NOISE AND SONIC BOOM CONSIDERATIONS IN THE OPERATION OF SUPERSONIC AIRCRAFT

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ABSTRACT

The nature of the community noise problem is reviewed and is evaluated particularly for initial climbout, landing approach, and ground operations. Mention is also made of the noise induced structural response problem during takeoff and cruise. Discussions are given of sonic boom ground overpressure exposures for current supersonic flight operation and how these exposures are affected by the atmosphere and by aircraft maneuvers. Brief remarks are included about various operations for which some sonic boom community response information has been obtained and for which building response is noted to be an important factor.

INTRODUCTION

Since future aircraft such as the supersonic transport will be integrated into existing air traffic systems, it is required that their community noise characteristics be acceptable. This is required for landing and takeoff operations during which power plant noise is an important consideration, and also for acceleration and cruise for which the sonic boom is important [1].

The scope of this paper is indicated in Fig. 1. Altitude distance profiles are shown schematically, the shaded regions indicating the phases of the operation during which engine noise, flow noise, and the sonic-boom problem are important considerations. Brief mention is first made of airport community noise considerations during landing approach, takeoff, and initial climbout. Some discussion is also included on the structural noise problems due to both the engine and airflow excitation. The main portion of the paper is then devoted to the sonic boom problem, particularly to several important phenomena related to its operational aspects. Discussions are directed toward factors that affect the sonic-boom ground pressure signatures. In this regard, atmospheric and weather effects on shock-wave propagation, community reaction, ground building responses, and the responses of other aircraft are also included.

ENGINE NOISE

TAKEOFF AND INITIAL CLIMBOUT

Noise in the community due to the powerplant of the supersonic transport is, of course, a function of the type of powerplant used and the manner in which it is operated, as well as the configuration of the aircraft in which it is installed. The manner in which the airport noise situation is affected by operational procedures is shown in Fig. 2. In the top sketch are initial climbout altitude distance profiles for a current fan-powered, subsonic,

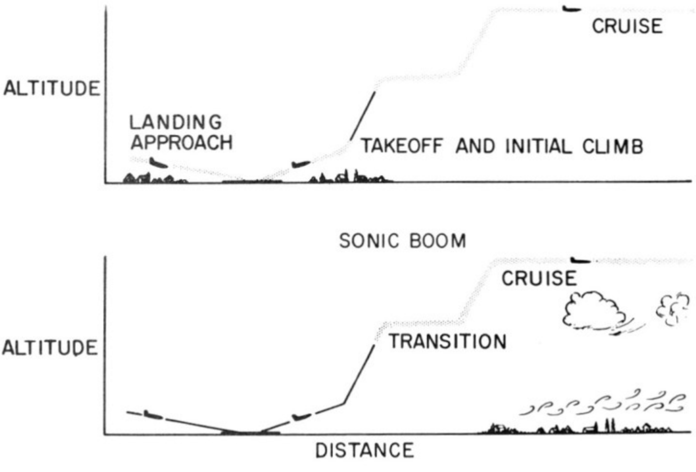


Figure 1. Altitude-distance profiles for a proposed supersonic transport mission showing noise and sonic-boom problem areas.

2,500-mile-range jet (solid line) and for some proposed supersonic transports (cross-hatched area). In the lower sketch are shown corresponding 110-db perceived noise level contours for both aircraft, the origin representing the start of takeoff roll. Several observations may be made. Because of the greater thrust requirements, the noise levels to the side of the runway are generally higher than those for the subsonic airplane. The takeoff distance is generally shorter, however, and the altitude over a given location in the community will be generally higher for the supersonic transport. Due to the operational flexibility of this type of aircraft, community noise levels may be comparable to or less than those of the current long-range aircraft. Power cutbacks during initial climbout are widely used for current aircraft because of noise considerations, and will no doubt be a standard procedure for the supersonic transport operations.

LANDING APPROACH

The noise during landing approach, which involves the geometry of the engine installation and the aircraft operating characterisitcs, is indicated schematically in Fig. 3. Shown in the figure is a range of perceived noise levels as a function of distance from touchdown as estimated for some proposed supersonic designs and a comparable current fan-powered subsonic transport. A 3° glide slope has been assumed in all cases. The solid line

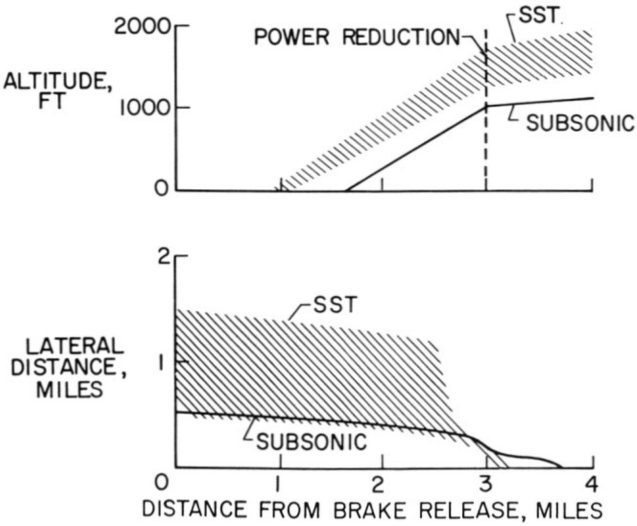


Figure 2. Altitude-distance profile for the climbout of a proposed supersonic transport, along with the estimated 110-db perceived noise-level contours on the ground.

represents the average perceived noise levels on landing approach for the current subsonic airplane. The shaded area represents the estimated landing approach noise levels for supersonic transport operations for a range of operating conditions and inlet configurations. The extent of the shading represents mainly the variation expected for varying amounts of suppression of inlet noise. The main point to be made is that some inlet noise suppression will be required to bring the landing noise levels of the supersonic transport below those of the current subsonic transports.

STRUCTURAL RESPONSE TO NOISE

The noise-induced structural response problems of the supersonic transport which are important from the standpoint of maintaining acceptable cabin noise levels and minimizing sonic fatigue are indicated in Fig. 4. The shaded areas of the airplane plan-view sketch at the top of the figure represent regions where noise loads may be a design consideration. At the bottom of the figure are sample flow noise and engine noise input spectra estimated for the proposed operating conditions of the airplane. The flow noise loading will exist for nearly the entire duration of the flight (see Fig. 1). The curve of the left diagram is based on recent NASA free-flight measurements at the appropriate Mach numbers and Reynolds numbers [2]. For local flow separation, surface roughness, or shock-wave interaction conditions, the levels would be higher as indicated by the shading [3].

The noise from the engines is believed to be significant for only a short period during each mission, and only the structure in the vicinity and to the rear of the engines, as indicated by the cross-hatching in the sketch, will be affected. It can be seen that the estimated spectra peak at lower frequencies and reach higher sound pressure levels than the flow noise spectra

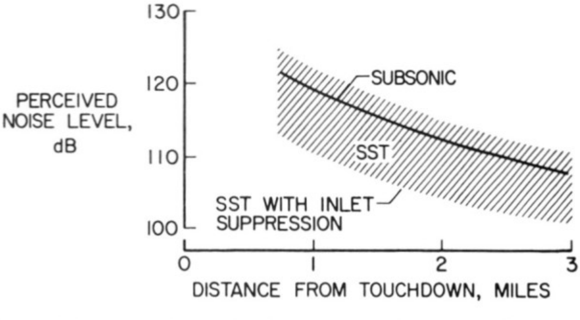


Figure 3. Estimated ranges of perceived noise levels for proposed supersonic transports during landing approach as a function of distance from touchdown.

[4]. It is believed that engine noise structural response experience to date is directly applicable; however, the flow noise problem has not been satisfactorily defined, particularly for long-term exposures at elevated temperatures.

SONIC BOOM

Over the past several years there have been many studies relating to the problem of predicting sonic boom ground pressure exposures as well as their significance with regard to community responses (see, for instance, Refs. 5–15). The details of the pressure signatures are believed to be of particular significance in the response problem. Thus the opportunity is taken to discuss several detail factors which influence signature shape and to make brief remarks regarding sonic boom induced response phenomena.

FACTORS AFFECTING SONIC BOOM WAVE SHAPE

Aircraft Configuration and Altitude. During a series of special supersonic flight tests at altitudes below 400 ft, there was opportunity to measure the shock-wave ground pressure signatures for two different aircraft configurations [16]. These results, along with sketches of the aircraft configurations involved, are shown in Fig. 5. It can be seen that

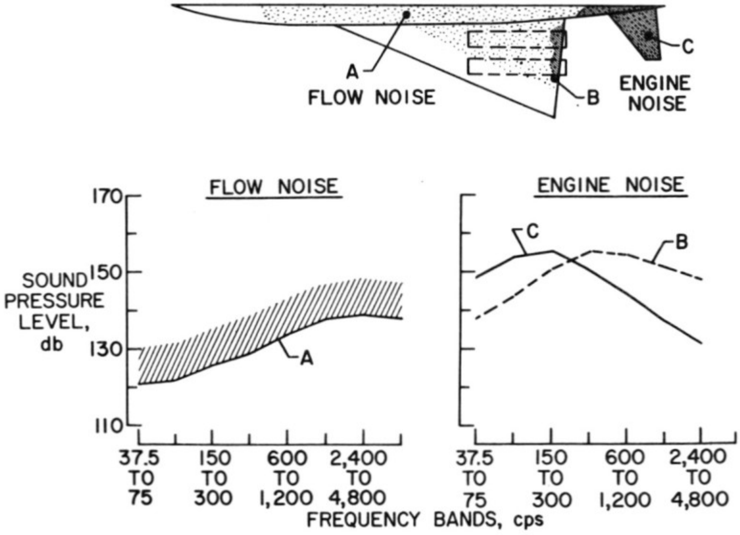


Figure 4. Estimated flow noise and engine noise input spectra to the structure of proposed supersonic transports.

the pressure traces contain a number of peaks, and that these occur in a different sequence for each of the aircraft. A correlation was established between the discontinuities in the near-field pressure traces and the protuberances in the external geometry of the airplanes. This correlation is especially evident in the right-hand figure for airplane *B* since, in this case, each pressure discontinuity occurs at a time interval consistent with the geometric details of the airplane and the airplane passing rate.

These waves develop in a systematic manner from the rather complex near-field signatures of Fig. 5 to the more usual "*N*-wave" shapes at larger distances. The manner in which this development occurs as a function of distance for airplane *A* is illustrated by the record traces of Fig. 6*a* which are directly comparable. The top pressure signature trace is for an altitude of 10,000 ft, the middle trace is for an altitude of 30,000 ft, and the bottom trace is for an altitude of 50,000 ft. This particular fighter aircraft has an inlet shock which propagates slowly in the forward direction and is evident in the pressure signatures at altitudes up to about 50,000 ft. At altitudes above this, the signature has the characteristic sonic boom *N*-wave shape.

In Fig. 6*b* comparable shock-wave signatures are shown for a bomber type airplane, and these are seen to differ in detail from those previously presented. For altitudes from 30,000 to 70,000 ft, the signatures remain essentially *N*-wave in character. It should be noted, however, that the wavelengths for the bomber aircraft are markedly greater than those for the fighter aircraft due to the increased aircraft size. The relation between wavelength of the signature and aircraft operating conditions is shown in greater detail in Fig. 7.

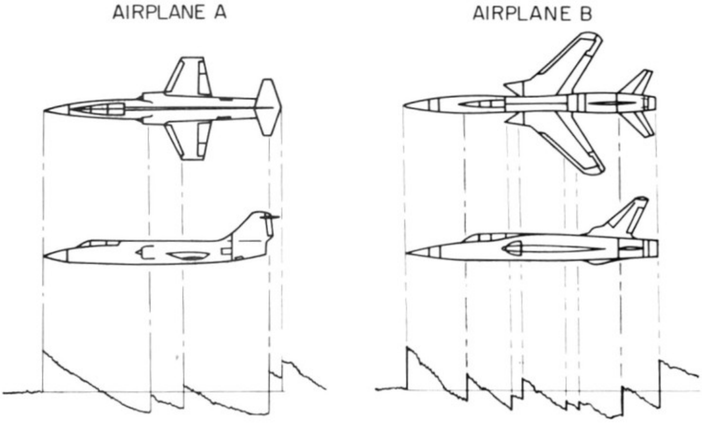


Figure 5. Measured near-field shock-wave ground-pressure signatures for two fighter aircraft in steady flight at a Mach number of about 1.10.

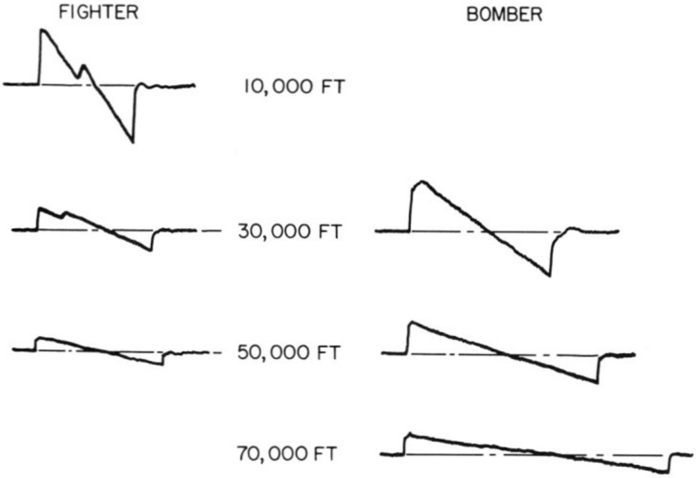


Figure 6. Measured shock-wave ground-pressure signatures for various altitudes for both fighter and bomber aircraft in steady flight in the Mach number range 1.2 to 2.0.

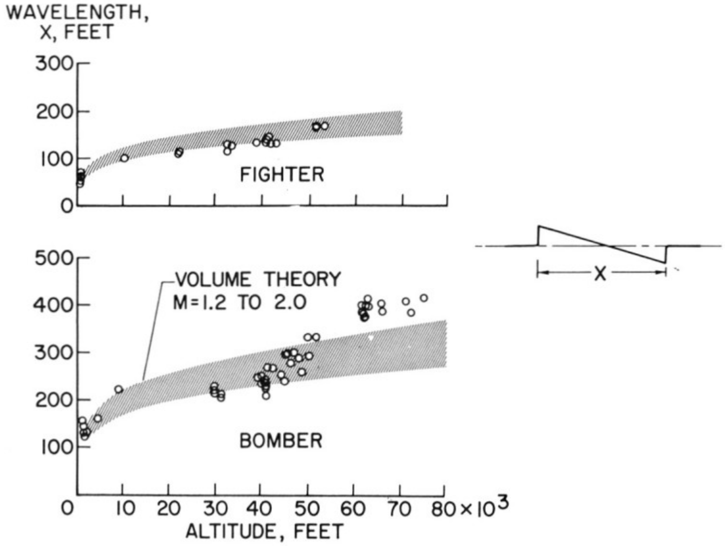


Figure 7. Measured and calculated sonic-boom ground wavelengths for fighter and bomber aircraft in the Mach number range 1.2 to 2.0 as a function of altitude.

In Fig. 7 the wavelength is shown as a function of altitude for the fighter and bomber aircraft of Fig. 6. The wavelengths were determined, in all cases, from measurements of time interval between the two compression phases of the wave and the measured true ground speed. The data for the fighter airplane are noted to be in good agreement with the calculated curves based on volume theory [6], and these calculated curves in general bracket the data points. In the case of the bomber airplane, however, the wavelength values exceed the calculated values based on volume theory, particularly at altitudes above 50,000 ft for which conditions it is known that lift effects are important.

Accelerated Flight. During accelerated flight of an aircraft, whether it be longitudinal, lateral, or vertical, the resulting ground pressure patterns will be affected in several ways, as suggested by the data of Figs. 8 and 9. In order to provide a picture of the sequence of events that occur during the formation of the shock-wave pattern on the ground for a longitudinal acceleration maneuver, Fig. 8 has been prepared [17]. This figure gives a perspective view sketch of the shock-wave patterns at successive times during the maneuver, and for simplicity only the bow shock-wave patterns are shown. At the bottom of the figure are tracings of actual pressure signatures measured during a programmed longitudinal acceleration flight, and these pressure signatures are believed representative of those occurring at such locations along the ground track as (a), (b), and (c) of the top sketch. It can be seen that multiple-shock patterns exist in the vicinity of points (b) and (c), and thus a more complex pressure signature, as confirmed by measurements, would be expected too ccur at these points. A progression can be seen of decreasing time interval between the individual N-waves in moving from point (c) back up the track toward point (a), until at point (a) the waves essentially coalesce. This coalescence at point (a) results in a so-called "superboom," for which the peak overpressure is higher than would be experienced for an aircraft in steady flight at the same altitude and Mach number.

Similar results would be obtained for other maneuvers involving aircraft acceleration. One important consideration is the shape and size of these superboom areas on the ground. Such areas are shown in Fig. 9 for some common flight maneuvers. The longitudinal acceleration case is illustrated at the top of the figure. As indicated in the sketch by the thin shaded areas, superbooms occur over relatively small expanses on the ground. The dimensions are such that total superboom area (area of shading only) is approximately one square mile. The pressure buildups in these shaded areas are believed to be a function of the rate of acceleration of the aircraft, but for a practical operating range are approximately two times the corresponding steady-flight values. Also of possible concern in the operation of

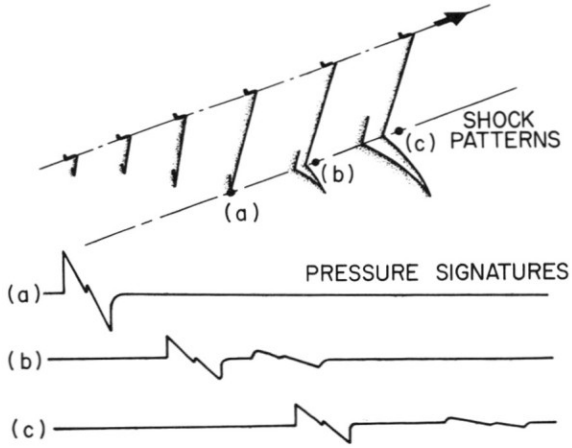


Figure 8. Measured sonic-boom pressure signatures at three locations on the ground track of a fighter aircraft accelerating from about Mach number 0.98 to 1.20 at an altitude of 14,000 feet.

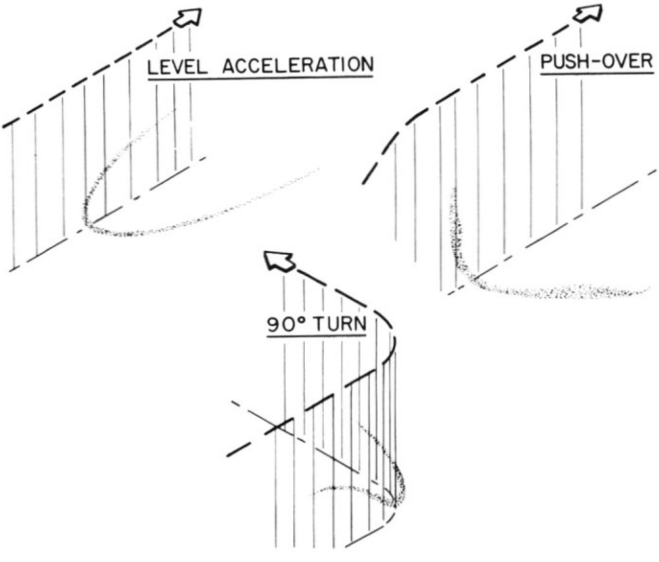
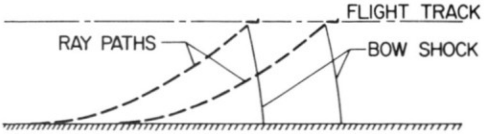


Figure 9. Areas on the ground exposed to superbooms resulting from three different aircraft maneuvers.

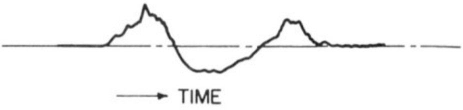
supersonic aircraft are such maneuvers as horizontal turns and pushovers as might occur during changes in course and airplane attitude. In these latter instances the ground patterns of pressure buildups are different in shape as indicated in Fig. 9, and because of the higher accelerations involved the buildup factors may tend to be higher (values up to 4.0 have been measured) and the areas smaller than for the case of longitudinal acceleration.

Atmosphere and Weather. The propagation of shock waves through a real atmosphere involves many interesting phenomena, some of which are associated with the normal undisturbed atmosphere and others with the so-called weather effects involving the dynamics of the atmosphere. It is important that all of these phenomena be understood since they may be significant factors in the operation of supersonic aircraft.

For an aircraft in steady-level flight, the rays are curved forward due to the normal temperature gradients in the atmosphere and the higher associated sound speed near the ground. For the special case of grazing incidence, as indicated in the sketch of Fig. 10, the rays are squeezed together in the region of the ground with an associated pressure enhancement. Such a pressure buildup was predicted analytically in Ref. 8. Experimental confirmation was obtained during a recent flight test for which the airplane altitude was 36,000 ft, the Mach number was about 1.39, and there was a headwind condition at altitude. The resulting overpressure on the ground track was somewhat greater than would normally be expected for these flight conditions and had the waveform shown at the bottom of the figure. It should be noted that such pressure enhancement is



(a) SCHEMATIC OF SHOCK FRONT AND RAY PATH



(b) SONIC BOOM GROUND PRESSURE SIGNATURE

Figure 10. Measured sonic-boom pressure signature on the ground track for a condition of grazing incidence.

not due to geometric focusing similar to that already discussed for the acceleration case, but rather is due only to the refraction effects of the atmosphere.

When the aircraft is operated such that a definite ground intersection pattern is established, the normal refraction of the atmosphere will determine the lateral extent of the pattern as indicated in the sketch of Fig. 11. Normally the overpressure will decrease as the lateral distance increases. Shown on the figure are some sample waveforms measured under stable atmospheric conditions at different distances from the ground track. The only marked difference in the character of the waves occurs in the region of lateral cutoff, for which the pressure traces depart from the characteristic *N*-wave shape and assume the more complicated form of the lower tracing of the figure. This lateral pressure trace is associated with observed rumbling rather than with the explosive type noise normally observed.

Superposed on the effects of a quiescent atmosphere with a normal temperature gradient are those of such other phenomena as wind and temperature anomalies. Such anomalies at relatively higher altitudes may, for some conditions, produce significant effects [18]; however, it is believed that the strongest effects are associated with the lower layers of the atmosphere, particularly the earth's boundary layer. An illustration of the type of result believed to be associated with atmospheric turbulence near the earth's surface is given in Fig. 12.

The data of Fig. 12 were derived from an accurately calibrated and oriented array of matched microphones in a region where the atmosphere

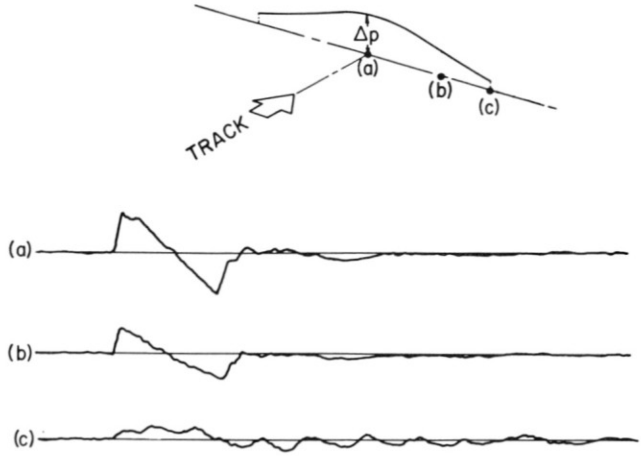


Figure 11. Measured sonic-boom ground-pressure signatures at three lateral distances from the ground track.

was believed to be turbulent in the lower layers. The variations in the wave shape as measured during one flight of a fighter aircraft are sketched in for the appropriate measurement locations. It can be seen that a wide variation in wave shape occurred, even over a distance on the ground of a few hundred feet. This resulted in substantial variations in the peak ground overpressure, the larger values being associated with the sharply peaked waves and the lower values with the rounded off waves. The scale of the ground pressure pattern variations is compatible with the predicted scale of turbulence in the lower atmosphere.

For some situations, particularly those involving the response of building structures, the impulse function of the wave may be more significant than the overpressure. The positive impulse, which is proportional to the area under the positive phase of the curve, is indicated schematically by the shading in Fig. 12. There is, of course, also a variation of the impulse function due to the effects of the atmosphere. The magnitude of such variations is, however, only about one-third of that noted for the overpressures.

RANGE OF OVERPRESSURE EXPERIENCE

Before some of the effects induced by sonic booms are discussed, it is helpful to become familiar with the range of sonic boom exposures for which some operational experience is available. The ground overpressures due to routine training operations involving two types of military aircraft

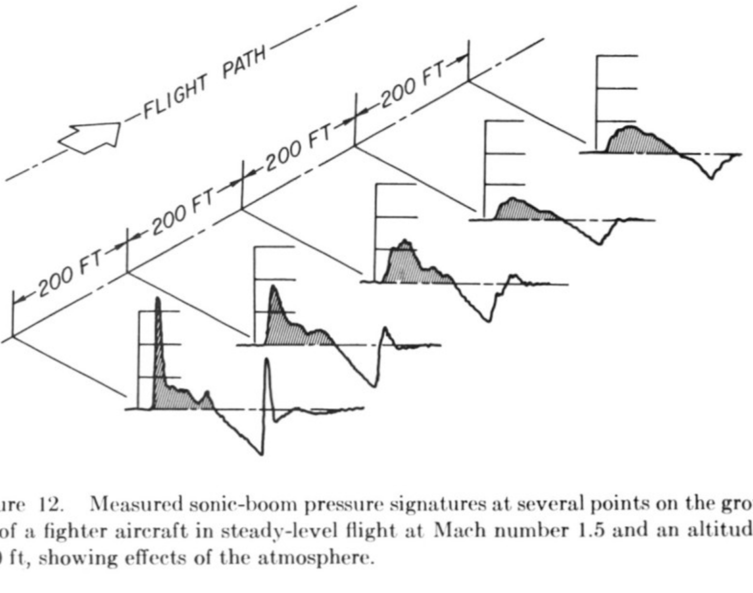


Figure 12. Measured sonic-boom pressure signatures at several points on the ground track of a fighter aircraft in steady-level flight at Mach number 1.5 and an altitude of 29,000 ft, showing effects of the atmosphere.

are shown in Fig. 13 as a function of aircraft altitude. It should be noted that such operations are limited to altitudes above 30,000 ft but have been carried on over many metropolitan areas in the United States. The vertical extent of the regions is determined largely by the weather effects. The stippled region relates to fighter aircraft for steady flight operations, and it can be seen that depending on the altitude of the operation, the associated overpressure range varies from less than 0.3 lb/sq ft to in excess of 2 lb/sq ft. The cross-hatched region relates to bomber operations. It can be seen that the overpressure range associated with these operations varies from less than 1.0 lb/sq ft to in excess of 3 lb/sq ft, again depending on the altitude. The upper hatched region is not well defined but has been estimated, based on fragmentary data, to encompass the superboom overpressure range associated with training maneuvers of both fighter and bomber aircraft.

RESPONSE PHENOMENA

Types of Complaints Reported. Of serious concern to the designers and operators of such aircraft as the supersonic transport is the manner in which communities will react to repeated sonic boom exposures. Studies to date have not been definitive enough to provide the final answers; however, the nature of the community response problem is suggested by the results tabulated in Fig. 14. These data were derived from a study of over 3,000 registered complaints in Air Force files and have been broken down into several categories, as indicated in bar graph form in the figure. It can

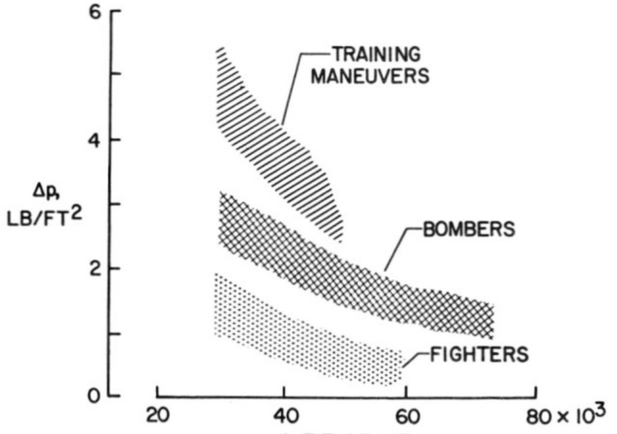


Figure 13. Estimated sonic-boom ground overpressures as a function of altitude for fighter and bomber aircraft during steady flight and for training maneuvers.

be seen that plaster cracks were reported most frequently and, in fact, were mentioned in 43 percent of the complaints registered. Cracks in window glass, walls, tile, etc., were reported to have occurred less frequently. It is believed significant that a large percentage of the complaint reports mentioned some type of damage, whereas only about 7 percent mentioned miscellaneous effects including annoyance only. The implication here is that the ability of the sonic boom to cause buildings to vibrate is very significant in the community response problem and is quite naturally associated with possible damage to the building. It should be emphasized that the data of the figure represented complaint reports received and these have not been evaluated to establish whether or not the damage referred to was caused by sonic booms.

Building Vibrations. In order to illustrate the manner in which buildings respond to a sonic boom input, the strain responses of several individual components of the primary structure of the building are reproduced in Fig. 15. Several characteristic features can be noted. For instance, the transient strain responses last for a longer period of time than that of the initial pressure loading, and each of the structural components has its own characteristic response [19,20]. It was noted in several building response studies that the natural vibration modes of the primary structure of the building as excited by the sonic boom occurred at frequencies in the range 5 to 30 cps, and such vibrations were readily observable inside the building. A further result of such studies indicated that strain levels induced in

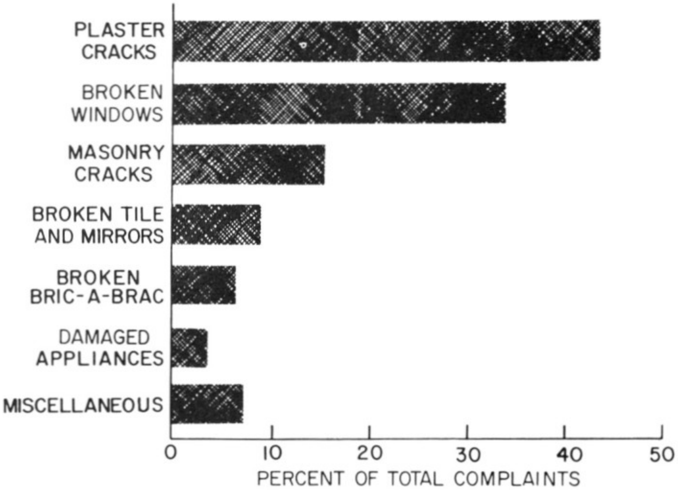


Figure 14. Breakdown of about 3,000 complaints due to sonic boom as recorded in U. S. Air Force files. (The above reported damage was not necessarily established as being due to sonic boom by engineering type evaluations.)

such primary structural members by sonic booms were very low in amplitude compared with the design loads of the building.

Most of the damage mentioned in the reports of Fig. 14 relates to the secondary structure of the building and, in most cases, to the interior surface treatments such as plaster, masonry, tile, glass, etc. There has been very little opportunity to observe directly the onset of damage to such secondary structural elements due to sonic boom exposure. There is available, however, some information developed as a result of the quarry blast problem [21], and in particular with regard to plaster ceiling surfaces. Some of these results are presented in Fig. 16. The amplitude of the ceiling being vibrated is plotted as a function of the frequency of vibration and, for convenience, lines of 0.1g and 1g accelerations are shown on the figure. The shaded region encompasses the data for which some plaster damage occurred during a large number of building vibration tests. Buildings exposed to actual blasting and for which measured acceleration amplitudes did not exceed 0.1g have exhibited no observable damage. It can be seen that the amplitude at which damage occurs falls off as frequency increases, and the shaded region seems to follow roughly the 1g acceleration line. The circle data points shown on the figure correspond to observations made during several sonic boom flight test programs and are associated with conditions of no observable damage. The limited results for sonic boom inputs are thus roughly consistent with the above vibration studies and quarry blast experience. It should be noted here that one difficulty in validating sonic boom induced damage is the fact that such damage as is reported to have been caused by sonic booms may also result from many other causes such as normal living activities, weathering, degradation of materials, settling, road traffic, etc.

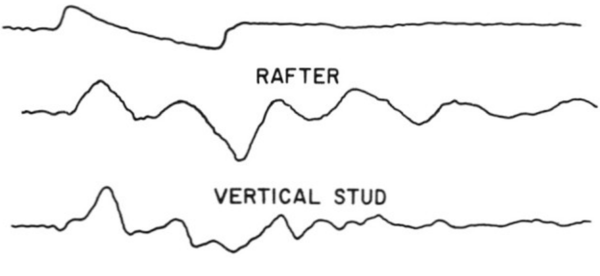


Figure 15. Sample strain time histories for components of a building exposed to sonic boom produced by bomber aircraft.

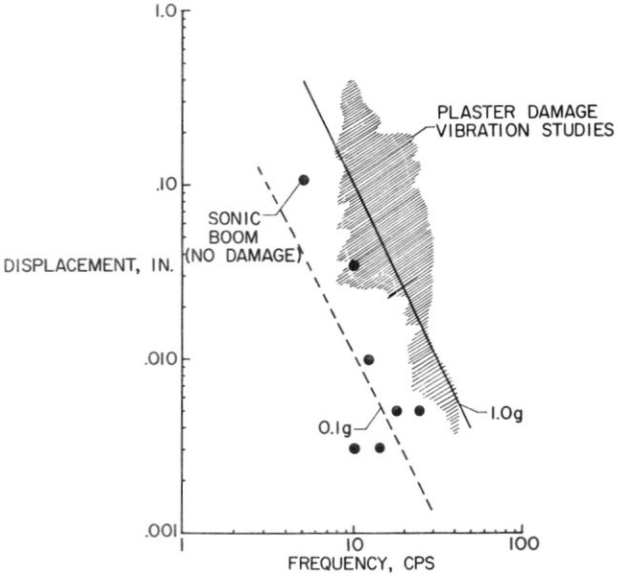


Figure 16. Summary of results from plaster ceiling vibration tests.

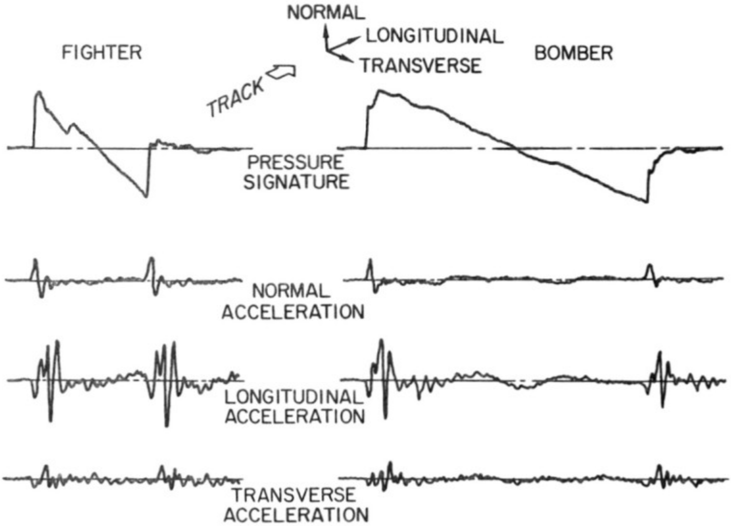


Figure 17. Measured sonic-boom-induced ground acceleration time histories along three axes for fighter and bomber aircraft.

Ground Motions. Since the passage of the shock front over the ground may excite accelerations in the surface layers of the earth, some definitive measurements have recently been made for two different types of aircraft. These data are shown in Fig. 17. The data shown on the left are for a fighter aircraft, and those on the right are for a bomber aircraft, the peak pressures being about equal. The acceleration traces of the figure correspond to measurements in three directions relative to the direction of flight of the airplane, as indicated in the sketch at the top of the figure. It can be seen that in all cases, short duration acceleration transients existed during the rapid compressions of the wave. The soil in this particular locality was such that the propagation speeds of disturbances in the surface layer were superseismic; i.e., faster than the apparent speed of propagation of the wave front along the ground surface. Several general observations can be made. For instance, the measured accelerations are consistently greater in the direction of flight and are consistently lowest in the direction perpendicular to the flight direction. The magnitudes of the accelerations for the conditions of the figure are apparently sensitive mainly to the overpressure value. The highest values of acceleration measured did not exceed 0.03g. These are noted to be markedly lower than the accelerations associated with the onset of earthquake damage.

Responses of Other Aircraft. There has been some concern in the past about possible adverse effects of shock waves on aircraft in flight, particularly small aircraft. A recent series of flight test experiments was

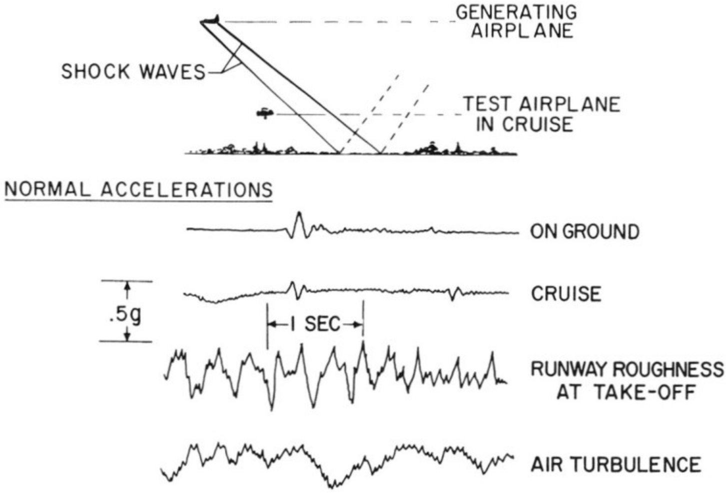


Figure 18. Measured normal accelerations of a light airplane exposed to sonic booms while on the ground and in flight.

accomplished in order to measure the acceleration response of several small airplanes to a range of shock-wave pressures [22). A sample of the type of result obtained is illustrated in Fig. 18. The highest level of acceleration measured during the experiments did not exceed 0.3g, even for pressures well in excess of those anticipated for normal supersonic commercial and military operations. These sonic boom induced accelerations, which were structural rather than rigid body motions, were judged to be small relative to those induced by such commonly encountered phenomena as runway roughness and moderate air turbulence. The general conclusions were that the sonic booms constituted no serious concern for the safety of all types of aircraft in flight.

CONCLUDING REMARKS

The engine noise, aerodynamic noise, structural response to noise, and sonic boom problems of future high-speed aircraft such as the supersonic transport have been briefly discussed. It was noted that the perceived noise levels close in to the airport and within its confines will probably be higher, whereas those in the surrounding community may be lower than for current transport aircraft. The physical nature of the sonic boom problem is fairly well understood, but some of its effects particularly on communities, are still not well defined. Although many hard-to-define human factors are involved, a major factor in shaping attitudes toward sonic booms is believed to be the matter of building vibration.

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COMMENTARY

BO LUNDBERG (*Director General, Aeronautical Research Institute of Sweden*): One may assume that a main object of the Oklahoma tests was to investigate public reaction and property damage for *average* boom intensities of 1.5 and 2.0 psf, respectively. Obviously, then, a fairly narrow band, or core, in the middle of the boom carpet is the most significant area if the flight tests are scheduled to produce 1.5 and 2.0 psf right beneath the flight path assuming steady flight and standard atmosphere.

In a paper by Mr. J. K. Power, FAA, "Sonic boom effects on light aircraft, helicopters and ground structures," June 1964, boom intensities are presented for all the 137 test flights which were made in February 1964 over Oklahoma City and scheduled to produce 1.5 psf. As only one value is given for each flight, one may assume that they were measured at one point on or close to the flight track. The mean of the 137 intensities is 1.21 and the standard deviation 0.31, the latter value agreeing very well with previous experience.

If follows that not even those Oklahoma citizens who live close to the flight track were subjected to a higher *average* boom intensity than about 1.2 psf, thus appreciably lower than the scheduled, significant level of 1.5 psf. In my opinion, this discrepancy could advantageously have been overcome by reducing the flight altitude sufficiently, so that the scheduled average value had been obtained.

More recently some information has been published by FAA—"Preliminary Data. Oklahoma City Sonic Boom Study"—for the whole 6 months test period, about boom intensities *exceeding* the two scheduled levels, 1.5 and 2.0 psf, the information apparently being based on several intensity measurements per flight. It is stated as a significant—perhaps encouraging—result that only about 15.6 and 11.7 percent, respectively, of the measured pressures actually did exceed the scheduled levels. Assuming normal distribution, the data yield mean intensities of only about 0.8 psf for the flights scheduled for the 1.5 and only about 1.0 psf for the 2.0 psf flights, the standard deviations being about 0.65 and 0.85, respectively.

I should add that it is open to considerable doubt whether the normal distribution applies to higher boom intensities. The value of mean intensity and standard deviation quoted are thus uncertain. Anyhow, the data indicate quite clearly for the intensity level scheduled at 1.5, a mean value lower than 1.2 and a standard deviation exceeding 0.31.

Could Dr. Hubbard tell us whether the measurements referred to (a) were also made on or close to the flight track or—which seems more likely—whether (b) some of them were made at an appreciable distance from the flight track and, if so, what was the lateral distribution of the masurement points and the proportion of the readings at various lateral distances?

Assuming that the measurements referred to were distributed over a considerable area on both sides of the flight track, it is clear that the very great variance has two causes:

1. Off-standard atmospheric conditions, winds and possibly also deviations from steady flight conditions, and
2. The appreciable lateral distance from the flight track of many of the measurement points.

It is, of course, to be expected that in the final report of the tests these two causes of the variance will be separated *so that the mean value and the scatter both on the flight track and on lines parallel to and at various distances from the track are presented or can be evaluated.*

Regardless of this, however, it is apparent that the overwhelming majority of the citizens living within the area in which intensity measurements were made has only been subjected to mean boom intensities *far below* the significant levels of 1.5 and 2.0 psf. In view of this it seems to me

(a) that the public reaction—and the damage to property—in Oklahoma City was surprisingly severe, and

(b) that the reactions and damage are certain to be much more severe in districts subjected to *mean* intensities of 1.5 or 2.0 psf, respectively, considering *both* daily disturbances of these magnitudes *and* the inevitable magnifications above these levels (due to atmospheric conditions and unsteady flight) which then might easily result in occurrences of at least 6.0 psf. I would be interested in the authors' comments to the last observation.

As magnifications above the average intensity can be caused both by flight maneuvers and atmospheric conditions, I wonder whether Dr. Hubbard believes that a particularly high magnification can be with certainty attributed to either one of the two causes? For example, if a surprisingly high reading is obtained and *suspected* to be caused by an inadvertent maneuver by the pilot, can it then be *proven* that this is so, thus that the possibility is excluded of the high magnification being instead caused by some especially adverse atmospheric conditions, such as an abrupt change in wind or temperature in the airspace *along* and below the aircraft?

Dr. Hubbard has rightly indicated that such damage to property that might be claimed by the owner to be caused by one or several booms "may *also* result from many other causes such as . . . road traffic." To this I wish to say that it is the combined effect that matters and, above all, that *the cumulative damaging effect of the repeated booms must be observed;* it is quite conceivable that some built-up areas will be subjected to something like 30 SST overflights per day, i.e., about 100,000 booms in 10 years. All or most of these are bound to cause a "partial precrack fatigue damage" according to the well-established cumulative damage theory. It follows that a secondary (or primary) structure that has suffered a considerable precrack damage due to a number of booms might finally fail, or suffer a visible crack, by the "triggering-off" action due to another cause, for instance, a severe storm or even a passing truck.

Thus, it is obvious

(1) that the justification of boom-damage claims should not be based on whether a particular crack or failure, say, in a window or plaster wall, was "triggered-off" by a particular boom, or whether the "immediate cause" was something else,

(2) that it will be exceedingly difficult, not to say impossible, to determine the extent to which sonic booms are responsible for partial cumulative damage contributing to an eventual crack or failure.

I wonder whether Dr. Hubbard can suggest a solution to this dilemma, which will confront the SST operators and their victims? In principle, the same dilemma (because of similar cumulative effects) applies for medical damage to people and animals.

Finally, I wish to draw attention to the statement of ICAO that "the (boom) intensity must obviously not be great enough to cause *any* damage to property. . . ."

REPLY

The authors have knowledge only of some of the physical measurements of the Oklahoma City sonic boom studies, and thus are not prepared to comment on all of the questions and philosophical points raised by Dr. Lundberg.

One of the main findings of the Oklahoma City sonic boom measurement studies was the wide variation in the sonic boom waveform signatures, as indicated in Fig. 12. Such variations have associated with them corresponding variations in the peak overpressure and, to a lesser degree, the impulse function. The significance of such wave shape variations is not obvious at this time. It appears that in cases where substantial variations occur, the mean or average values of pressure and impulse are lower than for situations where only small variations exist. Until a better understanding of the community response problem is obtained, it is difficult to say which situation is the more desirable.

It is recognized that the above variations may arise due to unsteady flight conditions of the aircraft (even when the pilot tries to hold steady conditions) and due to atmospheric disturbances. It would be very difficult if not impossible to make a judgement, merely from an inspection of measured signature data, concerning whether such effects were due to one of these causes and not the other. (In cases of some deliberate pilot maneuvers, multiple boom signatures are observed and would serve as reliable clues.) In the Oklahoma City situation, however, the variations observed were judged to be mainly due to weather effects.

The results of the Oklahoma City sonic boom pressure measurements are given in NASA TN D–2539. Published results for two different airplanes indicate that 22 to 40 percent of the measured overpressures exceeded the predicted values for an on-the-track measurement location. For stations 5 to 10 miles off the track, the nominal overpressures were exceeded 50 to 80 percent of the time. The tendency for wider variations to occur at the lateral stations is believed due to a longer path length through the earth's turbulent boundary layer, but may also have been affected by wind convection and large scale temperature anomalies. The longer samples of data could be represented by log-normal distributions (normal distribution of their logarithms). In place of the standard deviation, the values of overpressure which would be exceeded 1 percent of the time are noted to vary from 1.5 to 1.8 times the predicted value, depending on the type of airplane.

With regard to induced damage and the problem of fixing responsibility, it is obvious that insufficient information is presently available on which to make definite judgements. Although these latter problems are and will continue to be under intense study, and ways of minimizing the adverse effects of the sonic boom will probably result, it is nevertheless believed that the ICAO position on damage borders on the Utopian and is inconsistent with the ways of life in our modern civilization.