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The Impact of Shock Wave Control on the Structural Design of Supersonic Aircraft

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Abstract. Aviation technology keeps developing, so supersonic aircraft have become a key research focus. This is because they have advantages in efficiency and speed. However, the shock waves from supersonic flight cause problems. They increase aerodynamic drag and also bring intense heat and complex structural responses. These factors significantly affect the flight safety and performance. This paper studies the causes of shock waves during supersonic flight. It also covers the effects these waves have on the plane's air movement, heat stress, and body structure. Additionally, the research looks at how to make aircraft fly better by changing the outer shape. This work also reviews shock wave control methods, like active and passive control. By reviewing and analyzing relevant literature, combined with current research findings in aerodynamics, thermodynamics, and structural mechanics, it delves into the shock wave mechanisms, load characteristics, and their influences on the structural design of supersonic aircraft. The results demonstrate that shock waves hurt how supersonic planes fly; they increase heat and cause problems with the plane's structure. In addition, changing the shape and using ways to manage the shock waves, like using active and passive control, makes things better. This lowers the forces on the plane, evens out the pressure, and cuts down on shaking, which means better safety and performance.

Keywords: Supersonic Aircraft, Shock Wave Control, Aerodynamic Performance, Thermal Load, Structural Optimization

1. Introduction

Aerospace technology is developing quickly, so supersonic aircraft have become a major research hotspot. They have clear advantages, like breaking the sound barrier, increasing flight speed, and potentially reducing operational costs. But the shock waves from supersonic flight cause significant problems. They increase the aircraft's drag, thermal loads, and structural vibrations, plus they create the sonic boom effect. These issues limit their widespread application. People have made progress in aerodynamic design and structural optimization. Also, traditional shock wave control methods, such as aerodynamic shape optimization and active/passive control, can reduce drag and optimize thermal loads a little bit. But there is still not enough research on how shock waves impact the structures and how to use that knowledge in structural optimization. This gap is especially clear in the challenge of balancing strength, stiffness, and lightweight design, which remains a key problem.

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Thus, this paper investigates the load effects, thermal effects, and vibration responses caused by shock waves on the aircraft structure. It also explores structural optimization strategies based on aerodynamic optimization methods. By reviewing existing research, this paper helps to understand how optimization design can reduce the impact of shock waves on supersonic aircraft.

2. The characteristics of shock waves in supersonic aircraft

2.1. The mechanism of shock wave formation

The concept of shock waves was first introduced by Riemann B. in 1859, defined as a disturbance that gradually becomes sharper during propagation as a result of the compression of the wavefront, eventually leading to the formation of a shock wave. These waves usually appear when the flow speed is faster than the speed of sound and cannot travel like simple, straight waves. Instead, they show up as a sudden, sharp rise in pressure [1]. Shock waves fall into groups based on the fluid type and the object's shape [2]. These types are normal, oblique, detached, and conical shock waves. A normal shock wave forms when the moving air hits the object straight on. This creates sharp rises in pressure and temperature. In contrast, an oblique shock wave appears when the air hits the object at an angle; these waves are usually less strong. However, shock waves bring several problems for aircraft parts [3]. These include trouble with the engine air intake, the plane's skin getting too hot, loud sonic booms, and more flight drag. In fact, shock waves not only threaten the safety of aircraft but can also reduce flight speed and stability.

2.2. The characteristics of shock wave loads

Shock waves hurt plane structures mainly through their strength, how sharp they are, and how they change. When a shock wave hits the plane's surface, it suddenly jumps in pressure, which makes a lot of dynamic force. The way this shock force spreads is usually not even; the pressure is highest near where the shock starts, and it gets lower farther away. Besides, the shock wave's power and position can shift as the plane's speed and air conditions change. And this causes the force on the structure to be unstable. More specifically, the impact of shock waves differs across various aircraft components. The leading edges of the wings and the nose are the most susceptible to shock wave impacts, frequently experiencing higher localized pressures. This concentration of pressure can amplify stress in specific areas, potentially resulting in localized fatigue and structural damage. The plane's main body and tail, by contrast, have pressure that is more spread out and with lower high points. Therefore, the parts need different design and material choices to deal with these pressure changes. And shock waves also cause fast, small shaking (vibrations) in the structure. This happens mostly because the shock waves are not stable and the air forces keep changing in a cycle. This shaking can make the structure wear out and break faster, especially when the plane flies very fast. To lessen this shaking, engineers use tools like modal analysis to predict and fix the vibration patterns. This helps make sure the final design is as good as possible.

2.3. The structural response to shock waves

Under the influence of shock wave loads, the aircraft structure exhibits a complex response. First, the shock wave generates extremely high peak pressures, which require the aircraft's load-bearing components to have adequate strength and rigidity to endure the static deformations and possible damage induced by these pressures. Especially in the peak pressure regions, where the air is almost stationary and the pressure is at its maximum, materials must possess higher compressive strength.

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At the same time, the high-gradient pressure from the shock wave causes an extremely uneven load distribution, resulting in excessive localized pressure on certain components. The influence on the engine is particularly significant, especially at the intake, where airflow vibrations create pressure variations that can harm internal engine components, such as blades, ultimately compromising the engine's overall performance. Moreover, unstable shaking is a main reason for structural vibrations in planes. This shaking starts because the shock wave is not steady and the air forces keep changing in a cycle. This problem makes structural wear worse and causes metal parts to break down faster. Especially during high-speed flight, this shaking creates changing forces inside the plane's structure, which raises the chance of damage. During transonic flight (speeds near the speed of sound), shock waves sometimes form only in certain spots on the wing. These waves then act with the air layer close to the surface (the boundary layer). This action can cause more shaking and shape changes, which threatens the plane's ability to stay steady.

3. Shock wave control technologies and aerodynamic effects

3.1. Aerodynamic shape optimization design

In supersonic aircraft design, aerodynamic shape optimization is a key technology, commonly used to reduce shock wave effects. By precisely adjusting the shape of the aircraft's surface, such as employing a high-sweep wing or sharp leading edges, the compression of supersonic airflow can be significantly altered, reducing the negative effects of shock waves on the aircraft. Specifically, the optimization of the wing shape can guide the airflow to form oblique shock waves, thus replacing normal shock waves, which effectively reduces the drag caused by shock waves. For example, the design of a swept-wing helps delay the formation of shock waves, while lowering the effective Mach number in front of the wing, thus reducing the intensity of the shock wave and slowing its propagation. However, this optimization also introduces new challenges. Taking the swept-wing design as an example, although it performs well in weakening the impact of shock waves, it often reduces the lift of the wing, affecting the aircraft's takeoff and landing performance. Particularly in low-speed and high-maneuverability flight phases, this can compromise the aircraft's controllability and stability [4].

3.2. Active control intervention methods

Active control is an advanced method employed to manage how shock waves start and travel by changing the air flow around the plane. And the main idea is simple: engineers move internal parts or change their state to affect how steady the air flow is. This stops shock waves from forming. Common methods for this include changing the engine exhaust/inlet and using energy injection.

Firstly, the exhaust/inlet technique involves creating openings before and after the shock wave formation region, utilizing suction to remove the low-energy boundary layer. This delays airflow separation and stabilizes the position of the shock wave, reducing shock wave oscillations. While this method is effective in controlling shock waves, it requires extensive piping, pumps, and circuits to transport fuel and control components, thus inevitably increasing the aircraft's weight and fuel consumption. Additionally, energy injection technology involves injecting plasma or using lasers to heat the air in key areas, altering airflow characteristics to weaken or change the structure of shock waves. This method offers greater flexibility and can be adjusted in real-time according to flight conditions, making it more efficient in certain situations. However, it requires additional energy input, leading to increased fuel consumption, and the system's complexity is higher. Consequently,

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while both methods help manage shock waves, they also have clear limits. The exhaust/inlet method makes the plane more complex and heavier. Also, energy injection needs more power. For this reason, when using these methods, engineers must consider the effect on how the plane flies and how much fuel it uses, based on the specific need [5].

3.3. Passive control improvement methods

Passive control technology lessens the effect of shock waves on the structure by making the plane's design better. This mainly includes making the outer shape as good as possible and designing parts to block shaking.

For the outer shape, changing it improves how the plane moves through the air, which cuts down the shock wave's strength. The other method, blocking shaking, adds soft materials or structures that dampen in specific directions. This reduces the fast, small shaking caused by shock waves. This fast shaking is a big risk to the plane, mainly at key spots like the wing base, body supports, and tail parts. By using materials like damping pads, honeycomb structures, or mixed materials, these designs take in and use up the shaking energy. This lowers the effect of shaking on structural wear. This action not only makes the plane last longer but also helps stop cracks started by the shock waves from spreading.

Though passive control technologies offer significant advantages in reducing the effects of shock waves, they also have certain limitations. For example, changing the shape of the plane can make shock waves weaker. Engineers do this by making the wings sweep back more or by adding sharper front edges. However, making the shape too good can hurt other important parts of how the plane flies. Lift (the upward force), for instance, may go down because the wing angle is smaller. The plane's ability to turn and control may become worse, often because the point where the air forces act (center of pressure) or its stability limits have changed. Besides, while the blocking-shaking design cuts down on vibrations, it may also make the structure heavier and more complex. For this reason, during the design stage, engineers must find a good balance between making the plane fly better and making it heavier. This ensures the plane works best across all key measures [6].

4. The impact of shock wave control on structural efficiency and durability

4.1. Aerodynamic design and weight reduction

By optimizing aerodynamic performance, shock wave control technologies play a crucial role in significantly enhancing the structural efficiency of aircraft, especially through the reduction of peak pressures and the optimization of pressure gradients. And this optimization leads to a more uniform distribution of loads, which minimizes localized stress concentrations and, in turn, reduces the overall weight of the aircraft structure. Specifically, making the outer shape better cuts down the plane's weight. Engineers do this by making the outside layer thinner, setting up the internal ribs in the best way, and removing extra parts that make the plane too stiff. This helps the structure use its material better and carry its loads well.

The main emphasis of aerodynamic shape optimization is on modifying the aircraft's surface contours, such as the wing's angle of sweep, the streamlined fuselage design, and the sharpness of the leading edges. These design features effectively reduce shock wave intensity and local pressures, lowering structural demands. Moreover, they enable further reduction in the thickness of structural components (such as skins and ribs) without compromising the aircraft's strength or stability. This optimization reduces the aircraft's drag and enhances the potential for structural lightweighting [7].

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Furthermore, shock wave control technologies increase the potential for structural lightweighting by optimizing the aircraft's load distribution and thermal management. Through the application of techniques such as topology optimization, designers can rearrange materials according to new load paths, achieving further weight reduction without sacrificing performance. The use of advanced, mixed materials, especially carbon fiber (CFRP) and ceramic composites (CMC), helps to keep the forces on the structure and the material quality in check during shock wave control. These strong materials cut down the plane's weight a lot. And they also stay strong and stiff even in very harsh conditions, which makes the plane last longer and be safer [8].

4.2. Fatigue reduction and durability enhancement

The technologies for shock wave control, particularly through passive and active control methods to reduce oscillations induced by shock waves, can significantly decrease high-frequency vibrations and flutter responses in the structure. Passive control methods, such as the use of damping materials like viscoelastic materials and composites, effectively absorb vibration energy, thereby reducing the amplitude of alternating stresses and minimizing fatigue accumulation. By contrast, active control technologies, like shape memory alloys and piezoelectric actuators, dynamically adjust the vibration modes of the structure, effectively reducing vibration amplitudes and extending the fatigue life of the structure.

Methods for checking how long a part will last (fatigue life analysis), like rainflow counting and Miner's rule, are widely used to guess how vibration control affects the structure's life. By using these methods, engineers can measure how much damage builds up in the structure when shaking is small. This helps to figure out the fatigue life of the structure. For example, through low-amplitude vibration control, the number of loading cycles in the structure is greatly increased, preventing fatigue failure caused by frequent vibration fluctuations. Also, guessing the life span correctly gives a good base for the initial design. This also makes the structure's long-term safety and ability to last much better.

In practical scenarios, especially in the design of high-speed aircraft and spacecraft, controlling the strength and distribution of shock waves effectively reduces localized stress concentrations caused by high-frequency oscillations. This, in turn, helps prevent the formation of fatigue cracks in high-stress areas [9]. These technical measures significantly lower material fatigue damage and wear rates, reduce structural maintenance frequency and repair costs, and further enhance the overall life cycle efficiency of the system [10].

5. Conclusion

This paper investigates the critical role of shock wave control technology in the structural design of supersonic vehicles. Accordingly, the results indicate that through aerodynamic shape optimization, active and passive control techniques, shock wave control can effectively reduce structural loads, optimize aerodynamic performance, and markedly improve durability and reliability. Shock wave control helps to distribute pressures across the structure, mitigate vibrations, and, by optimizing material selection and structural layout, reduce the overall weight of the aircraft, while enhancing its strength and fatigue life. However, there are still limits to using these methods in real planes. This includes problems with making them work, how well different technologies work together, and the need to prove the results with test data. Future research should focus on better mixing shock wave control with the plane's other design needs. This means specifically using smart materials and

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control technologies, and also putting together design frameworks that cover many different fields. This will make the overall performance and design of fast planes much better.

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