HIGH SCHOOL EDITION
Journal of Student Research

Volume 11 Issue 3 (2022)

Towards a Supersonic Transport: Minimization of Sonic Boom

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ABSTRACT

An aircraft exceeding the speed of sound can cover large distances in short amount of time and has several important applications. Thus, there has been an interest in producing a Supersonic Transport (SST) Aircraft for commercial usage in recent decades. However, the problem of sonic boom restricts operations over inhabited areas. This work explains the basic concepts of sonic boom and reviews the effects of the sonic boom on people and structures, including the impact on indoor listeners inside these structures. We explain the impact of aircraft design and operational parameters like aircraft Equivalent Area, Altitude, and Mach Number on the boom signature. We also reviewed the literature on proposed boom- reduction methods, which are generally classified into Aircraft operations, Design, and Exotic methods. This paper reviews the significant methods proposed under each of these categories with special emphasis on design. Interestingly, the different types of reduction proposals aim to produce smaller and stretched- out shocks, which are not likely to produce a response in an outdoor listener. However, an indoor listener can still perceive the vibrations and rattles even from a highly modified sine-shaped signature causing safety concerns and annoyance. This is likely to prove an obstacle to overland flights. We acknowledge that significant challenges still exist in the commercial SST aircraft development, but the X-59 research aircraft through NASA's QueSST Program is very promising, and it makes this field of study one of the most exciting in the aviation industry today.

Introduction and Context

This paper aims to review existing knowledge and decades of research surrounding the fascinating development of Commercial Supersonic Flight and the lesser socially- acceptable phenomenon of Sonic Booms. We start with a brief description of sonic booms, followed by their effects on society and end with past and ongoing research to reduce booms. We explain the science behind sonic booms, their impact, and mitigation methods in a concise and clear manner.

With the advent of supersonic flight in the late 1940s and early 1950s, a phenomenon of explosive sounds was noticed as the supersonic aircraft flew by, thousands of feet above. These were termed 'Sonic Boom'. Since then, there have been multiple attempts to understand and to minimise the sounds- with the goal of removing the ban on over-land supersonic flight [1]. Supersonic flight was made commercial with the launch of the Concorde. However, it was restricted to transoceanic routes because of the societal impact of sonic boom, making it economically unviable as a mode of large-scale transportation.

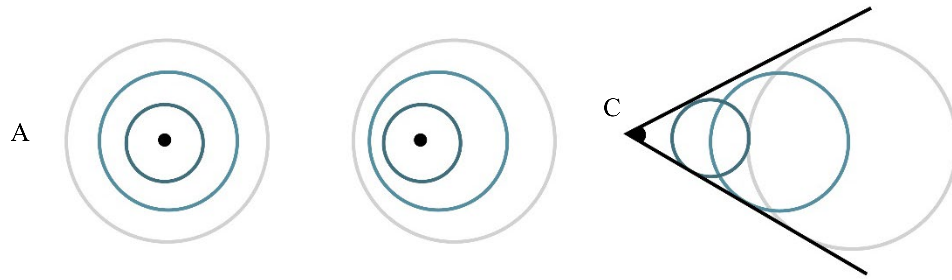

Figure 1. Wave Propagation from Stationary and Moving sources. 1A shows the waves when the source is stationary; 1B illustrates the waves when the source speed is subsonic; 1C represents formation of waves at supersonic source speeds [2]

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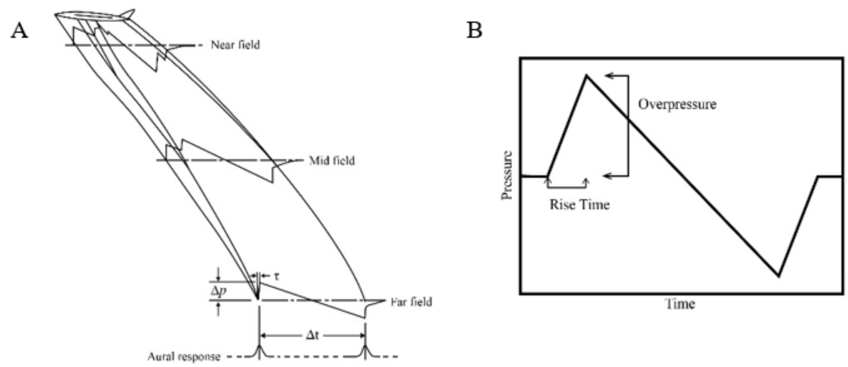
As a body in a fluid moves faster than the local speed of sound, it compresses and pushes aside the particles of the medium, creating a system of shock waves (Fig. 1c). When the source moves at supersonic speeds, the pressure waves travelling at sonic speeds lag, and the compressed shock waves pile up in front of the source to create an ‘overpressure’. These pressurised waves spread outward from the source path in a ‘conical’ pattern and the ‘Sonic Boom’ is heard when these waves reach the receiver on the ground. The extent to which the disturbances extend to are called the ‘primary boom carpet’ [2]. The exact overpressure signature is categorised into near- field, mid field and far- field, and it depends on the type of aircraft and local atmospheric conditions.

Early knowledge of this field was limited to shock- wave technology of projectiles like bullets and shells that often exceeded the barrier of speed of sound when fired. Further research and theories have provided insights into the generation, propagation, and prediction of sonic boom. Research has primarily focused upon the mathematical formulation for wave signatures and underlying factors affecting of propagation of the overpressure compressions, along with the effects of overpressure fluctuations upon the wildlife, settlements, and structures [2]. A resumption of interest in commercial supersonic transport has led to many innovative studies by NASA and aerospace corporations along with the entrance of private companies like Boom Supersonic. Today, researchers look at the feasibility of methods that can make boomless flight possible because of the advancement in technology. Computational fluids dynamics (CFD) software like AutoDesk are used for aerodynamic designing and pressure propagation tools like PCBoom can be used to calculate the near and far-field signatures for supersonic aircraft under varied conditions. This research promises to revolutionise air travel and the applications of Supersonic transport are exciting like life-saving organ transplants across continents. However, this hinges on the future advancements towards ‘boomless flight’.

The purpose of this paper is to provide a review of the existing literature on the sonic booms, pressure disturbance mitigation methods and a method suggested for future studies. Existing reviews on these topics are mostly written for specialised advanced researchers. This paper is written for high- school students interested in the phenomenon of sonic booms and its mitigation, and for researchers in other fields who are interested in a quick scientific introduction.

Sonic Boom as Far- Field Signature

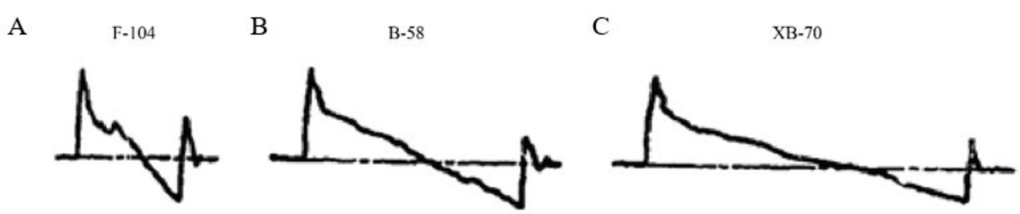
Aircrafts produce systems of shock waves originating from different parts of the aircraft (inlets, canopy, etc.), depicted as higher-pressure peaks in the near- field pressure signature of an aircraft. Early research used the XB-70 aircraft flying at Mach 1.5 at 37000ft above ground level along with 2 probes flying 2000ft and 5000ft



below the aircraft to measure the overpressure variations [3]. It showed that there is a conical Mach-plane produced with a vertex at the nose cone, as the aircraft flies along a steady path. This experiment proved that the more complex pressure signatures were measured closer to the aircraft and individual shock waves tend to coalesce into a bow and tail wave with increasing distance below the aircraft [3]. The bow wave is formed from coalescence of disturbances originating from the nose, engine inlets, leading wing edges, etc. The tail wave is formed from the disturbances from the tail. The shock waves reach the ground (receiver) forming the characteristic N- wave signature. This signature moves along with the supersonic motion of the aircraft. A listener facing an approaching supersonic aircraft would first perceive the bow wave compression shortly after the aircraft passes, which steeply raises the local pressure from p to $p + \Delta p$.

Figure 2. The N- wave signature. 2A: Near-, mid- and far- field boom pressure signatures. 2B: Illustration of overpressure and rise time definitions of an N- wave. [4]

The human ear can only hear higher frequencies due to changes in pressure and this sudden rise in pressure is heard as a first loud boom. As the aircraft moves forward, a slow linear expansion of pressure occurs to a point below p at the listener's position, in a time interval Δt (Fig. 2a), but the ear cannot hear this due to a lower frequency. After the interval, Δt, the tail wave arrives, and a recompression occurs, causing a second bang sound, raising the pressure back to p. However, Δt must be $0.10s$ or higher for the ear to be able to perceive the 2 distinct blasts of the N-wave, otherwise a crack or blast is heard like the sonic boom from bullets or whips. The rapid compression and recompression are of similar amplitude and are separated by the linear pressure expansion. The 'primary sonic boom carpet' is the defined as the region on the ground where the N-wave is formed as the aircraft flies overhead. 'Secondary' boom signatures are shockless and of an order of magnitude lower in overpressure and frequency than those of primary booms. As a result, they are difficult to sense outdoors but can be noticed indoors as slight vibrations [4]. Thus, these need not be the



focus of low-boom aircraft projects and response studies.

Figure 3. Sonic Boom Signatures for different sized aircraft configurations. 3A: small- (F-104), 3B: medium- (B-58), 3C: large- (XB- 70) [2]

This N-wave signature shape is characteristic of each aircraft configuration (Fig. 3), and there are several atmospheric conditions that influence the propagation and interpretation of the pressure signature. These include Macro- atmospheric conditions like temperature, pressure and wind gradients, and micro- atmospheric factors such as the time of day, rise with gusts and turbulence, and atmospheric absorption. The loudness of the sonic boom has been shown not to follow a linear pattern vis-à-vis the maximum intensity of the N-wave. The shape of the N-wave, i.e., the rise time and the amplitude of the bow shock compression, affects the perceived loudness of the boom. Thus, a major focus of studies like Sullivan et al., (2006) [9], von Gierke [10], and A. Dancer and P. Naz. [12] had been to understand the effects of far- field sonic boom signatures of living creatures and structures on the ground, to institute socially acceptable benchmarks for future commercial low- boom flight. Other studies try to develop methods to reduce the amount of noise generated by supersonic aircraft.

Wide scale agreement exists that it is possible to design an aircraft with low- boom signatures, but the actual challenge lies in this design meeting the mission requirements (payload, fuel efficiency, flight path) and aerodynamic efficiency.

Effects of Sonic Boom

Effect on People

The perceived loudness, i.e., the level of loudness of noise heard, cannot be linked only to the amplitude of the far- field N- wave signature. Studies have shown that human judgement of loudness is far more complicated.

The purpose of studies has been to understand the minimum acceptable loudness levels to set the benchmarks and develop aircraft designs accordingly. Research and surveys have documented the effects of different levels of overpressure on living organisms on the ground [15, 16] and on building structures [21,22]. Sonic Overpressure responses depend upon the location of the receiver- outside, where direct exposure occurs, or inside a closed structure, in which case the wave is filtered by the materials of the structure. It determines the nature of the wave reaching the receiver. To quantify loudness, Steven's Mark VII algorithm [45] is widely used in conjunction with a programme written in the Python Programming Language called 'PyLdB'. This tool is useful when designing and optimising low- boom supersonic aircraft and conducting experiments which analyse the effects of over-land supersonic flights. The Mark VII metric uses a reference frequency of 3150Hz to quantify loudness since the frequency falls within the human ear's most sensitive frequency range. The major parameter used for the ground loudness estimations is the pressure wave signature and involves a three-step process resulting in a quantified perceived loudness, given in units of PLdB. Steven's Mark VII metric has proved to be a better metric for comparison of both indoor and outdoor listening conditions. However, there is yet no consensus within regulatory community about the metrics for sonic boom assessment.

For humans, the complaints received are more psychological than physiological. There have been studies which indicate that the annoyance from loud blasts or sonic booms is connected to the wave signature- mainly the maximum overpressure and the rise time, though the overpressure plays a bigger role in determining the perceived loudness levels. Further, both indoor and outdoor listeners are prone to be 'startled' by the burst when the pressure impulse reaches the ear, adding to the primary issue of annoyance. A similar loud blast is anticipated by an aware observer during fireworks display but is still startling. For purposes of context, that an aerial burst during fireworks displays would produce a much higher waveform overpressure than a F-104 flying at M 1.4 at 22000ft [13].

A study by Schomer concluded that the overpressure led to intense rattling of structures as sudden overpressure waves passed through them. The annoyance from rattling was twice as high as that from startles and other factors like sleep or being frightened of physical damage. People fear that their houses will be damaged and blaming the rattling of objects like windows as cause of regular inconvenience [14]. An acceptable overpressure level is estimated to be in the range of 0.1 to 0.75 lb/ft^2, depending upon the local conditions. However, there is no scientific data to strongly back this range estimation, it is arrived at through experimentation and perception records [10]. From early overland supersonic experiences with the Concorde, as well as studies by von Gierke and Nixon, it was determined that overpressures above 2 lb/ft^2 and the accompanying startle effects were not at all acceptable [10]. A mid- 1980s study in Nevada by United States Air Force found no evidence that intermittent exposure to sonic booms lead to adverse health conditions although prolonged exposure could have health effects or make existing conditions worse [15, 16].

An interesting study involved residents near Edwards Air Force Base where they were exposed to 4-8 sonic booms every day for a year. When surveyed, over 60% respondents had grown more accustomed to these booms, indicating them acceptable, perhaps due to reduction in fear of destruction and measures taken indoors to ignore the rattles, but reported no reduction in being startled. A drawback of widespread application of the conclusions of this study was that it involved residents in sparsely populated areas while the primary source of opposition to overland flight is that of densely populated urban areas [17]. This field will require research before above- land, low- boom commercial travel becomes a reality. Many such studies are presently under progress and many previous studies are not a part of the discussion here due to the inconclusive results.

Effect on Structure

Besides the human responses, the structural response to sonic booms forms a necessary line of research for the formulation of sonic boom guidelines. For N- waves, only high overpressure values have been directly correlated with reported damage [18, 19]. Studies to gauge damages to property have been conducted indicating that majority of the energy of the wave must be concentrated at a similar frequency to the resonance frequency of the structure, for vibrations to be 'felt' (either through direct contact or visually perceived by looking at shaking windows) inside the structure. Literature mentions that the mechanical effect of conventional N-shaped booms is 'one order of magnitude smaller than the required value for the structural breaking' and is comparable to the existing household disturbances like a slamming door [20]. This is by no means to say that the impact of such booms is negligible and does not cause any visible damage to structures over longer periods of time.

Haber's study notes that in absence of pre-existing damage or stress in components, no damage was observed for overpressures upto 20lb/ ft^2 given that the level of vibrations is too low for instantaneous damage. However, progressive generation of stress levels and damage due to cumulative sonic booms is a possibility. They can also trigger apparent damage if the structure is weakened because of natural cyclic factors like weather, wind, etc [21]. Another quantitative study [22] focused on damage caused to poorly assembled or maintained buildings by sonic booms. It said that the sonic booms alone cannot induce damage to regular structures but do add to stress created by other environmental factors, reducing strength over time. Well-constructed structures are unlikely to take superficial damage from a single boom of overpressure well below 5-10 lb/ft^2 [23].

There have been several other studies to determine damage to lighter windows, plasters, wooden boards, etc. but these subjects require further investigation because the materials and construction practices in densely populated areas may have changed since these studies were last conducted.

Aircraft Design and Operational Parameters Impacting Boom

Equivalent Area

Attempts to produce an ideal far- field sonic boom signature through 'Shaping' of aircraft are based primarily on the equivalent area concept. According to this concept, if a supersonic aircraft is replaced by a body of equal effective area (A_e) distribution across the length of the aircraft, similar sonic boom signatures will result [23, 24]. Such an equivalent body is called an equivalent body of revolution. Slight variations do exist between the actual model and its equivalent body, especially in the tail shock recompression. However, these variations are inconsequential for major shaping features and designs that are tested for the aircraft. Further, for simplification, the area effect is divided into volume and lift components, and each effect is calculated separately. Basic numerical analysis of signatures requires the modelling of lift and volume effects on the sonic boom. Linearised methods have shown that depending upon the rate of increase in the A_e, across the length of the aircraft different kinds of disturbance patterns can be observed. Results of Carlson et el. [25] are depicted in Fig. 4 which uses the A_e distribution for an aircraft configuration to define a corresponding equivalent body of revolution. This A_e distribution graph has contributions from both the lift and volume effects. Then their extrapolated boom signature graphs are compared, and the bow wave is similar. The tail shocks are diminished for the body of rotation, as the lift effect of the wing tips is ignored in this theory.

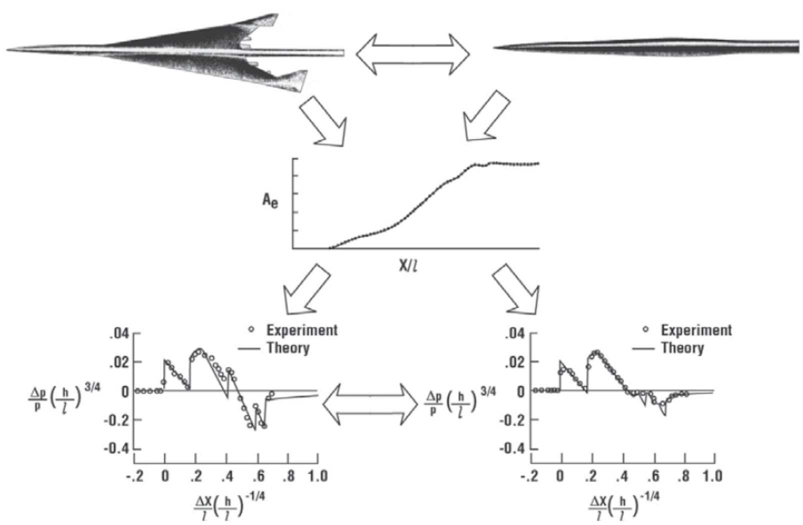


Figure 4. Illustration of the 'equivalent body of revolution' concept and the corresponding sonic boom, Mach 1.41, CL= 0.1, h/l= 10 [25].

Modern methods have been developed on the foundation provided by the A_e concept. Today, instead of linearised analysis that was proposed in Whitham's work [23] more precise methods like Euler- equations, real aircraft geometries and mathematical optimization techniques are used [4]. Complex Computational Fluid Dynamics (CFD), optimisation software and other shock wave propagation tools have evolved and continually add environmental factors and variations for realistic boom prediction. Unlike linearized methods, CFD does not distinguish between lift and volume contributions. These two effects are combined into one for near field pressure signature calculations.

It is because of equivalent area concept that most modern supersonic designs are slender and long structures. The volume and lift components do not rise and reach the maximum value together along the length of the aircraft. This is unlike a conventional aircraft, where lift producing wings and volume/ weight carrying body need to be at the same place to make it a commercially feasible design [11].

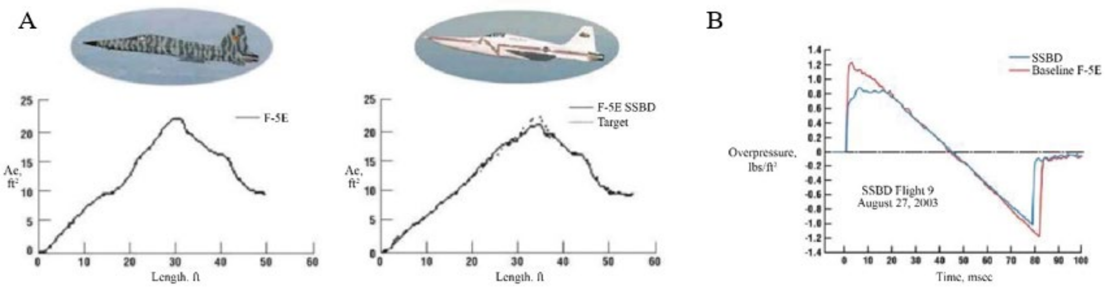
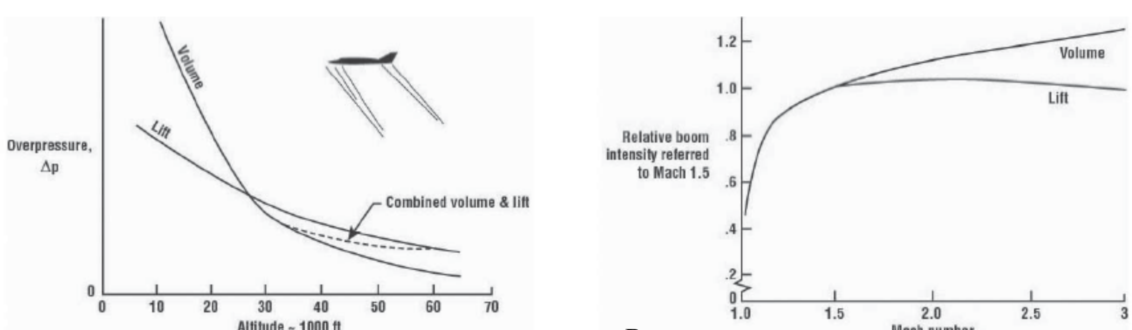


Figure 5. Shaped Sonic Boom Demonstrator Results. 5A: Modification of F-5E into the SSBD and corresponding A_e distribution curves. 5B: First Measurement of a Far-field Shaped Sonic Boom [26].

<u>Shaped Sonic Boom Demonstrator (SSBD):</u> To prove this concept, a flight test in 2002, as part of the QSP programme, a Shaped Sonic Boom Demonstrator was designed from an existing F-5E aircraft by modifying the nose of the plane, to achieve the goal of reducing the positive/ front overpressure and creating a flat-top wave signature. The nose was made longer and narrower while the fairing under the fuselage was lengthened and deepened. On comparison with the regular F-5E, a smoother increase of the A_e curve and a spread of the energy of the sudden overpressure over a larger time, was achieved. The programme was successful in proving the propagation of shaped wave signatures (to far-field). No changes were made to the rear of the signature or aircraft. It is virtually impossible to modify a plane to completely change its boom signature. Fig. 5 depicts the smoother increase in A_e of SSBD model compared to more non-linear increase for F-5E , especially around the at a point around 17ft of length. This in- turn, affects the boom signature (Fig. 5B) by reducing the peak overpressure of both bow and tail waves, although by varied amounts. The SSBD programme proved that far-field boom shapes can be configured using airplane designs and encouraged further ideas for low- boom configurations to begin being tested [26].

Role of Altitude and Mach Number

The sonic boom of an aircraft is attributed to both its volume and the lift it generates implying that the size and weight play a major role in establishing the far- field wave intensity/ amplitude. Studies have been conducted to identify relationships between boom effect of lift and weight with respect to the altitude and Mach



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number of the flight.

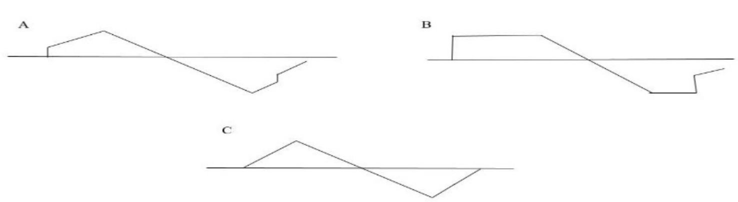
Figure 6. Influence of altitude and Mach number on sonic boom. 6A: Contribution of aircraft lift and volume on boom level. 6B: Influence of Mach Number on Boom level [27].From the graphs (Fig. 6), the contribution of volume and lift vary with increasing altitude or Mach number, but the general trend in overpressure is consistent.

For a constant speed and path, overpressure contributions of different factors, like volume and lift, have been identified. At lower altitudes, the volume of the aircraft plays a major role. As the altitude increases while the airspeed is constant, the angle of attack increases to maintain a higher lift, [11], so increasing the contribution of lift in the overpressure. Overall, the total overpressure decreases significantly with increase in altitude. For a given aircraft at a fixed cruise altitude, with increasing supersonic speeds, the boom intensity increases because of both lift and volume factors, though the effect of lift is more than that of volume, especially for large transports like HSCT. For a smaller and lighter supersonic fighter aircraft, the opposite is true with the volume effect being more dominant. A larger supersonic business jet would have both the lift and volume effects comparable in its sonic boom.

It is interesting to note that when cruising altitude is increased by few thousands of feet (to reduce overpressure through attenuation) (Fig. 6A), the local speed of sound starts to decrease (at higher altitudes, air is less dense). Consequently, the aircraft flies at a higher Mach number relative to the local speed of sound, leading to a louder boom (Fig. 6B). This phenomenon of gradation in the speed of sound effectively reduces the attenuation advantage of flying higher, above a certain altitude. So, in the trade-off between high altitude and the high Mach speeds needed for aerodynamic and cost efficiency, if optimum cruising conditions needs to be found for the particular aircraft design, such that there is the possibility of attenuated booms for the receiver [4].

Types of Ground Signatures

Different types of ground signatures have been obtained and correlations have been made between rate of A_e change (the shape of curve) and the signature shape. The shape of the signature depends upon the slope of Ae, Mach number, flight altitude and aircraft length. Additionally, designs with a smooth optimum progression for A_e from nose to its maximum value result in a 'flat- top/ plateau' or a 'ramp'-type signature. The plateau signature would have the minimum overpressure with some shock effect while the ramp- type signature would have lesser shock effect because of its stunted rise at the bow and tail shock. Spreading the A_e over an even longer distance and lower overpressure can result in a 'finite rise- time' signature, which can approach a sine curve where the outdoor shock is negligible. The sine wave is a combination of the characteristics of the plateau and ramp time signatures (Fig. 7). Parameters of the signature that are the focus of shaping research are the (i) the maximum overpressure value, determined by the maximum A_e value, (ii) the rise time of the overpressure, determined by length and thickness of fuselage, (iii) the period of the shock wave, influenced by



a complex set of factors, and (iv) a smooth recovery [5].
Figure 7. Types of Shaped- wave signatures. 7A: Ramp Type. 7B: Plateau or Flat- top. 7C: Sine wave- type.

Further, Shephard and Sullivan [28] depicted that a symmetrical wave signature with initial over-pressure rise in 2 pressure- steps (Fig. 8A) would lead to less loudness because it keeps the initial rise time and amplitude small in comparison with the secondary rise time and amplitude. This low- boom signature eases the annoyance without reducing the overpressure because the energy of the wave at higher frequencies (more sensitive to the human ear) significantly diminishes.

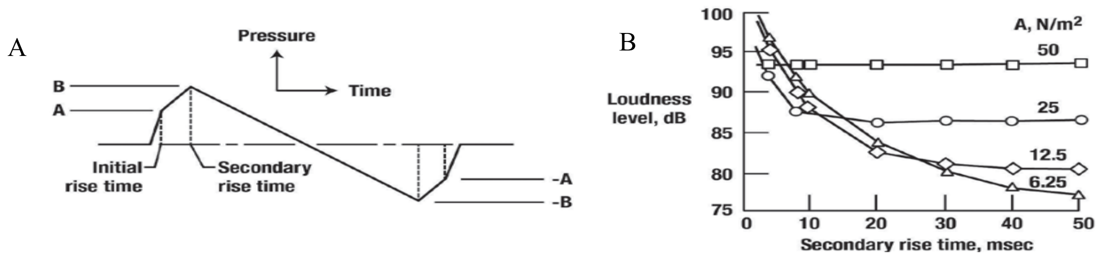


Figure 8. Shaped boom Signature. 8A: Symmetrical 2- step wave signature. 8B: Calculated loudness for shaped boom for outdoor listening conditions [28].

Other Factors

Several other factors like the focus boom formed during transonic acceleration, local macro and micro atmospheric effects, aircraft manoeuvres, flight path angle, etc [4]. influence the perceived loudness of the booms. For the purpose of this paper such factors would not be discussed owing to their complex nature and limited studies for each area.

Methods

Sonic Boom reduction has been a source of great interest over time- with numerous theoretical solutions having been proposed and tested. After the prohibition of supersonic flight over land, however, no substantial progress has been made in boomless supersonic commercial travel.

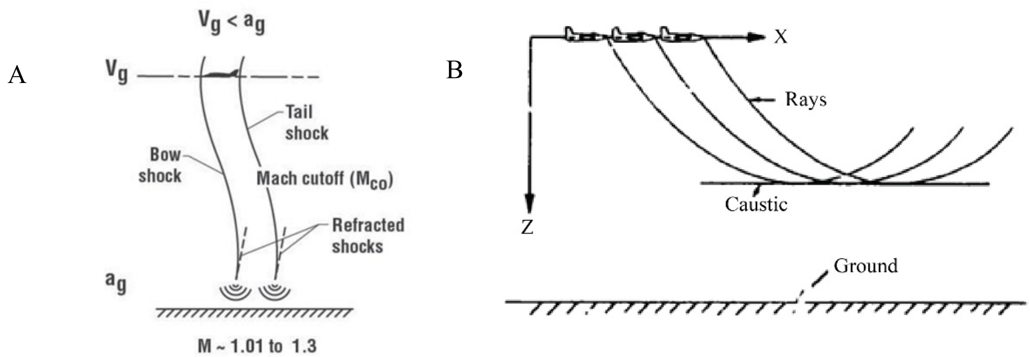
Different types of attempts have been made aiming to muffle or reduce the noise generated on the ground by the far- field shock waves, these include aircraft operations, aircraft design and some extraordinary or 'exotic' concepts [41] which have undergone feasibility studies in wind tunnels. Many new studies continue, although the results are not public to- date.

Additionally, from the discussion so far, we can conclude that any practical discussion on true boomless flight is not just that of aircraft design or configurations, rather that of several factors like altitude, operations, local atmospheric conditions, etc involved in the prevention of propagation of the shock waves to the listener. Basic aerodynamic designing is still required alongside this research for the purpose of increasing flight efficiency and feasibility. Below we discuss some major methods of aircraft operation and design which have been proposed till date.

Aircraft Operations

Mach Cut-Off

Perhaps, the most straightforward method suggested is to conduct 'Boomless Supersonic Flight' based upon the eventual termination and reflection of shock waves. For an aircraft flying below its Mach Cut-off (M_{co})-, the shock waves would reach an altitude after which they bend upwards and start moving in the opposite direction. Mach Cut-off is a low, supersonic Mach number such that the aircraft's ground speed (V_g) is less than speed of sound at ground (a_g) The reflection of the waves occurs due to refraction effect through the atmosphere. At this point of reflection, a focus phenomenon (caustic line) forms where a wave with upto 3 times the overpressure of a similar aircraft flying above its M_{co} is formed, and the boom can be heard if the focus level is within a few hundred feet above the ground. Consequently, a jet flying higher would have a higher caustic line and a possible dissipation of the focused energy before reaching the ground. A higher cruise altitude would require a larger wingspan with a bigger effective area (A_e) and more powerful/ bigger engines, increasing both volume and lift parameters for sonic boom generated. Such trade- offs during airplane design exist between each new feature/ requirement and its possible implementation utilising current technologies. However, even if the concept of M_{co} speed is employed for a commercial aircraft at feasible altitudes, speeds would be limited to under M1.3. This can be effectively used to transition into supersonic



cruise overpopulated areas to reduce the focus boom and allow for subsequent acceleration [4].

Figure 9. Mach Cut-off. 9A: Schematic for Shock waves for aircraft at Mach Cutoff speeds. [4] 9B: Caustic or focus line formation for aircraft flying at Mach Cut- off Speed.

Aircraft Design Methods

The second domain of boom- reduction methods focus on aircraft feature designing and configurations for sonic boom signature shaping to produce a wave that is acceptable both indoors and outdoors. Boom shaping, to change parameters of the far- field signature, as explained above, has been the major focus of recent research in the industry. Attempts are in progress to understand whether the coalescence of the independent disturbances can be avoided over short propagation distances to distribute the overpressure over more time.

High Finesse Ratio or Lengthening Aircraft Body

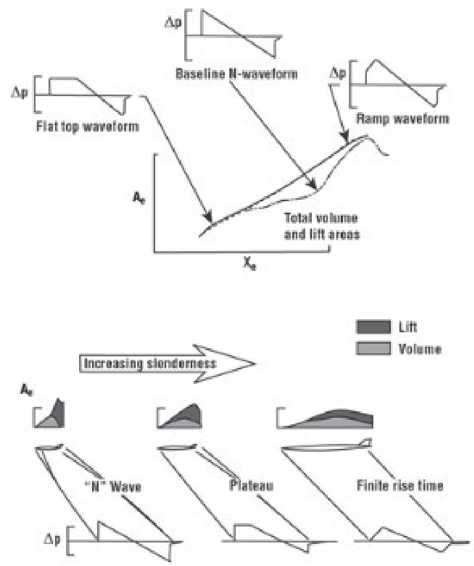


Figure 10. Distribution of Ae. A: Shaped wave signatures based on varied Ae. B: Contribution of Lift and Volume factors to area development and its relationship with the signature shape. [4]

Aircraft shaping has been most successful by increasing the finesse or slenderness ratio of the fuselage, employing a spread out lift and volume arrangement to reduce the rate of increase in A_e distribution. Basically, this implies increasing the length of the fuselage and creating a smoother increase in A_e reaching a maximum value, which determines the amplitude of the boom signature. As shown in 'Types of Ground Signatures' above, a typical N- wave can be smoothened from the nose to the maximum area to form a shock ramp- wave which can further be made less loud in the form of a plateau or flat- top by means of reduction in the A_e curve near the nose and the point of maximum value. However, for any significant reduction in the PLdB values, a finite rise time signature would be required. For this, the body length should exceed 500ft such that the A_e is sufficiently low and smooth over a larger distance. Fig. 10 shows the variations in the rate of increase of the $A_{e,}$ and the corresponding types of ground signatures. In the graph, a smooth rate of increase in A_e leads to shaped signatures while a regular N-wave is formed for a variable rate of increase [4].

Wing Dihedral

Wing Dihedral is the upwards tilt or angle of the wings and tailplane above the horizontal. This dihedral angle has been shown to reduce shock strength directly along the path and in the lateral areas. It achieves this by changing the angle at which the shock waves propagate to the ground, creating a more uniform boom laterally. The dihedral angle allows the trailing edge of the wing to lie in plane with the wing apex and leads to effective wing length increase for purposes of A_e calculations. For vehicles having a 10–15-degree dihedral angle, reductions of 18-28% of overpressure have been predicted directly below the wings of the aircraft [29]. Although the benefits of lower boom do not reach the lateral cut-off distance of the primary boom carpet, 30% of the lateral distance experiences lower shock levels.

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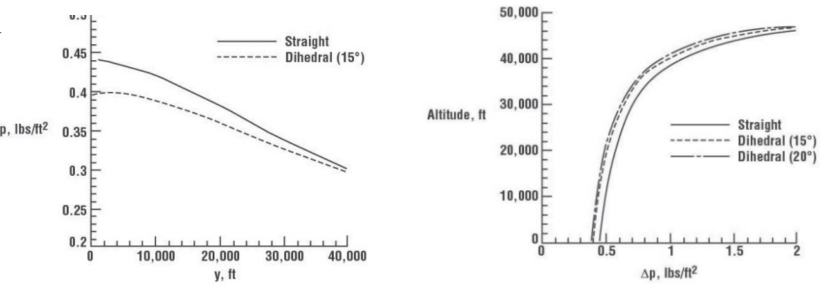


Figure 11. These results from an aircraft with a 60-foot chord, delta wing with 5% bi- convex section flying at Mach 2 at 50000ft and lift co-efficient of 0.077. 11A: Variation of Bow shock strength with Lateral Distance and 11B: Variation of Bow shock strength below wings. [30]

As can be seen from ‘variation of bow shock strength below wings’ chart, the reduction of overpressure of dihedral (20°) is seen till an altitude of 45000ft, after which the overpressure difference between straight and dihedral wings is diminished. In the chart for ‘variation of bow shock strength with lateral distance’, there is appreciable reduction of overpressure using dihedral (15°) until 30000ft laterally in the boom carpet, signifying the effect of dihedral both on and off- track. Increasing Wing Dihedral, however, causes aircraft instability, specifically roll- yaw coupling. Thus, more research and solutions are needed to incorporate a significant dihedral angle without causing stability issues, for any possible utility in supersonic passenger travel. Consideration of both lift and volume factors is required for understanding of adverse effects of dihedral angle on aerodynamics and structural penalties [31].

Wing Configurations/ Planforms

Scale models of various wing configurations have been tested in wind tunnels and under several atmospheric conditions to come up with a possible design that solves the problem of sudden overpressure rise. Here, both volume and lift effects contribute concurrently to shocks and must be optimised together for low- boom A_e distribution. The lift distribution on the wing can be optimised by altering planform, wing section thickness, wing twist, wing camber and dihedral [32]. Planforms studied include unswept trapezoidal, sweptback arrow, delta with dihedral and anhedral, and swept forward- giving a large range in overpressures generated. The delta planform with dihedral showed significant reduction in overpressure values and along with the arrow planform and has been subsequently employed as the choice planform in many concepts for low- boom transports. The fundamental problem of aerodynamic efficiency is not resolved by either wing planform.

Figure 12. Rough Sketches of Wing Planforms. 12A: Delta. 12B: Swept- back [32].

<u>Effect of wing sweep:</u> Other Studies have used wind tunnel tests to identify the possible boom mitigation of a variable geometry forward- swept wing planform. Hunton et al. [33] compared a swept forward wing with aft-swept wing by measuring the overpressure at different C_L. Due to tunnel size constraints, experimental pressure readings taken at h/l of 3.6 were extrapolated to h/l 130 for a more practical comparison. Examination of the extrapolated data shows that overpressure generated by the forward swept wing is more and unlike the aft-swept planform, occurs as a single, steep rise in pressure, implying a louder boom. The result of the study was that wing planforms could reduce the magnitude of overpressures by 20-40% over conventional designs.

Although, it also concludes that any configuration would have to tailored specifically to a given Mach Number, cruise altitude and C_L implying that over a range of operating conditions (as required for commercial flights), implementation of these concepts would not be concurrent with maximum aerodynamic efficiency and performance. As it is, the margins for performance penalties in commercial operations are little to none.

Fig. 13 shows the experimentally observed overpressures for various wing planforms at M 1.68 and multiple Co-efficient of lift: 0, 0.098, 0.15. The results for models from the discussion above are also represented.

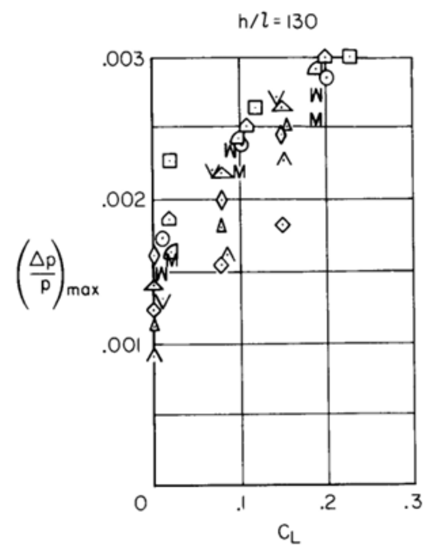


Figure 13. Graph comparing the overpressure for aft- swept and forward- swept wing planforms. The upward- directing arrow for aft-swept wing and downward- directing arrow for forward- swept wing. [33]

Another Planform study by Horinouchi [34] provided for a possible solution to the above problem utilizing a variable sweep wing. The sweptback cranked arrow planform is used as the reference and experimental analysis was conducted for both configurations. The premise is that the wing can move forward, effectively changing the A_e distribution- increasing the spread (smoother and more symmetrical) and reducing the maximum area and hence changing the signature shape and intensity. It also provides for a 30% engine size reduction over delta and arrow wing forms, with the engine intake over wing, reducing the boom generated due to lift. This blended- wing body concept also has a high Lift to Drag ratio (L/D) reducing the landing strip length by 1500ft than that of the arrow- SSBJ. The study identifies several improvements in technology to be implemented before any prototypes are developed. These include aero elastic tailoring for the variable sweep mechanism, environmental considerations (engines), other low- boom technology development and operational cost reductions. This study contradicts the results of the previously mentioned study (Hunton et al. [33]) in that the swept forward wing produces lower boom signature in the CFD analysis of Horinouchi 2005 [34], perhaps, because the earlier study did not integrate real atmospheric effects on coalescence of shock waves during extrapolation at h/l of 130, for instance the effect of molecular relaxation process during propagation through the atmosphere.

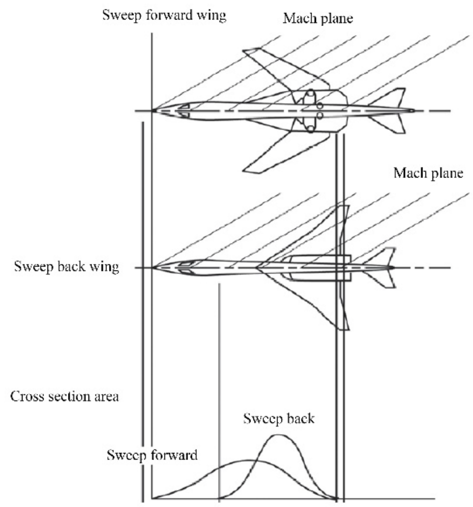


Figure 15. Mach cuts for swept back and forward swept wings. Rate of corresponding cross- sectional areas. [34]

It should be noted that above concepts focus on the small supersonic business jet (SSBJ) Concept carrying 10 passengers due to the practical low- boom possibilities of a smaller aircraft (a lower volume).

Over Wing Engine Placements and Exhaust Plumes

Engine exhaust is a major influence on the tail- end boom signature. Exhaust plumes and flow is categorised as an addition of area to the A_e for CFD analysis of the aircraft. A study on the influence of X-15 Hypersonic Research Aircraft aft- flow field on sonic boom signatures was conducted comparing booms generated by two configurations- one where the engine operated at 50% thrust and speed breaks were engaged, with the other being free flight with no engine or speed break operation. The results were significant in that there was a gradual recovery for the tail- shock due to the engine exhaust and wake from the speed brakes increasing the effective length of the plane without altering its lift or volume characteristics. A single boom was heard from the bow shock wave. The latter case had a rapid rise in pressure for both bow and tail shocks resulting in 2 audible blasts. [35]

Similarly, engine placement (through exhaust and size) can affect the sonic boom signature during overpressure increase, contributing to boom loudness. An over the wing engine exhaust would add beyond A_e max and smoothen the distribution, reducing or eliminating the aft boom. There have been other studies using CFD and boom propagation programmes testing the feasibility of over the wing engine placements for both large- scale supersonic concepts and SSBJs indicating that engine location and size needs to be optimised in conjunction with wing planforms and fuselage, to avoid A_e increases (tail or bow) and intermittent booms. These results favourably suggest integrating into aircraft above the wing engines as part of shaped low- boom signatures of amplitudes lesser than 1lb/ft^2. [4]

Exotic Methods

Proposed methods which can reduce the overpressure booms by changing the total enthalpy of the airflow surrounding the aircraft and rely on physics beyond current comprehension are termed as 'exotic methods' in this field. Several concepts and configurations like Phantom Body Concept [36. 37, 38], forward swept kneel [39], thermal fins [40], and dispersion of shock wave. Due to the complexity of theories [4], they are beyond the scope of this paper, only methods of shock wave dispersion will be discussed.

Shock Wave Dispersion

Shock wave dispersion involves spreading of the N-wave over a larger area on the ground such that the average intensity is reduced. The primary theory says that when the surfaces producing the shock waves are made to periodically vibrate through a calculated angle, at a particular frequency, thicker shock waves are produced on the ground, distributing the overall pressure over a larger footprint. Consequently, the amplitude of the N-wave is reduce and the rise time increases. This is achieved by varying the semi- angle, i.e., angle between the leading-edge surface and the chord of the wing. The horizontal surfaces of the wing and empennage produce oblique shock waves which coalesce into the tail shock and by periodic changes in semi-angle, the angle between the chord and shock wave increases disproportionately. This theory is suggested as an alternative to compromises in aircraft design or operations [41] which render commercial supersonic flight operation infeasible.

The first method proposed is to create the vibrations of a particular frequency in an elastic membrane stretched over the leading-edge wing surface by means of pressure pulses propagated through a hydraulic fluid. For maximum amplitude and efficiency of vibrations, the frequency of pulses should match the resonant frequency of the membrane. Further, for a known Mach cruising speed, there exists a limit of semi--angle beyond which, even a small increase transforms the oblique shaped wave into a detached shock wave, perpendicular to the chord at the point of contact. Here, determination of the optimum frequency of vibration and technology for the membrane and pulse generation mechanisms are obstacles for desired implementation.

The second method involves a thin carbon- fibre composite elastic fairing on the nose or leading edge of wings vibrating with pressure variations in the air manifold located below the fairing, within the wing. As in the first method, the vibrations must be controlled at an optimum resonance frequency using minimum power to get maximum amplitude. The compressed air is then let go via an evacuation hole with every vibration to avoid excessive pressure build-up. These two methods can be incorporated in a future European supersonic aircraft. The drawback is that there is more research required into the optimum frequency for vibrating surfaces and factors that need to be considered include the tension of the fairing- which changes the resonance frequency of the surface- as well as the duration and thickness of the shock waves on the ground.

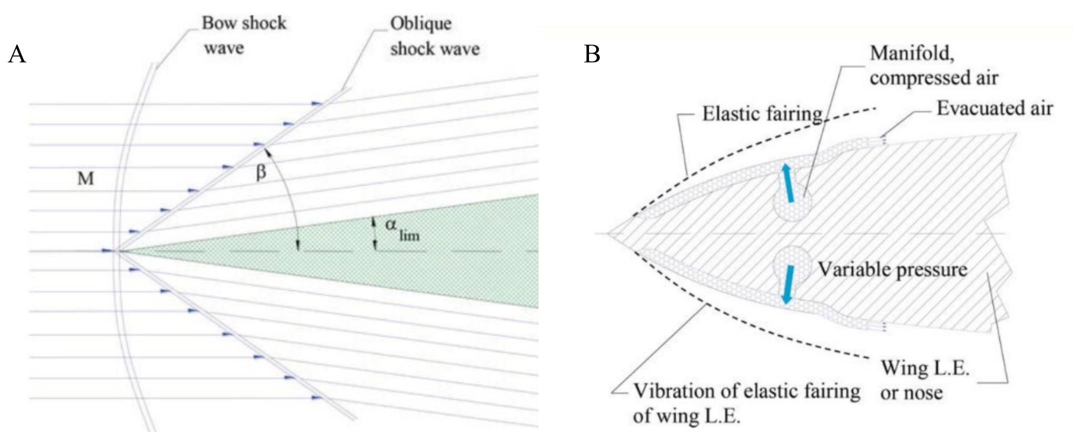
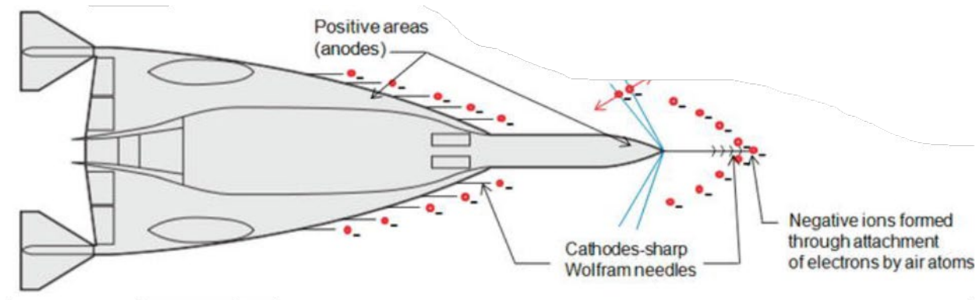


Figure 15. Dispersion of Shock Wave as a method of Boom reduction. 15A: Sketch depicting the detaching of shock wave and semi- angles alpha and beta. 15B: Schematic of the wave dispersion through vibration of Elastic Fairings induced by compressed air [41].

A third non- mechanical method that has been extensively researched recently is the injection of electrons in the surrounding airflow upstream through sharp electrodes. The negative electrode (cathode) consists of multiple sharp Wolfram (Tungsten) needles on rods placed on the nose or leading edge of wing. Positive electrodes (anodes) consist of copper plates fixed around nose and wing suction. It is designed to form a high potential electric connection (1000s of Volts), releasing many electrons through sharp cathode tips. These electrons move along with other gas molecules to form a mixture of ions, free electrons, and molecules in the thin, high- density compression of shock wave. Due to the small space, there is excessive electro-



static repulsion amongst these particles, forming a thicker shock wave, as was the case for the mechanical methods. This negative mixture is then neutralised by the anode on the aircraft surfaces. The caveat is that more experiments are required before any data about the exact voltage required and its effect on the wave can be ascertained and safely implemented on the commercial scale. An advantage of this method is that there is relatively less penalty on fuel efficiency and aircraft performance compared to 'shaping' methods and other operations.

Figure 16. New Solution Proposed for dispersion of shock wave through injection of electrons in surrounding airflow by sharp electrodes mounted on rods [41].

Modern Studies: NASA QueSST Program

A significant ongoing study is the NASA 'Quite Supersonic Technology' program where the 'X-59' supersonic aircraft will be tested. It aims to achieve a noise target of 75 PLdB, equivalent to a car door shut 20ft away or in line with the ambient noise of cities. It is designed to fly at M 1.4 at an altitude of 54000 ft and produce a thump- like sound instead of an explosive boom [43]. It will shape the volume and lift distributions such that shocks and expansions are generated throughout the length of the aircraft at different positions leading to a sine- wave type ground signature, distributing a high overpressure over longer duration of time. It prevents the singular disturbances from coalescing and causing a loud explosive boom [42]. The signature-shaping features include a long unconventional nose that shapes the bow shock and forms a third of the total length of the aircraft and a t- tail to minimise aft shock in addition to other features explained in this paper. It consists of an above- fuselage mounted single engine configuration preventing additional shock waves from reaching the ground, a sweptback delta wing planform that reduces the wave drag on the aircraft and a unique overall shape called a 'outer mold line'. Further, the X-59 is predicted to produce a lower boom than the design accounted for in standard atmospheric conditions. Realistic atmospheric conditions would work to reduce the target overpressure. [1]

Figure 17. An illustration depicting what the completed X-59 might look like during flight. Source: Lockheed Martin©

While over- land and community tests have not yet been conducted, the program predicts that the startle effect would be all but eliminated and the indoor vibrations would be lower than acceptable levels based on previously conducted studies. Over land tests are planned for 2024 wherein the aircraft would be flown over several cities and surveys would be conducted to gauge the residents' responses and acceptability levels. The single seat X-59 technology demonstrator is part of a longer plan leading upto an International Civil Aviation Organisation meeting in 2028 when the results of this program will be presented, and a case made to reconsider the ban on commercial supersonic flight over land. The success of the X-59 flight could herald a new era in the development of supersonic commercial flights. More studies are required to gauge whether the features of X-59 prototype can be directly translated to a larger commercial transport and if so, its fly- worthiness [44].

Conclusion

The phenomenon of sonic boom has restricted the operations of commercial supersonic flights over inhabited areas. This work explains the basic concepts of sonic boom and reviews the effects of the sonic boom on people and structures, including the impact on indoor listeners inside these structures. We explain the impact of aircraft design and operational parameters like aircraft Equivalent Area, Altitude, and Mach Number on the boom signature. With the development of high- fidelity CFD and wave propagation programmes like PCBoom, analysing new designs has become easier and understanding of the contribution of various configurations on ground signatures has improved. We also reviewed the literature on proposed boom- reduction methods. Interestingly, the different types of reduction proposals aim to produce smaller and stretched- out shocks, which are not likely to produce a response in an outdoor listener. However, an indoor listener can still perceive the vibrations and rattles even from a highly modified sine-shaped signature causing safety concerns and annoyance. This is likely to prove an obstacle to overland flights. We agree with Haglund's [31] conclusions that while concepts like wing dihedral, etc. could be employed for boom softening, the constraint of limiting penalties in aircraft performance would limit softening modifications and configurations. These configurations and modifications have adverse effects on aerodynamics, low- speed efficiency and minimum take-off field lengths and noise problems which require significant developments before any commercial developments. In spite of the challenges in designing boom-free supersonic aircraft, the development of X-59 research aircraft through NASA's QueSST Program looks very promising, and it makes this field of study one of the most exciting in the aviation industry today.

Acknowledgments

I would like to thank my advisor for the valuable insight provided to me on this topic.

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