research question: *To what extent does the optimization of supercritical and symmetrical airfoils improve aerodynamic efficiency in the transonic flight regime?*

This study uses a secondary data analysis method to evaluate published Computational Fluid Dynamics (CFD) investigations, NASA technical studies, and peer-reviewed aerospace research related to transonic airfoil optimization. The sources were analysed using a comparative, thematic analysis to examine trends in aerodynamic performance.

The findings reveal that optimization significantly improves aerodynamic efficiency for both symmetrical and supercritical airfoils. The drag coefficient decreased by approximately 39.5% for the optimized NACA 0012 symmetrical airfoil. Meanwhile, the optimized supercritical airfoil demonstrated an absolute increase of 0.12 in drag divergence Mach number, from 0.67 to 0.79, representing a relative improvement of approximately 18%. Across the evaluated literature, these performance gains were consistently associated with adjustments to wing cross-section design that improved pressure recovery and managed shock-wave behaviour.

These findings suggest that airfoil optimization serves as a reliable method for boosting aerodynamic performance in transonic flight. This study contributes to the existing literature by combining data from both symmetrical and supercritical optimization studies, highlighting the critical role of shock-wave control in future transonic airfoil geometries.

KEYWORDS: Transonic Aerodynamics, Airfoil Optimization, Supercritical Airfoil, NACA 0012, Drag Divergence Mach Number, Shock-Wave Control, Computational Fluid Dynamics

1. INTRODUCTION

As modern aircraft aim to achieve higher speeds while maintaining fuel efficiency, optimizing airfoil geometry has become an important area of aerospace research. The transonic flight regime typically ranges

from Mach 0.8 to 1.2. Modern commercial aircraft cruise at the lower boundary of this range, generally between Mach 0.78 and 0.85, where localized supersonic flow develops over the wing despite the aircraft itself remaining subsonic. It presents one

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of the most challenging aerodynamic conditions because in this range of velocity, shock waves begin to form on aerodynamic surfaces, causing a rapid increase in drag, flow separation, and overall reduction in aerodynamic performance (García, 2025; Whitcomb & Clark, 1965).

Two major airfoil designs are of particular interest in this flight regime: supercritical and symmetrical airfoils. Supercritical airfoils are specifically developed to delay the onset of shock waves and reduce wave drag. This design allows aircraft to operate more efficiently at transonic speeds by improving lift-to-drag ratios and delaying drag divergence (Whitcomb & Clark, 1965; Sobieczky & Seebass, 1984). In contrast, symmetrical airfoils, such as the NACA 0012, provide balanced aerodynamic characteristics and are frequently used as baseline models for optimization studies (Leite et al., 2022). Recent computational investigations demonstrated that optimized symmetrical airfoils can achieve substantial drag reductions and improvements in aerodynamic performance under transonic conditions (Leite et al., 2022; Ntantis & Xezonakis, 2024; Chen & Agarwal, 2014).

This review uses the term “optimization” in two distinct senses. The first is algorithmic shape optimization, in which computational methods iteratively modify a geometry to minimize an objective function such as drag; this applies to the symmetrical airfoil studies examined here. The second is design-driven geometric refinement, in which a shape is developed from aerodynamic reasoning to delay or weaken shock formation; this applies to the supercritical airfoil literature originating with Whitcomb. Both produce improved transonic performance, but they proceed from different starting points and are evaluated against different baselines. This distinction is maintained throughout the analysis.

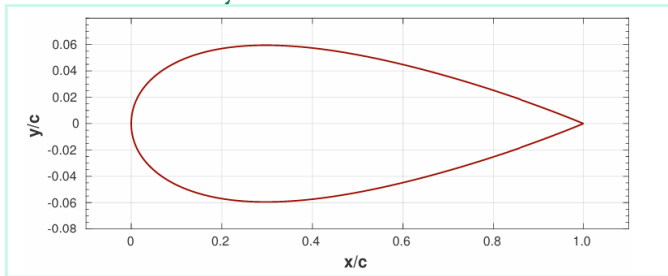
This research examines the extent to which optimizing supercritical and symmetrical airfoils improves aerodynamic efficiency in the transonic flight regime. It also compares both supercritical and symmetrical airfoils to evaluate the relative effectiveness of their optimization strategies under transonic flight conditions.

2. LITERATURE REVIEW

Research in aerodynamics consistently shows that optimization of airfoil geometry greatly improves aerodynamic performance (Leite et al., 2022; Hicks & Henne, 1978). Studies of symmetrical airfoils like the NACA 0012 show that numerical optimization can substantially reduce drag and improve lift-to-drag ratio in compressible flow, such as the transonic regime (Leite et al., 2022). Early research by Lee & Jang (2008) demonstrated that genetic algorithms could successfully optimize transonic airfoils. Their research focused on reducing drag while still meeting all the necessary aerodynamic requirements. More recent studies using advanced optimization techniques further support these findings (Chen & Agarwal, 2014; Ntantis & Xezonakis, 2024). An adjoint-based optimization study of the NACA 0012 airfoil reported a significant reduction in drag and enhanced pressure distributions under transonic conditions (Ntantis & Xezonakis, 2024). Similarly, Chen & Agarwal (2014) showed that optimization by multi-objective genetic algorithms can reduce drag while maintaining the required lift characteristics of transonic airfoils. This indicates that different optimization methods consistently improve aerodynamic performance. Such improvements are mainly attributed to a more controlled and favourable pressure distribution across the airfoils' surface. This delays shock-wave formation at transonic Mach numbers and reduces the intensity of adverse pressure gradients that typically cause early flow separation (Whitcomb & Clark, 1965; Leite et al., 2022). NASA transonic airfoil optimization studies further support this conclusion by showing that optimized airfoils significantly reduce wave drag and drag divergence through controlled shock positioning and smoother pressure recovery (Whitcomb & Clark, 1965). Supercritical airfoil geometry is specifically designed for the transonic regime. Its flattened upper surface reduces peak suction pressures, while aft camber redistribution allows for more gradual pressure recovery after a shock wave. This reduces shock-wave intensity and, therefore, the airfoil is more efficient. Flow separation is also reduced as weaker shock waves delay boundary layer separation, leading to reduced wake formation and improved aerodynamic efficiency (Sobieczky & Seebass, 1984; Harris, 1975). Together, these studies demonstrate that improvements in transonic

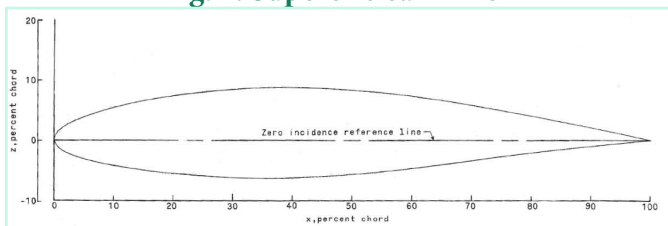
aerodynamic efficiency are not limited to a single optimization technique. Whether using numerical optimization, adjoint-based optimization, or multi-objective genetic algorithms, the existing literature consistently reports reduced drag, improved pressure recovery, and greater shock-wave control (Hicks & Henne, 1978; Lee & Jang, 2008; Ntantis & Xezonakis, 2024; Chen & Agarwal, 2014).

Fig. 1: Baseline Configuration of NACA 0012 Symmetrical Airfoil



Source: Adapted from Leite et al. (2022)

Fig. 2: Supercritical Airfoil



Source: Adapted from Whitcomb & Clark (1965).

However, there are also several studies that complicate the conclusion mentioned above. Multidisciplinary aerospace design optimization research shows that aerodynamic performance is not the only factor that has to be taken into consideration. Improvements in efficiency are often accompanied by trade-offs in structural weight, manufacturability, and stability. Thus, even though aerodynamic efficiency is enhanced, the design may not be practical for global real-world aircraft applications (Sobieszcanski-Sobieski & Haftka, 1997). Furthermore, studies in transonic and supersonic regimes show that optimized airfoil geometries are sensitive to small changes in airflow conditions (García, 2025). These include alterations in Mach number, Reynolds number, and angle of attack. Small variations in these parameters can significantly change shock-wave formation, boundary layer behaviour, and flow separation. Due to this, there is inconsistent performance through the different flight regimes

the aircraft has passed through to attain transonic Mach numbers. There is also inconsistency across different flight and weather conditions (García, 2025). Research focusing on supercritical airfoils with specific thickness ratios, such as the 10%-thick supercritical airfoil, further illustrates this variability. Even though these optimized airfoils outperform conventional airfoils specifically in transonic flow, the aerodynamic advantages depend heavily on precise operating conditions. In some cases, shock-induced flow separation can occur if the pressure recovery region is not optimized properly (Harris, 1975). Together, these findings indicate that while optimization improves aerodynamic efficiency, the magnitude and reliability of these improvements are not always universal (García, 2025; Harris, 1975; Sobieszcanski-Sobieski & Haftka, 1997).

Even though extensive research on both supercritical and symmetrical airfoil geometry optimization has been conducted over the decades (Leite et al., 2022; Sobieczky & Seebass, 1984; Whitcomb & Clark, 1965), a clear and significant gap remains in the literature. Existing research usually analyses both of these airfoils independently for the transonic regime. Supercritical airfoils are typically investigated only as transonic-optimized geometries (Harris, 1975; Sobieczky & Seebass, 1984; Whitcomb & Clark, 1965), while symmetrical airfoils are generally used as a baseline configuration for computational optimization (Chen & Agarwal, 2014; Leite et al., 2022; Ntantis & Xezonakis, 2024). Therefore, there is a lack of direct comparative analysis between the optimized airfoil geometries in the compressible flows of the transonic flight regime. The absence of this comparison makes it difficult to understand the relative extent to which each airfoil type benefits from optimization in terms of improvement in aerodynamic performance. Addressing this gap is essential for determining the comparative effectiveness of airfoil optimization strategies in the transonic regime, and it forms the central motivation and focus of this research.

3. METHODOLOGY

This study uses a secondary data analysis approach to understand the extent to which the optimization of supercritical and symmetrical airfoils improves aerodynamic efficiency in the transonic flight regime. The transonic flight regime is characterised by

compressible flow, shock-wave formation, and flow separation. This makes it a critical region for airfoil performance evaluation. This research is based on previously published Computational Fluid Dynamics (CFD) results, experimental data, and aerospace studies, instead of conducting original experiments or computational simulations (Harris, 1975; Leite et al., 2022; Whitcomb & Clark, 1965).

Sources were gathered using Google Scholar and NASA Technical Reports. Papers from peer-reviewed aerospace engineering journals were prioritised. Primary focus was given to studies related to airfoil optimization, transonic flow, and supercritical and symmetrical airfoils. Search terms included combinations of: “transonic airfoil optimization”, “Supercritical airfoils in the transonic regime”, “Symmetrical airfoils in transonic flow”, and “Supercritical and symmetrical airfoil optimization”. These search terms were selected to ensure coverage of both airfoil categories under similar aerodynamic conditions.

Sources were selected across a wide time range, including foundational NASA transonic research from the 1960s–1970s (Whitcomb & Clark, 1965; Harris, 1975; Hicks & Henne, 1978) and more recent CFD studies up to 2025 (Leite et al., 2022; Ntantis & Xezonakis, 2024). Ten sources were selected for detailed analysis and citation. Source inclusion was based on whether the source was credible, accurate, and relevant. Most sources were taken from peer-reviewed journals or university groups or aerospace institutions. The sources were chosen to address all the criteria stated above. The literature was analysed using a thematic approach, which grouped findings into 3 major categories: agreement, complication, and research gaps. This allowed for a structured comparison of how different studies describe the effects of airfoil optimization on aerodynamic efficiency.

This method was chosen because it acknowledges findings across multiple independent studies rather than relying on a single dataset. After analysing results from both historical NASA research and modern computational studies, consistent aerodynamic trends can be identified while also highlighting contradictions and limitations in the literature.

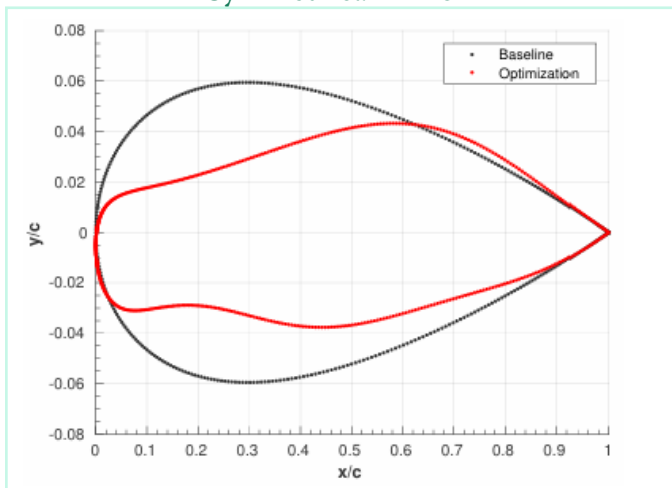
However, a key limitation of this approach is that it relies entirely on previously published data. This means that the differences in the setups of different simulations may affect direct comparability of results. There could be differences in Reynolds number, turbulence models, and boundary layer conditions between studies. Furthermore, the absence of original CFD simulations limits the ability to control experimental conditions directly.

4. RESULTS AND DISCUSSION

This research investigated the extent to which the optimization of symmetrical and supercritical airfoils improves aerodynamic efficiency in the transonic flight regime. The findings indicate that airfoil optimization significantly improves aerodynamic efficiency by reducing the drag coefficient, lowering the adverse extent of shock waves, and enhancing pressure recovery (Leite et al., 2022; Ntantis & Xezonakis, 2024; Whitcomb & Clark, 1965).

4.1 Symmetrical Airfoil Optimization Results

The airfoil NACA 0012 was analysed in this study. The airfoil exhibited comparatively poor performance in its baseline configuration in the transonic flight regime. At Mach 1.0, it generated a drag coefficient of 0.1113 while producing negligible lift. This behaviour is caused by the formation of strong shock waves on the airfoil surface, which increases wave drag and decreases aerodynamic efficiency (Leite et al., 2022). Substantial improvements were found after optimization. The drag coefficient reduced to 0.0673 and the lift coefficient increased to 0.20. This corresponds to a reduction in drag by approximately 39.5%. The optimized design also produced a lift-to-drag ratio of 2.97. This is a significant improvement compared to the baseline configuration (Leite et al., 2022).

Fig. 3: Baseline and Optimized NACA 0012 Symmetrical Airfoil

Source: Adapted from Leite et al. (2022).

This value should be interpreted in context. A lift-to-drag ratio of 2.97 is considerably below the range typical of cruise airfoils, reflecting the severity of wave drag at sonic conditions rather than a deficiency in the optimization. The relevant comparison is against the baseline configuration under identical conditions, not against performance at subsonic speeds.

These performance gains were mainly attributed to

geometric optimization. Leite et al. (2022) describe the optimized geometry as having a leading edge that extends outward before curving inward, with the point of maximum thickness displaced rearward toward the trailing edge. Both early and recent research show that using genetic algorithms and adjoint-based optimization can reduce drag on transonic airfoils while meeting necessary aerodynamic requirements. These studies show that optimized NACA 0012 airfoils achieve smoother pressure distributions and better overall performance by controlling shock waves effectively (Chen & Agarwal, 2014; Lee & Jang, 2008; Ntantis & Xezonakis, 2024).

An adjoint-based optimization study of the NACA 0012 airfoil demonstrated convergence to a drag coefficient of 0.00871 after 96 optimization iterations. This corresponded to a 62.2% reduction in drag compared to previously optimized designs (Ntantis & Xezonakis, 2024). Even though the operating conditions and optimization objectives are different from those of the current study, both investigations show that geometric optimization can greatly enhance transonic performance through improved shock-wave control and pressure distribution.

Table 1: Comparison of Baseline and Optimized NACA 0012 Symmetrical Airfoil Performance

Parameter	Baseline NACA 0012	Optimized NACA 0012
Flight regime	Transonic	Transonic
Mach number	1.00	1.00
Altitude (km)	10	10
Temperature (K)	223.25	223.25
Reynolds number	8.49×10^6	8.49×10^6
Lift coefficient (Cl)	0.00	0.20
Drag coefficient (Cd)	0.111338	0.067349
Lift-to-drag ratio (L/D)	Not applicable (CL = 0)	2.97
Drag reduction	—	39.5%
Leading edge	Rounded	More streamlined
Maximum thickness location	$x/c \approx 0.30$	Shifted aft
Shock strength	Strong	Reduced
Wave drag	High	Lower
Overall performance	Limited transonic performance	Significantly improved transonic performance

Source: Adapted from Leite et al. (2022).

4.2 Supercritical Airfoil Optimization Results

The reviewed NASA studies showed that supercritical airfoils were specifically developed to address the challenges associated with transonic flight (Harris, 1975; Whitcomb & Clark, 1965). One key finding was reported in Whitcomb's supercritical airfoil research. The supercritical airfoil increased the drag-divergence Mach number from approximately 0.67 for a conventional airfoil to approximately 0.79. This represents an absolute increase of 0.12 in drag

divergence Mach number, a relative improvement of approximately 18% (Whitcomb & Clark, 1965). This allows airfoils to operate at much higher speeds before experiencing a rapid increase in drag.

Unlike conventional airfoils, supercritical airfoils feature a flattened upper surface, increased aft camber, and a rearward thickness distribution (Sobieczky & Seebass, 1984). These geometric characteristics produce a more favourable pressure

distribution over the airfoil surface, which allows the flow to accelerate and decelerate more gradually. As a result, shock waves are weaker, wave drag is reduced, and drag divergence occurs at higher Mach numbers (Harris, 1975; Sobieczky & Seebass, 1984; Whitcomb & Clark, 1965).

Additional NASA studies comparing the supercritical Airfoil 12 and Airfoil 31 further demonstrated the benefits of geometric refinement within supercritical airfoil designs. Airfoil 31 showed lower cruise drag and reduced drag creep while maintaining similar lift characteristics, indicating that even small modifications to supercritical airfoil geometry can produce measurable improvements in aerodynamic performance (Harris, 1975).

Table 2: Comparison of Conventional and Supercritical Airfoil Characteristics in Transonic Flight

Parameter	Conventional (NACA 64A)	Supercritical
Thickness ratio (%)	13.5	13.5
Typical cruise Mach number	0.75–0.78	0.78–0.85
Reynolds number	$\approx 1 \times 10^7$	$\approx 1 \times 10^7$
Drag-divergence Mach number	0.67	0.79
Lift coefficient	0.65	0.65
Drag coefficient	Higher	Lower
Lift-to-drag ratio	Lower	Higher
Shock strength	Strong	Reduced
Boundary-layer separation	Significant	Reduced
Wave drag	High	Low
Pressure recovery	Abrupt	Gradual
Pressure distribution	Non-uniform	More uniform
Upper surface	Highly curved (cambered)	Flattened
Maximum thickness location	Forward	Shifted aft
Transonic performance	Moderate	Improved

Note: Exact drag and lift-to-drag ratio values were not reported in the reviewed studies. Therefore, qualitative comparisons are presented based on the reported aerodynamic trends.

Source: Adapted from Whitcomb & Clark (1965), Harris (1975), and Sobieczky & Seebass (1984).

4.3 Comparison Between Symmetrical and Supercritical Airfoils

The reviewed studies indicate that optimization improves the aerodynamic efficiency of both symmetrical and supercritical airfoils in the transonic flight regime. However, the extent of improvement is measured using different aerodynamic parameters in each case. This is because the studies evaluated different airfoil configurations and optimization objectives (Leite et al., 2022; Whitcomb & Clark, 1965).

For the symmetrical NACA 0012 airfoil, optimization

resulted in a reduction in drag coefficient from 0.1113 to 0.0673, corresponding to a drag reduction of approximately 39.5%. The optimized airfoil also generated a lift coefficient of 0.20, compared with negligible lift in the baseline configuration. These results suggest that geometric modifications can significantly improve the transonic performance of a symmetrical airfoil (Leite et al., 2022; Ntantis & Xezonakis, 2024).

For supercritical airfoils, the studies reported improvements through delayed drag divergence, reduced wave drag, and weaker shock-wave formation. Whitcomb’s supercritical airfoil increased the drag-divergence Mach number from approximately 0.67 to 0.79. This represented an improvement of nearly 18%. Additional NASA studies also reported lower cruise drag and reduced drag creep after further refinements to supercritical airfoil geometry (Harris, 1975; Whitcomb & Clark, 1965).

A further constraint on direct comparison concerns the baselines against which improvement is measured. The symmetrical airfoil studies compare an unmodified NACA 0012 against an optimized variant of the same geometry, isolating the effect of the optimization process itself. The supercritical literature, by contrast, compares a conventional airfoil against a supercritical airfoil, isolating the effect of a different design philosophy. These are not equivalent operations. The reported improvements therefore describe different quantities: the symmetrical figure represents the gain attributable to optimizing a fixed geometry, while the supercritical figure represents the gain attributable to adopting a different geometry altogether. A direct numerical comparison would be misleading, so we discussed the two findings separately in Sections 4.1 and 4.2 above.

Although direct quantitative comparison between the two airfoil categories is limited because the studies were conducted under different operating conditions and used different performance metrics, qualitative comparison remains possible as both airfoil types showed measurable improvements in aerodynamic efficiency following optimization. A common trend observed across the reviewed literature was that geometric modifications changed the pressure distribution around the airfoil, resulting

in weaker shock waves, reduced wave drag, and improved pressure recovery (Harris, 1975; Leite et al., 2022; Ntantis & Xezonakis, 2024; Whitcomb & Clark, 1965).

Overall, the reviewed evidence indicates that optimization substantially enhances the aerodynamic efficiency of both symmetrical and supercritical airfoils, although the improvements are expressed

through different aerodynamic performance metrics. These findings suggest that shock-wave control is a key mechanism through which airfoil optimization improves aerodynamic efficiency in the transonic flight regime. Regardless of airfoil type, designs that reduced the adverse effects of shock-wave formation generally exhibited improved aerodynamic performance (Chen & Agarwal, 2014; Harris, 1975; Leite et al., 2022; Whitcomb & Clark, 1965).

Table 3. Comparative Summary of Symmetrical and Supercritical Airfoil Optimization

Parameter	Optimized NACA0012	Supercritical Airfoil
Primary objective	Reduce drag at Mach 1.0	Delay drag divergence during transonic cruise
Typical operating Mach number	1	0.80–0.85
Representative lift coefficient	0.2	0.65
Typical drag coefficient	0.07	~0.012–0.020
Main geometric feature	Thinner leading edge, aft thickness	Flattened upper surface, aft camber
Shock-control method	Reduced shock strength	Shock-free or weak-shock recompression
Pressure recovery	Improved	More gradual
Primary aerodynamic benefit	39.5% drag reduction	18% increase in drag-divergence Mach number

Source: Compiled and adapted from Leite et al. (2022), Whitcomb & Clark (1965), Harris (1975), Sobieczky & Seebass (1984), Ntantis and Xezonakis (2024), and Chen & Agarwal (2014).

5. CONCLUSION

This study set out to examine the extent to which the optimization of supercritical and symmetrical airfoils improves aerodynamic efficiency in the transonic flight regime. The findings suggest that optimization significantly improves aerodynamic performance in both types of airfoils. However, the benefits are expressed using different aerodynamic performance measures (Leite et al., 2022; Whitcomb & Clark, 1965).

The reviewed literature for Whitcomb's supercritical airfoil showed that optimization increased the drag divergence Mach number by 18%. Airfoil 31 showed lower cruise drag and reduced drag creep while maintaining similar lift characteristics. As for the NACA 0012 symmetrical airfoil, optimization reduced drag by approximately 39.5% (Harris, 1975; Leite et al., 2022; Whitcomb & Clark, 1965).

The key findings of this study are threefold. First, optimization greatly enhanced the performance of the symmetrical airfoil by reducing drag and enhancing lift characteristics. Second, supercritical airfoils showed good transonic performance through improved shock-wave formation control and delay of sharp drag increase. Third, despite having completely different shapes, both airfoil shapes benefited from

the same aerodynamic principles: modification of the pressure distribution to reduce the negative effects of shock waves (Harris, 1975; Leite et al., 2022; Ntantis & Xezonakis, 2024; Whitcomb & Clark, 1965).

This review does not claim to have established a direct quantitative comparison between the two airfoil categories, which the available literature does not support. Its contribution is threefold: it synthesizes optimization findings for both geometries within a single analytical framework, identifies shock-wave control as the shared physical mechanism underlying both approaches, and specifies why direct comparison remains unavailable. That final point defines what future work must address, namely the evaluation of both geometries under standardized operating conditions with consistently reported performance metrics.

However, this study is not without its limitations. This research completely relied on previously published data. It did not include original CFD simulations and experimental testing. Also, the differences in experimental conditions and evaluation methods between studies limited direct quantitative comparison.

Future research should explore both airfoils under

identical experimental conditions using a common methodology. Such studies would offer greater direct comparison of their aerodynamic characteristics and ultimately advance our knowledge of airfoil optimization in the transonic flight regime.

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