Review of Current Sonic Boom Studies

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Several aspects of the sonic boom phenomena are currently under investigation at The Boeing Co. This work, supported by the NASA and the FAA, includes an in-depth analysis of sonic boom measurements recorded at the BREN tower, a summary and evaluation of sonic boom investigations done in the last decade and a half, and configuration studies to determine practical lower bound sonic boom limits. The BREN tower test program yielded unique and valuable data because it was the first time that vertical profile measurements were made through caustics produced by maneuvers and atmospheric refraction. The objective of the second effort is to compile in a single reference an annotated abstract, including significant results, for each published sonic boom study and to provide a comprehensive review of the current state of the art to aid future researchers. The configuration work is devoted toward determining the feasibility of supersonic transport type airplanes with a primary design goal of acceptable sonic boom characteristics. Each of these investigations is briefly reviewed and significant results are discussed.

Introduction

THE sonic boom phenomena has received considerable attention since its first observation shortly after World War II. Since then the accumulated knowledge resulting from intensive theoretical and experimental investigations has led to a broad understanding of the various aspects of this form of aerodynamic noise. Because of its influence on commercial supersonic transport operations it still remains a subject of interest. The purpose of this paper is to summarize the current sonic boom investigations underway at The Boeing Co.

This work includes an in-depth analysis of measurements recorded at the extremities of shock waves, a summary and evaluation of sonic boom literature and the state of the art, and airplane configuration studies to determine practical lower bounds for sonic boom intensity. The majority of this work has been funded by the NASA and the FAA as a portion of their advanced technology studies. Each of these investigations will be briefly reviewed and significant results will be summarized.

Analysis of Measurements Near Shock Wave Extremities†

A flight test program was planned and conducted by NASA during the fall of 1970 to obtain information on the behavior of airplane generated shock waves near caustics formed by atmospheric refraction and maneuvers.[1] This test series was of significant interest because of the inability of current theoretical methods to produce valid information near these extremes of the shock wave system. The methods are generally based on linear theory and they fail in these regions because the second order effects, which were ignored, become dominant. For this reason, it was felt that such test data would provide guidance for continuing theoretical investigations and would also yield a basis for checking the validity of resulting methods. These data were studied in depth to more fully interpret the results and to determine the range of validity of present methods.[2]

The test program was conducted at the BREN tower on the AEC's Proving Grounds in Nev. The tower was instrumented to obtain both pressure signature measurements and recordings of the meteorological conditions. Additional meteorological data were obtained by a nearly 100 ft tower, radiosondes, and an instrumented light airplane.[3] The ground around the tower was likewise instrumented. This test series was the first time vertical measurements had been obtained through shock waves produced during threshold Mach number flight, level flight accelerations, at the lateral extreme of the shock-ground intersection, and during near sonic flight. The vertical pressure surveys significantly increased the data gathering capability relative to previous programs. The sketches in Fig. 1 illustrate the flight procedures used to obtain data for the first three conditions mentioned above. These cases are reviewed in this paper.

Threshold Mach Number Data

Weak shock waves produced during supersonic flight travel at nearly the local propagation speed of sound. For this reason, gradients in the propagation speed will influence the path the shock waves will follow to the ground. If the propagation speed increases as the ground is approached, the shocks will be refracted away from the ground. Because of this it is possible to fly at Mach numbers greater than 1 without producing sonic boom noise on the ground. Such an operation has been called flying below the threshold Mach number.

The threshold Mach number is the value for which the shock waves will just reach the ground; Mach numbers below this will result in no shocks on the ground; Mach numbers above this will result in noise on the ground. A series of passes were made directly over the tower at and slightly below the threshold value so that the shock wave characteristics at its extremity could be measured. (This is depicted in the left-hand sketch in Fig. 1.) In general, the measurements indicated that the sonic boom pressure pattern preserved its identify above the extremity (which is also termed a caustic), was slightly amplified at the caustic (about 1.5 to 1.8 times the free air value) and degenerated to an acoustic type disturbance of very low intensity below the caustic.

Nearness to the threshold flight condition (i.e., caustic above the ground) can be obtained by comparing the airplane ground speed to the local propagation speed. When the ground speed is less than the local speed of propagation the caustic will be above the ground and the characteristic sharp booms will not be observed. The variation of observed overpressure and subjective responses with speed

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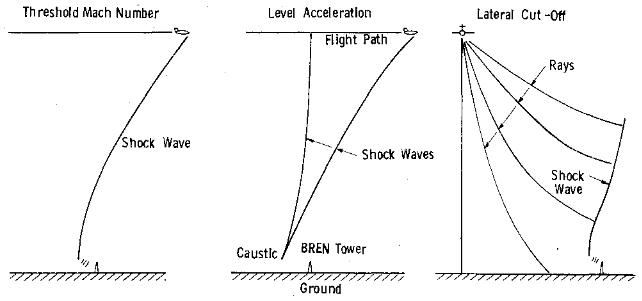

Fig. 1 Summary of test conditions.

increment is illustrated in Fig. 2. The subjective observation is noted by the data symbol and typical measured signatures are also indicated. For the meteorological conditions which existed during these passes it appears that the airplane ground speed should be 20 to 30 fps less than the local propagation speed so that nothing greater than low rumbles would be observed. This noise could be equated to very distant thunder. These data also clearly demonstrate that it is possible to predict with reasonable accuracy the threshold Mach number. This is evidenced by the fact that all the pressure signatures observed for flights at speeds more than about 10 fps below the local propagation speed were acoustic in nature, i.e., they did not contain the sharp pressure rise typically induced by shock waves. Such results indicate that the caustic is above the point of measurement.

When weak shock waves intersect the ground at an oblique angle the are reflected from it at the same angle. This reflection causes the observed overpressure to be higher than the value in free air. For smooth reflecting surfaces the overpressures are nearly doubled. Since sonic boom calculations are made for free air conditions a factor is applied to account for the influence of the ground. This is called the reflection factor, K_R, and is the ratio of the free air pressure to the ground observed pressure.

This test series provided a unique opportunity to measure the variation of the reflections factor with shock wave angle. Data measured on the tower and on the surrounding ground microphones were used to compute an experimental value of K_R. The results are shown in Fig. 3 which indicates a gradual decay toward a value of 1 as the shock waves become normal to the ground. This phenomena yields some interesting conclusions. As was pointed out above, some slight magnification in signature pressures was observed on the tower near the threshold Mach number caustic. However, as the caustic is formed the shock waves become normal to the ground, the usual doubling due to reflection would not occur and one would expect to

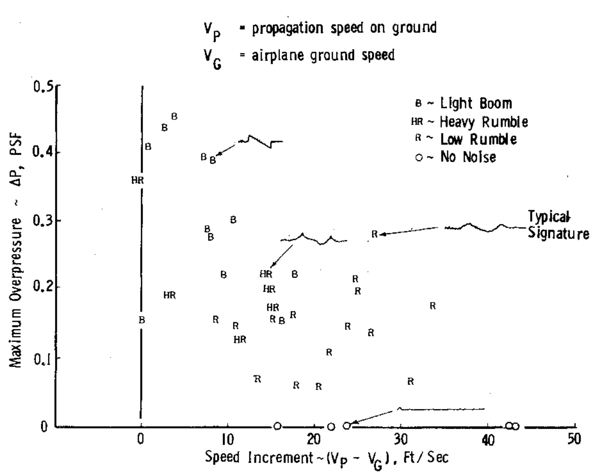

Fig. 2 Noise measurements near threshold mach number.

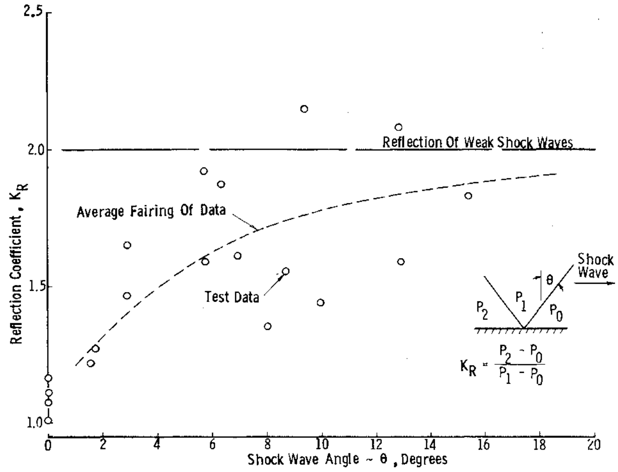

Fig. 3 Variation of reflection factor near cutoff.

observe little or no increase on the ground. This reasoning was supported by the ground microphone measurements.[2]

Level Acceleration Data

Airplane maneuvers such as accelerations and turns form caustics which are a result of folds in the shock waves. This aspect was measured by accelerating the test airplane over the tower so that the caustic would intersect it somewhere between the ground and the top. Previous calculations assuming average meteorological conditions were used to position the airplane and these were quite acceptable. This indicates that the location of the caustics for a given maneuver can be predicted with good accuracy.

The characteristics of the acceleration caustic are illustrated in Fig. 4 which shows a cross section through the shock wave and several observed signatures as measured on the tower. To obtain these results shock wave arrival times were converted to distance relative to the tower. The shock system can be seen to consist of a leading wave and a trailing wave, joined at the caustic (or fold) about 100 ft above the ground. This case illustrates the development of the caustic and the history of the pressure signatures approaching and leaving it.

As the shock wave pattern develops during the acceleration, signatures move down the leading wave, through the caustic and then back up the trailing wave. The signature shape approaching the caustic along the leading wave remains relatively unchanged until it is very near the caustic. When it reaches a distance of 200 to 500 ft above the caustic nonlinear effects begin to dominate the signature shape and it changes from an "N" shaped wave to a "U" shaped wave similar to that shown at the caustic. Signatures in the trailing shock resemble the caustic signature

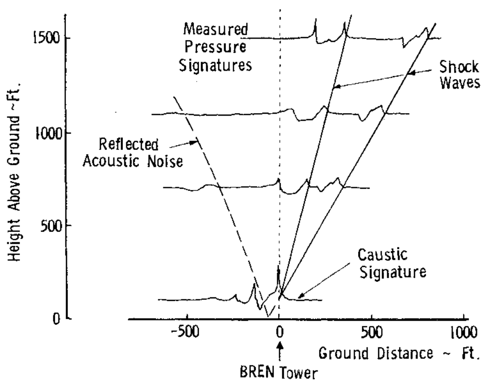

Fig. 4 Measurement of acceleration caustic.

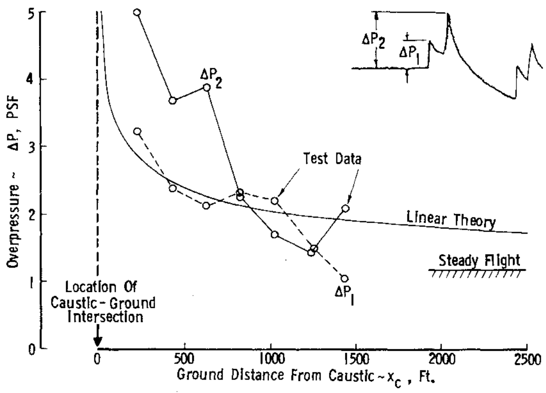

Fig. 5 Overpressure magnification near acceleration caustic.

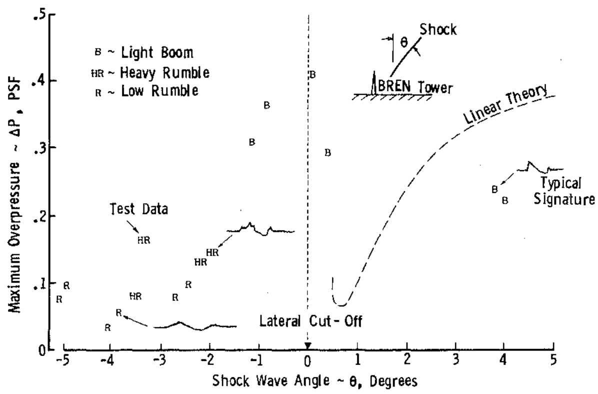

Fig. 6 Overpressure variation near lateral cutoff.

illustrating the effect of passing through the caustic. These data also indicate that some acoustic disturbances precede the caustic to the ground. These disturbances are indicated in the figure and can be seen in the signatures.

As the pressure signatures approach the caustic they become amplified and change shape. The variation in overpressure for this set of data is shown in Fig. 5 as a function of the horizontal distance from the caustic-ground intersection. The first pressure jump of the leading and trailing waves are compared with the predictions of the linear theory of Hayes.[4] The theory is not valid for the trailing wave (ΔP_2) because these signatures have passed through the caustic and have been dominated by second order effects. For this case, the leading shock pressure magnitudes are predicted reasonably well very close to the caustic while the trailing values are considerably higher. A reference value of overpressure is shown and the maximum observed pressure is about five times the steady flight value. This magnitude of amplification is consistent with previous measurements.[5,6]

Lateral Cut-Off Data

The sonic boom-ground intersection under the flight path is of finite width because the increasing propagation speed refracts the shock waves traveling to the side of the airplane. The lateral edge of the carpet experiences complete cutoff of the sonic boom noise in much the same manner as that described for the threshold Mach number flight. Data were recorded in this region by displacing the airplane to the side of the tower. Again, previous calculations were used to position the airplane and the results were quite acceptable, indicating the ability to accurately predict the location of lateral cutoff.

The data shown in Fig. 6 summarizes the measurements obtained during this phase of the test. Measured overpressures and subjective responses are shown as a function of the shock wave angle with respect to the vertical. The theoretical variation is shown for comparison. Complete refraction occurs when the shock waves are perpendicular to the ground, so that for positive angles N shaped waves were recorded, with booms and rumbles occuring near zero degrees and low rumbles occuring shortly beyond cutoff. Typical signature shapes are sketched on this figure for reference.

A slight increase in overpressure at cut-off relative to those measured just prior to it is evident from these data. (The maximum overpressure under the flight path for this case is about 1.2 psf.) The low magnitude of the increase is the result of the formation of a caustic with some amplification being off-set by a halving of the usual ground reflection effect. Linear theory would predict infinite overpressures at lateral cutoff due to the neglect of higher order effects, but it appears to be reasonably accurate to within about 2 to 3° of cutoff.

Summary and Evaluation of Sonic Boom Studies‡

During the past decade and a half over 800 technical papers have been published on the subject of sonic boom. This work has led to the depth of our current understanding of the subject. Such a substantial number of papers represent a considerable challenge to new workers in the field who are attempting to determine the objective of worthwhile studies and the location of accurate references. In an effort to preserve this knowledge in a workable form, an annotated review of these papers is currently being prepared.

The purpose is to compile in one document the analytical and experimental results to date of all sonic boom investigations. This document will contain two major sections. The first will consist of a comprehensive basic review of the state of the art and the second will contain individual capsule summaries of work pertaining to sonic boom generation, propagation, and response. Thus, a comprehensive reference volume of all sonic boom work performed to date will be provided. The content is illustrated in Fig. 7 in block diagram form. This document will be available in late 1973 or early 1974.

Minimization of Configuration Sonic Boom Characteristics

In principle it is possible to design an airplane configuration to produce any type of sonic boom signature. Whether or not this design represents a reasonable commercial airplane is quite another matter. Both conventional and unconventional means of boom minimization have been suggested. Recently a figure of merit was introduced by Seebass and George[7] to judge the effectiveness of these schemes. Howell, Sigalla, and Kane[8] investigated the influence of configuration modifications to minimize sonic boom on the factors which affect airplane viability and Ferri[9] has studied several low sonic boom aerodynamic designs.

This portion of the paper contains a summary of recent work on determining the physical constraints on an airplane with a primary design goal of acceptable sonic boom.

Constraints

A practical airplane configuration must satisfy many varied and often conflicting constraints. For instance, maximum aerodynamic efficiency during cruising flight is achieved by designing the wing to have a large sweep

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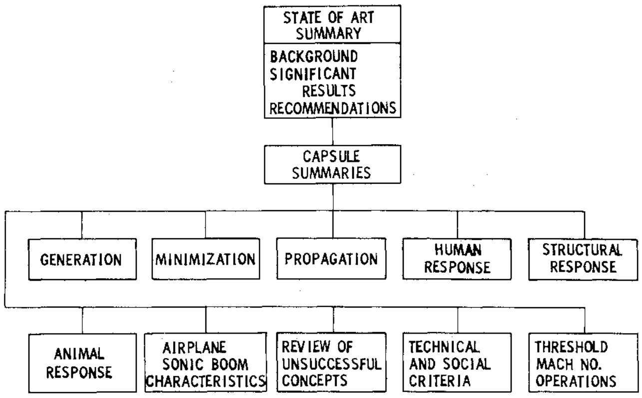

Fig. 7 Summary of sonic boom literature.

angle. The airplane must, however, takeoff and land and this would dictate a wing with a small sweep angle. In addition, for a fixed span the structural weight of the wing increases with increasing sweep. These considerations lead to selection of a compromise value of wing sweep.

Other practical constraints are discussed in more detail in Ref. 8. Some of the obvious limitations are those on airplane size and weight. The physical airplane cannot be unlimited in size because the structure would become too heavy. On the other hand, the minimum weight is limited for a given size because the airplane must be structurally safe, must carry a payload and fuel and must be able to operate over practice ranges at reasonable costs. Airplane weight and size are the two most influential parameters that the airplane designer has to work with when considering sonic boom minimization.

Effect of Area Progression

The procedure for calculating the relationship between an airplane and the sonic boom signature it produces is well established. Basically, it consists of converting the geometry into an equivalent body of revolution and then computing the pressure field surrounding it. The method is schematically illustrated in Fig. 8.

Given a particular airplane shape it is converted into an equivalent area distribution by passing cutting planes through it and calculating the magnitude of the area intersected. The orientation of the cutting plane is determined by the Mach number and the azimuth angle of the point of interest in the surrounding flowfield. The total distribution of equivalent area is composed of two contributions. These are the portion due to the airplane volume and the portion due to the lift that is generated during flight. The base area is directly related to the airplane weight. The resulting distribution of area is used to compute the pressure signature produced at the point of interest. This calculation procedure is explained in more detail in Ref. 10.

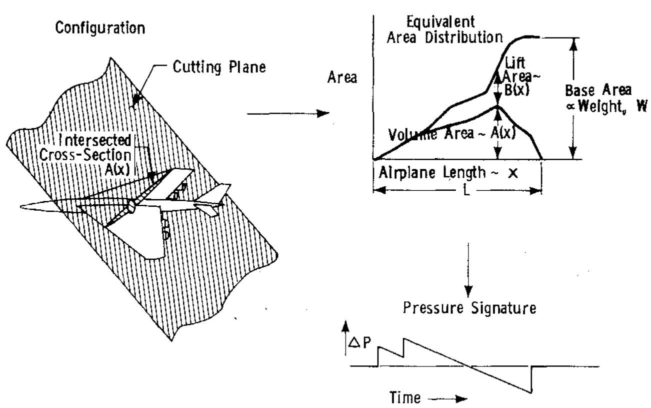

Fig. 8 Determination of configuration influence on signature shape.

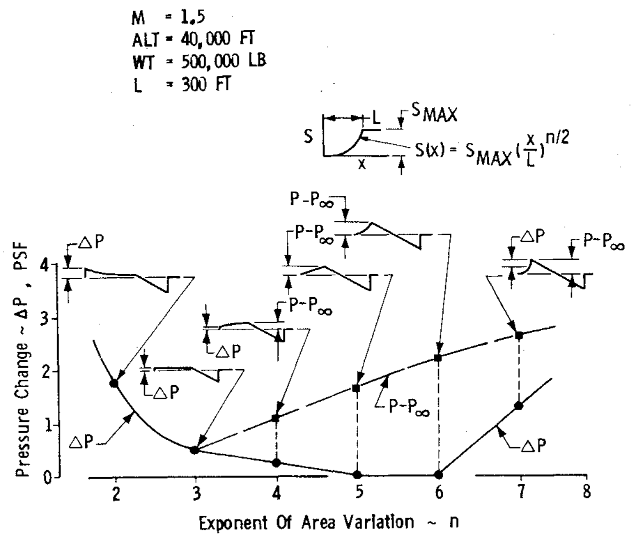

Fig. 9 Effect of area distribution on pressure signature.

The relationship between the equivalent area distribution and the pressure signature makes it possible to approach the design procedure in reverse, i.e., specify a pressure signature and determine the airplane shape required to produce it. The data in Fig. 9 show the relationship between signatures and area distributions for a particular family of progressions. These results show that a wide range of signatures are possible with a relatively simple family of area progressions. It is also apparent from these data that the signature shape is closely related to the shape of the equivalent area distribution, and hence to its length and base area. These in turn are dependent on the length of the airplane and its weight.

With this knowledge, it is possible to calculate the required airplane length and weight to produce a given signature with a given overpressure. An example of such an exercise is shown in Fig. 10 for some of the family of area distributions shown in the previous figure. These data were calculated for a required overpressure of 1.0 psf, a flight altitude of 60,000 ft and two Mach numbers, 1.5 and 2.7. The results show that increased weights can be flown at the given overpressure by either increasing the configuration length or by reducing the airplane Mach number.

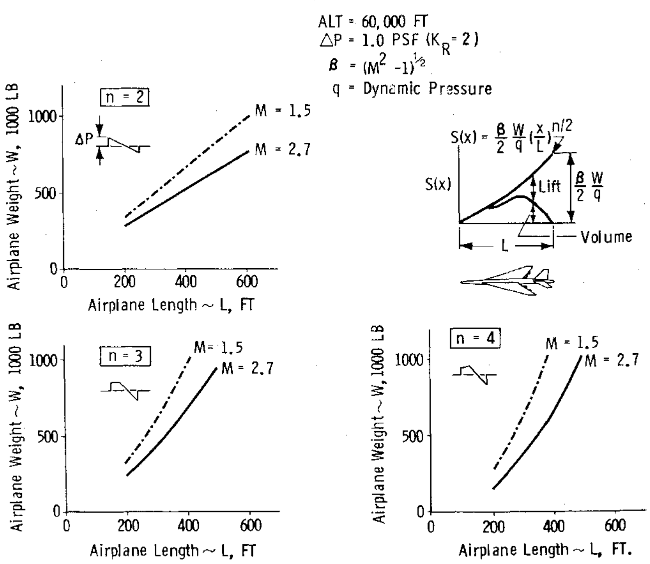

Fig. 10 Configuration characteristics required for overpressure of 1 psf.

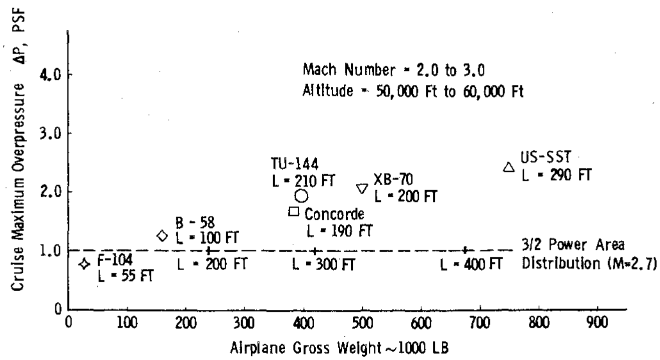

Fig. 11 Current supersonic airplane configuration and sonic boom characteristics.

The former is not too surprising, but the latter would not intuitively be expected. This occurs because shock waves have a tendency to coalesce more rapidly at higher Mach numbers in a stratified media. In addition, calculations at other altitudes have shown that altitude reductions will also allow weight increases. These trends were noted earlier by Buseman.[11]

To give some perspective to the results shown in Fig. 10 a summary of current supersonic airplane characteristics is shown in Fig. 11. The cruise overpressure of each is shown as a function of its maximum taxi gross weight and length. For reference the weight and length required to produce a 1.0 psf overpressure with a 3/2-power area distribution is reproduced from the previous figure. A comparison of these data indicates that if the total area distribution of the US-SST conformed to the 3/2-power shape it would have to be about 350,000 lb lighter in cruise than its estimated weight just before takeoff to produce the 1 psf level. Similarly, the Concorde would have to be about 150,000 lb lighter. This illustrates the magnitude of the task facing airplane designers.

The above results indicate that substantial improvements in current technology standards would be required to achieve viable commercial airplanes with low sonic boom levels. The work outlined above is continuing with the objective of defining the magnitude of technology advances required to achieve the goal of an acceptable sonic boom. This effort will represent a significant contribution toward defining a sonic boom lower bound in terms of practical transport configurations.

Conclusions

The sonic boom phenomena is still a subject of active interest. Current activities at The Boeing Co. include a detailed study of data measured at the extremities of shock waves, a summary and evaluation of the state of the art and sonic boom literature and configuration studies devoted to establishing a lower bound sonic boom intensity for practical transport airplanes. The results of these studies are directed, respectively, toward: a) an improved understanding of the phenomena at caustics formed by atmospheric refraction and maneuvers; b) a single reference volume designed for use by future researchers in determining the extent of past research and areas of useful future research; and c) defining a sonic boom lower bound for viable transport type airplanes.

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