Supersonics Introduction

Fan Lok Kong

1 Overview

1.1 Supersonic

The term "supersonic" refers to any speed that is greater than the speed of sound. In dry air at a temperature of 20 degrees Celsius, the speed of sound is approximately 343 meters per second, or 1,235 kilometers per hour (767 miles per hour). Speeds are often categorized as follows:

- Subsonic: Speeds less than the speed of sound
- Transonic: Speeds around the speed of sound (approximately Mach 0.8-1.2), where some parts of the airflow over an aircraft are subsonic and others are supersonic
- Supersonic: Speeds greater than the speed of sound but less than five times the speed of sound (Mach 1-5)
- Hypersonic: Speeds more than five times the speed of sound (Mach 5+)

A supersonic commercial aircraft is a type of passenger plane that is capable of flying at supersonic speeds. The most famous example of such an aircraft is the Concorde, which was operated by British Airways and Air France. The Concorde could fly at speeds of over Mach 2, more than twice the speed of sound, and it could carry up to 120 passengers. This enabled it to cross the Atlantic Ocean in less than half the time of a conventional aircraft.

1.2 History

1.2.1 Concorde

The first and most iconic supersonic commercial aircraft was the Concorde. It was developed and produced as a collaboration between the British Aircraft Corporation (BAC) of the United Kingdom and Aerospatiale of France. The Concorde made its maiden flight in 1969 and entered commercial service in 1976. With the capability to travel at speeds exceeding Mach 2, the Concorde significantly reduced travel time between London and New York to less than three and a half hours, compared to the typical eight hours required for subsonic flights. This garnered the Concorde a reputation for luxury and attracted affluent passengers.

Nevertheless, the Concorde encountered several noteworthy challenges throughout its operational years:

- Noise Pollution:
  Breaking the sound barrier resulted in a sonic boom, leading to flight path restrictions. Overland supersonic flights were largely prohibited due to the noise, limiting the Concorde's routes primarily to transatlantic journeys.
- Fuel Consumption and Cost:
  The Concorde exhibited poor fuel efficiency compared to subsonic aircraft, resulting in high operating costs and expensive ticket prices. Consequently, its market appeal was largely confined to luxury travel.
- Environmental Concerns:
  The Concorde faced criticism for its environmental impact, including noise pollution from sonic booms and high emissions resulting from its fuel consumption.
- Accidents:
  While the Concorde maintained a generally good safety record, a high-profile crash near Paris Charles de Gaulle Airport in 2000 resulted in 113 fatalities and damaged the aircraft's reputation.
- Economic Conditions:
  The economic downturn following the 9/11 attacks in 2001 caused a decline in demand for luxury air travel, negatively affecting the profitability of the Concorde.
- Maintenance Costs:
  As the Concorde aged, the expenses associated with its maintenance escalated. Coupled with other factors, this ultimately led British Airways and Air France to retire the Concorde in 2003.

Despite these challenges, the Concorde remains an iconic symbol in the history of aviation. It is recognized for its technical achievements and the luxurious travel experience it provided. Its ability to fly at speeds exceeding twice the speed of sound enabled it to complete transatlantic journeys in significantly less time than conventional aircraft.

Figure 1: Concorde[2]

1.2.2 Tupolev Tu-144

Around the same time, the Soviet Union also developed a supersonic commercial aircraft, the Tupolev Tu-144. This aircraft entered commercial service before the Concorde in late 1975, but it had a short-lived career due to several issues and was permanently withdrawn from passenger service by 1978.

The Tupolev Tu-144 encountered significant problems during its development and operational history:

- Technical Problems:
  The Tu-144 experienced numerous technical issues. Its engines were prone to failures, and the airframe had a shorter lifespan compared to the Concorde. Additionally, the aircraft had limited range, limiting its operational capabilities.

- Safety Concerns:
  Several accidents occurred during the Tu-144's development and operational lifespan, raising serious safety concerns. One notable incident was a crash at the 1973 Paris Air Show, resulting in the death of all six crew members and eight individuals on the ground.

- Noise and Comfort:
  The Tu-144 was reputed to be louder and less comfortable than the Concorde. It also provided a rougher ride at supersonic speeds.

- Economic Viability:
  Similar to the Concorde, the Tu-144 was not economically viable. It consumed significant amounts of fuel and required frequent maintenance, leading to high operational costs.

- Political and Economic Factors: The development and operation of the Tu-144 coincided with a period of economic and political change in the Soviet Union. It is believed that national pride and a desire to compete with the West played a larger role in the decision to proceed with the project than economic considerations.

These challenges combined to result in a very short operational life for the Tu-144. The aircraft commenced passenger service in 1977 but was withdrawn just a year later, in 1978. Subsequently, the Tu-144 primarily served for cargo and test flights before being completely retired in the mid-1980s.

Figure 2: TU-144[1]

1.3 Challenges

The creation of a commercially viable supersonic aircraft presents a multitude of formidable challenges:

- Aerodynamics and Heat Management:
  Supersonic flight entails rapid aerodynamic heating as an aircraft surpasses the speed of sound. This heightened air friction leads to substantial heat buildup on the aircraft's surface. Proper management of this heat is crucial to prevent structural weaknesses or melting of materials. Additionally, the aircraft's design must accommodate the diverse aerodynamic forces experienced at high speeds, necessitating an aerodynamically efficient shape capable of withstanding the generated heat.

- Engine Design:
  Supersonic aircraft demand engines capable of delivering robust thrust and operating efficiently across both subsonic and supersonic speeds. Designing and

developing such engines pose significant technical hurdles. Moreover, these engines must endure the extreme temperatures associated with supersonic flight while adhering to noise and emissions standards.

- Sonic Boom Mitigation:
  Sonic booms, the pressure waves formed when an aircraft exceeds the speed of sound, can be disruptive and potentially damaging to ground structures. Mitigating these sonic booms is crucial to comply with noise regulations and enable supersonic flights over land. Advancements in aircraft design are necessary to mitigate the formation of these pressure waves and minimize their impact.

- Fuel Efficiency and Emissions:
  Supersonic flight demands substantial energy consumption, resulting in high fuel usage. This not only escalates operating costs but also contributes to elevated carbon dioxide (CO_2) emissions, exacerbating climate change concerns. Additionally, the combustion processes within supersonic engines produce significant amounts of nitrogen oxides (NOx) emissions, which further contribute to environmental pollution. Developing advanced engine designs, combustion technologies, and alternative fuels is vital to enhance fuel efficiency and reduce emissions.

- Environmental Impact:
  Supersonic flight may have broader environmental implications. For instance, flying at high altitudes can lead to increased emissions of water vapor and other gases in the stratosphere, potentially affecting the ozone layer. Comprehensive understanding and mitigation of the environmental effects of supersonic flight are essential to comply with environmental regulations and address climate change concerns.

- Regulatory Approval:
  Regulatory bodies, such as the Federal Aviation Administration (FAA), have established stringent rules governing supersonic flight, especially over populated areas. These regulations encompass noise levels, safety standards, and environmental impact. Securing regulatory approval for a new supersonic aircraft necessitates comprehensive testing and validation to demonstrate compliance with these regulations.

- Safety:
  Safety is of paramount importance in supersonic flight, requiring meticulous attention to all aspects of aircraft design and operation. From ensuring the structural integrity of the airframe to guaranteeing the reliability of onboard systems, every facet must meet rigorous safety standards. Emergency procedures, such as rapid decompression or engine failure, become more intricate at supersonic speeds and demand meticulous planning and execution.

- Cost of Development and Operation:
  The development of a supersonic aircraft entails substantial costs due to the sophisticated technologies and materials involved. Once operational, the aircraft's high fuel consumption, maintenance expenses, and other operational overheads can pose challenges to achieving profitability. Innovative solutions are essential

to mitigate these economic challenges, reduce costs, and enhance operational efficiency.

- Market Demand:
  Even with a technically advanced supersonic aircraft, successful operations require sufficient market demand to ensure economic viability. Factors such as ticket prices, the perceived value of time saved for potential passengers, route availability for supersonic flights, and competition with other modes of travel all influence market demand. Understanding and accurately forecasting market dynamics necessitate careful analysis of the potential customer base and the competitive landscape.

2 Terminology

2.1 Shockwave

A shock wave is a type of propagating disturbance or wave. It occurs when a wave moves faster than the local speed of sound in a medium, such as a gas or liquid. It is characterized by a sudden compression of the medium, leading to a large amplitude wave. Shock waves carry significant energy and can propagate through various materials, including solids. They cause an almost instantaneous, abrupt change in pressure, temperature, and density of the medium they travel through.

Here are a few key points about shock waves:

- Formation: Shock waves can be generated by explosions, rapid pressure changes, seismic activity, or objects surpassing the speed of sound. For example, supersonic aircraft compress the air in front of them, creating a shock wave.
- Speed: Shock waves travel faster than the speed of sound, with their velocity depending on the properties of the medium and its conditions.
- Physical Impact: Shock waves can cause disturbances and damage when interacting with other objects. Explosions create shock waves that can be destructive, and supersonic aircraft produce sonic booms, which are a type of shock wave.

2.2 Sonic Boom

A sonic boom is a loud sound kind of like an explosion that's associated with the shock waves created by any object that travels through the air faster than the speed of sound. Sonic booms generate a lot of energy, sounding much like an explosion to the human ear.

As an object, like an aircraft, moves through the air, it generates pressure waves both ahead and behind it. These waves move outward from the object at the speed of sound. If the object's speed is less than that of sound, these pressure waves continue to propagate forward. However, when the object surpasses the speed of sound, approximately 767 miles per hour or 1235 kilometers per hour at sea level, it outpaces these pressure waves.

As the supersonic object continues to move, the pressure waves from its consecutive positions start to overlap and compress together due to their inability to escape each other quickly enough. This results in the formation of a single, intense shock wave on either side of the object. The pressure directly behind the object sharply increases, then decreases, eventually returning to the normal level, culminating in the "boom" sound – the sonic boom.

This sonic boom isn't a one-off event occurring at the moment the object breaks the sound barrier, nor is it uniformly heard in all directions from the object. Instead, the shock wave forms a narrow, cone-shaped "boom carpet" that spreads across the landscape along the path of the flight. As the object travels, this continuous sonic boom follows, effectively shadowing its path.

For an observer on the ground, the sonic boom is experienced as a rapid, explosive noise when the boom carpet passes over their location. Often, this is perceived as a loud double "boom" because the booms from the front and the tail of the aircraft reach the observer at slightly different times, given their different distances. The rapid change in pressure as the shock wave passes can be disruptive or even damaging, leading to restrictions on overland supersonic flights in many regions worldwide.

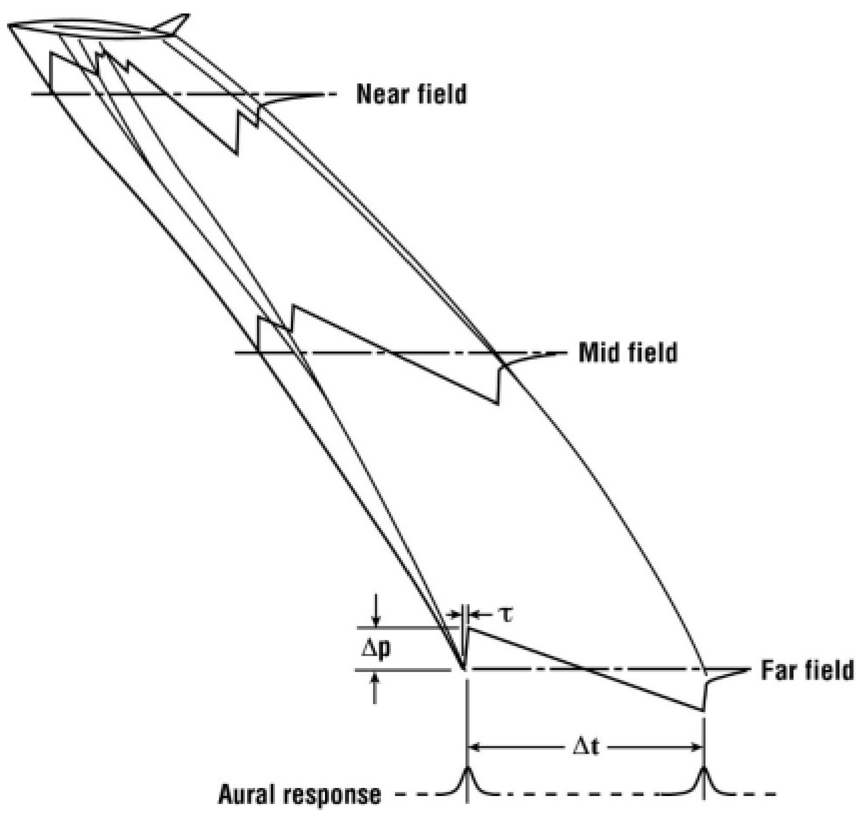

Figure 3: Sonic Boom Generation[3]

2.2.1 N-wave

The "N-wave" is a term used to describe the specific shape of the pressure wave generated by a sonic boom as it is observed or recorded at a single point on the ground. The name "N-wave" derives from the characteristic shape of the wave, resembling the letter 'N' when plotted on a graph with pressure change on the y-axis and time on the x-axis.

When an aircraft moves through the air at supersonic speed, it creates a series of pressure waves ahead of and behind it. These waves combine to form a single shock wave, or "Mach cone," that moves outward and away from the aircraft. As this shock wave passes over a point on the ground, it causes the atmospheric pressure at that point to sharply spike (representing the leading edge of the 'N'), then drop below normal atmospheric pressure (forming the trough or middle of the 'N'), and finally recover back to normal pressure levels (forming the trailing edge of the 'N').

The N-shaped pressure wave corresponds to the double "boom" sound of a sonic boom. The initial pressure spike represents the first "bang," followed by a quiet period, and then the pressure recovers, resulting in the second "bang."

While the N-wave shape is typically associated with sonic booms, the actual shape of the pressure wave can be influenced by various factors, including the size, speed, and altitude of the aircraft, as well as atmospheric conditions and the observer's distance from the aircraft's flight path. This means that real-world sonic booms can exhibit more complex waveforms than a simple N-wave model suggests.

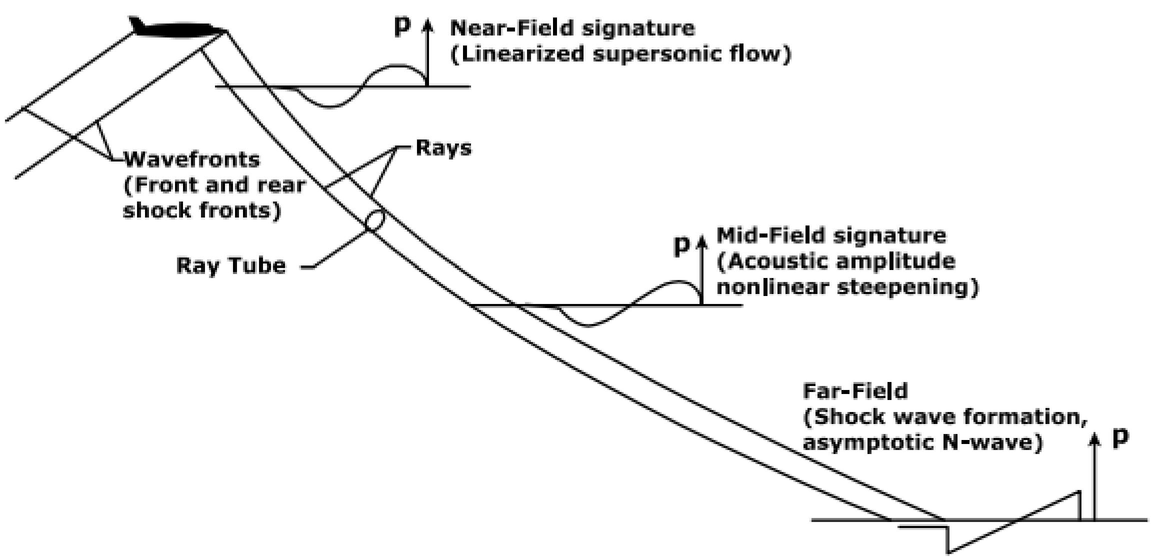

Figure 4: Sonic Boom Propagation[3]

2.3 Boom Carpet

The term "boom carpet" refers to the area over which the sound of a sonic boom can be heard as a supersonic aircraft flies overhead. It is a long, narrow region resembling a carpet.

A sonic boom is not a singular event but an ongoing phenomenon that occurs as long as the aircraft is flying faster than the speed of sound. As the aircraft moves, it continuously generates new pressure waves that travel away from it at the speed of sound. Since the aircraft is also moving at or above this speed, it constantly catches up with and combines these pressure waves, creating a single shock wave that moves outward and downward. This shock wave forms a cone of pressurized air molecules called the Mach cone.

The edges of the Mach cone define the boom carpet, which extends outward in a triangular shape from the aircraft's flight path. The sonic boom is heard on the ground when the Mach cone or the boom carpet passes over observers. It's important to note that the sonic boom is only heard once by an observer when the boom carpet crosses its location. The boom carpet does not "follow" the aircraft along its flight path but rather moves away from it.

The size and shape of the boom carpet depend on factors such as flight altitude, aircraft speed, aircraft size and shape, and atmospheric conditions. Generally, the boom carpet is narrower at higher speeds and altitudes and wider at lower speeds and altitudes.

2.4 Mach Cone/Ray Cone

In the context of a sonic boom, a "ray cone" or "mach cone" refers to the path along which the energy of the sonic boom, generated at a particular time, propagates.

When an aircraft travels faster than the speed of sound, it creates a series of pressure waves. Due to the aircraft's speed, these waves combine and form a shock wave in the shape of a cone known as the "ray cone" or "Mach cone". The rays on the cone are perpendicular to the shock wave fronts and represent the path along which the sonic boom energy generated at a specific time travels. This energy propagates along these rays and eventually reaches the ground, causing the sonic boom that we hear.

The point on the ground where a particular ray intersects is referred to as an "isopemp". These isopemps form a line on the ground that is always ahead of the aircraft's position when that particular sonic boom was generated. The distance from the aircraft's position (at the time the boom was generated) to the isopemp, measured along the flight path, is often called the "forward throw" of the boom. In other words, the forward throw represents how far ahead the aircraft the sonic boom reaches the ground.

This forward throw is another important factor that contributes to the shape and extent of the boom carpet. The faster the aircraft's speed, the smaller the forward throw, meaning the sonic boom reaches the ground closer to the path directly beneath the aircraft. Conversely, at slower supersonic speeds, the forward throw is longer, and the sonic boom reaches the ground further ahead of the aircraft's direct path.

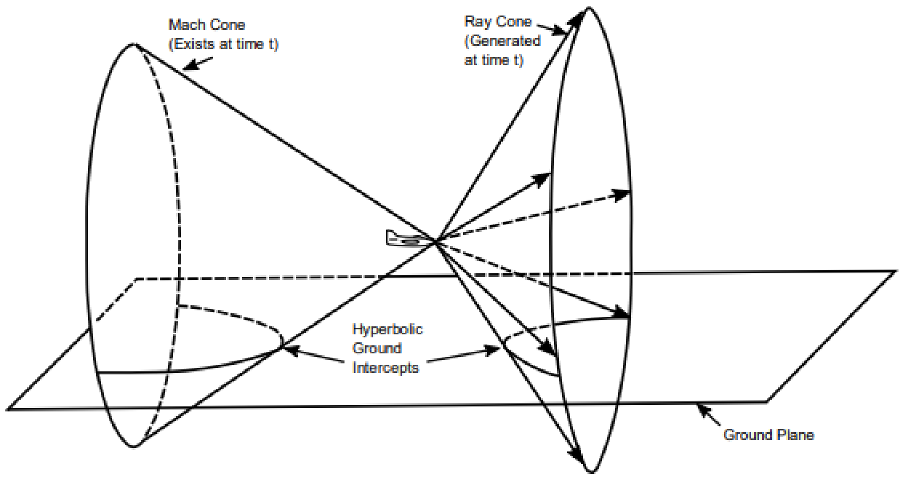

Figure 5: Wave and Ray Viewpoints[3]

References

[1] Tupolev tu-144, May 31, 2023. URL https://en.wikipedia.org/wiki/Tupolev_Tu-144.

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