Analysis of Sonic Boom Flight Test Measurements Near the Shock Wave Extremity

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A NASA flight test program conducted by Langley Research Center personnel during the summer and fall of 1970 was devoted to investigating the sonic boom phenomena near caustics formed by steady flight near the threshold Mach number, during accelerations, and at the lateral extremes of the ground carpet. The vertical extent of the shock waves attached to near sonic (M < 1.0) airplanes was also investigated. The flights were conducted over the 1500 ft instrumented BREN tower so that vertical surveys through the shock waves were measured. These data on caustic phenomena near the shock wave extremity were analyzed in detail and compared with linear theory. Amplifications of shock wave strength varied from 2 to 5 during longitudinal accelerations, from 1 to 1.8 during steady threshold Mach number flight, and up to 3 for small inadvertent accelerations during flight near the threshold Mach number. Caustic-like pressure signatures were also measured near lateral cutoff. However, these were of very low intensity, less than one-half the intensity beneath the flight path. The analysis has indicated the range of validity of linear theory.

Introduction

DURING the last two decades a large amount of work has been devoted to the development of theoretical methods for predicting sonic boom characteristics. Fundamental contributions were made by Friedrichs, Hayes, Landau, and Whitham.[1-6] The current state-of-the-art in sonic boom prediction is represented by the comprehensive analysis and computer program assembled by Hayes, Haefeli, and Kulsrud.[7] Although the basic theory is linear in nature a wide range of effects can be accounted for, such as the effects of airplane configuration and lift, nonstandard meteorological conditions, and airplane maneuvers. This basic theory has been verified by wind-tunnel tests and flight test data.[8]

During the last 15 years there have been a number of flight test programs that have contributed substantially to the current understanding of sonic boom phenomena near duced by airplane maneuvers and/or by atmospheric refraction. Although significant advances have been made in theoretically describing the pressure field in the vicinity of a caustic, these methods need further refinement before detailed results can be obtained.[9-14] Flight test measurements have been most helpful in identifying the phenomena and will in the future serve to confirm theories that may be advanced.

During the last 15 years there have been a number of flight test programs that have contributed substantially to the current understanding of sonic boom phenomena near caustics. One of the earliest was conducted at NASA Wallops Station, where seven threshold Mach number flights were flown.[15] The tests at Edwards Air Force Base in 1961 consisted of several different airplane maneuvers, including four longitudinal accelerations.[16-18] Another series at Edwards Air Force Base in 1964 included five threshold Mach number flights and five longitudinal accelerations.[19] Other programs have provided information on the variability of sonic boom due to atmospheric effects as a function of lateral displacement from the flight track.[20-24] Reference 25 contains a general discussion of the variability of sonic boom and some preliminary analysis of the BREN tower lateral cutoff data, and Ref. 26 contains a preliminary analysis of the BREN tower threshold Mach number flights. French flight tests demonstrated that the method of linear geometric acoustics is satisfactory for predicting caustic locations.[27] These test results also demonstrated that a dense array of microphones was necessary for observing the caustic phenomena, since they occur over small ground areas.

One aspect that required further investigation was the sonic boom characteristics near lateral cutoff since several investigators have postulated large pressure magnifications at lateral cutoff.[28-30] Another was the caustic and acoustic disturbances associated with threshold Mach number flight where a caustic (and cutoff) is produced at some distance above the ground. Finally, the caustic produced by the transonic acceleration of supersonic airplanes is of particular interest since it would be produced by SSTs. These considerations prompted the NASA Langley Research personnel to design, implement, and conduct the 1970 test program at the BREN tower. During this flight test program, 121 sonic boom generating flights were made and were designed to provide information on several aspects of sonic boom, including caustics produced by longitudinal accelerations, sonic boom characteristics near lateral cutoff, and the vertical extent of shock waves attached to low altitude near sonic (M < 1.0) airplanes. By use of the 1529 ft BREN tower, sonic boom signature measurements as a function of altitude were obtained for the first time. The primary goal of this test series was to obtain definitive data on caustics produced by accelerations and by atmospheric refraction (threshold Mach number and lateral cutoff). The phenomena are presented and described in summary form. More detailed results can be found in Ref. 31, except for the analysis of the low altitude near-sonic test data. Preliminary results were given in Refs. 25, 26, and 32.

Program Description

Flight Test Arrangement

The test program was conducted at the BREN tower on the AEC Proving Grounds in Nevada. The 1500 ft BREN tower was instrumented with microphones to obtain sonic boom pressure signature measurements at 100 ft intervals

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Table 1 Summary of 1970 BREN tower tests

Type of flight	Approximate altitude above ground (ft)	Approximate Mach number	Number of flights
Threshold Mach number	30,000	1.07–1.20	79
Level acceleration	30,000	0.95–1.3	19
Lateral cutoff	29,000	1.3	9
Low altitude near-sonic	3,000	0.95–1.05	14
			121

from the ground. Pressure signatures were also measured at 14 ground locations at 200 ft intervals in a line parallel to the nominal flight path. Meteorological data were obtained from measurements on the BREN tower, a 100 ft tower located 700 ft south of the BREN tower, standard rawinsonde observations, and an instrumented light airplane.[33]

Sonic booms were generated by NASA F-104 airplanes. The flight track was nominally on a true heading of 035° in line with the linear ground microphone array, except for the lateral cutoff flights which were on a 125° heading and displaced to the south by 11.4–15.0 st. mile. The airplane altitude was generally near 30,000 ft above the ground. All flights were controlled by radar and the flight tracks were recorded for later analysis. Table 1 summarizes the flight conditions and Fig. 1 illustrates the flight procedures used to obtain the desired measurements.

Analysis Methods

The objectives of the detailed analysis of the test data were to interpret the observed data guided by theoretical

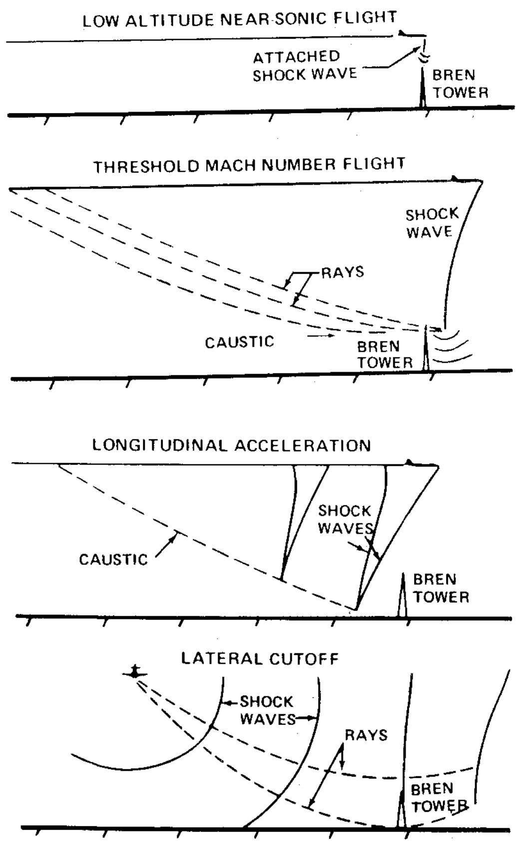

Fig. 1 Summary of test conditions.

study of the test conditions, and to determine the validity and accuracy of current sonic boom calculation methods near the shock wave extremity. Theoretical sonic boom calculations are based on the method of geometrical acoustics. Calculations were accomplished by use of the comprehensive method of Hayes, Kulsrud, and Haefeli.[7] This method accounts for the effects of a variable stratified atmosphere, airplane maneuvers, and airplane configuration. Sonic boom pressure signatures, ray trajectories, and shock ground intersections were calculated.

To provide a sound basis for a study of the maneuver effects and to aid in the interpretation of the test data, calculations were also made of shock wave vertical profiles. The method of geometrical acoustics (as in Ref. 7) was used to calculate the ray trajectories and location of the bow shock wave from the known airplane trajectory and meteorological conditions. This provided a comparison between linear theory and experiment for both the shock location (and arrival time) and the shock wave shape. Observed shock wave profiles were provided by the observed tower pressure signatures. In comparing linear theory and experiment, only the onset of bow shocks was considered.

Results

The major results are presented for the four test conditions beginning with the low altitude near-sonic passes, followed by the threshold Mach number flights, the longitudinal accelerations, and the lateral cutoff flights.

Low Altitude Near-Sonic Flights

The objective of the near-sonic flights was to determine the vertical extent and nature of the shock waves attached to an airplane during near-sonic flight. To accomplish this the test airplanes were flown at an altitude of about 2800 ft above the ground at Mach numbers ranging from 0.95 to 1.00. An additional flight was made at Mach 1.05. The distinguishing feature of the test results is the large difference in the observed sonic booms on the BREN tower for similar airplane flight conditions. For example, of the three flights at Mach 0.98 two produced booms and one of the two flights at Mach 0.99 produced a sonic boom on the tower.

At high subsonic Mach numbers, shock waves are produced locally as the airflow becomes supersonic over certain portions of the airplane. These shock waves extend a small distance beneath the airplane and induce a Mach number gradient around the airplane due to its own flowfield. To aid in determining the effects of the meteorological conditions and the airplane induced Mach number gradient it was convenient to calculate a local shock Mach number M_s. This Mach number is the sum of the freestream Mach number M_0, the Mach number increment due to wind and temperature changes below the airplane, and the induced Mach number gradient. The latter was estimated from the maximum strength of the local shock wave profile measured for a flight at Mach 1.05.

Analysis of the local shock Mach number M_s data indicated that the meteorological conditions influence the vertical extent of attached shock wave during near sonic flight. In all cases when $M_s < M_0$ (an unfavorable meteorological condition for shock wave propagation) no disturbances were observed. On the other hand, for $M_s > M_0$ shock waves were observed. At Mach 0.98 the shock wave extremity varied from about 560 ft to 1600 ft below the airplane due to the different meteorological conditions. Both airplane Mach number and meteorological conditions appear to have an influence on the extent of the attached shock waves. It is not clear, however, how much farther the shock waves would have propagated under more favorable meteorological conditions.

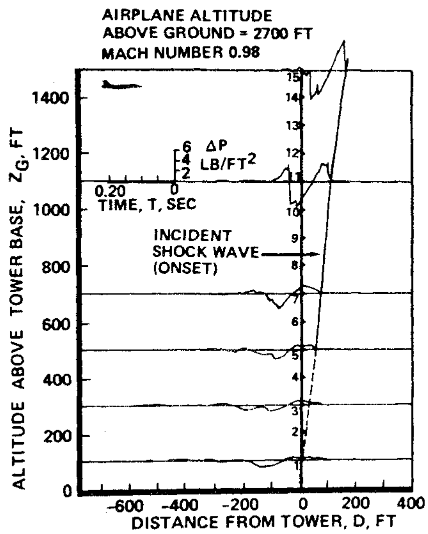

Fig. 2 Shock wave profile and tower pressure signatures, low-altitude near-sonic flight.

The observed pressure signatures and the shock wave profile for a Mach 0.98 pass over the tower are given in Fig. 2. The pressure signature at the tower top is very similar to those produced during supersonic flight. This suggests that shock waves are produced near the airplane nose (canopy) and tail during near-sonic flight. Below midtower the shock waves are not present and the pressure signatures become rounded, low intensity acoustic disturbances.

Threshold Mach Number Flights

The threshold Mach number has been defined to be the airplane Mach number for which the shock waves will just reach the ground. Mach numbers below this will result in no shocks on the ground, while 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 Fig. 1.) In general, the measurements indicated that the sonic boom pressure pattern preserved its identity above the extremity (which is also termed a caustic), was slightly amplified at the caustic (about 1.5–1.8 times the overpressure value just above the caustic), and degenerated to an acoustic type disturbance of very low intensity below the caustic.

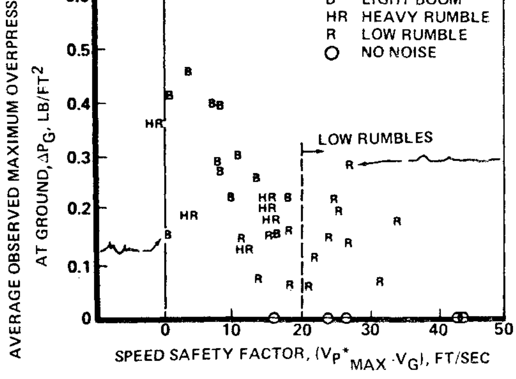

Fig. 3 Noise measurements for flight near threshold Mach number.

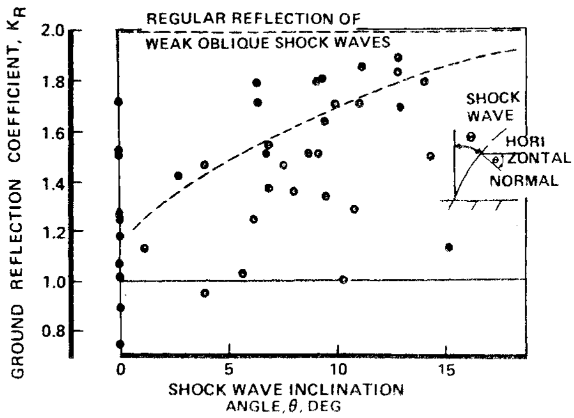

Fig. 4 Variation of ground reflection factor near cutoff.

Cutoff Criteria

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 increment is illustrated in Fig. 3. 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 20–30 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 slower 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.

Ground Reflection Factor

When weak shock waves intersect the ground at an oblique angle they are reflected from it at the same angle. This reflection causes the observed overpressure at ground level to be higher than the value in free air. 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 ground 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 reflection 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. Despite the scatter, the results shown in Fig. 4 indicate a gradual decay toward a value of 1 as the shock waves become normal to the ground (dashed line). This phenomena yields some interesting conclusions. As was pointed out previously, 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 observe little or no increase on the ground. This reasoning was supported by the ground microphone measurements.

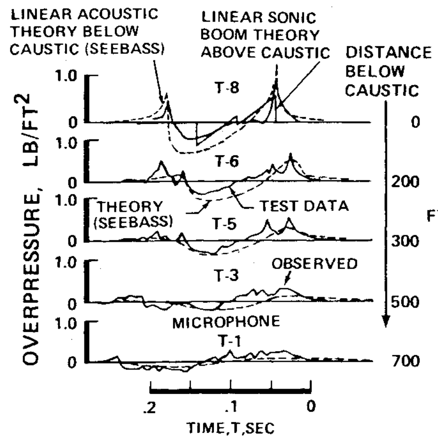

Fig. 5 Measurements near threshold Mach number caustic and theoretical results.

Pressure Characteristics Near Cutoff

Near the shock wave extremity significant changes in the signature shape occur over a relatively small distance. At the caustic the incoming N-wave is transformed into a U-shaped wave with relatively high peak amplitudes; several hundred feet below the caustic the signal degenerates into a low amplitude acoustic wave. Figure 5 contains measured data for a case where the caustic was measured on the tower. An N-wave signature calculated by linear theory[7] that is valid above the caustic is shown, along with pressure waves calculated by Fung and Seebass using linear acoustic theory. The linear acoustic theory applies below the caustic; calculated pressure waves are given at several distances below the caustic in Fig. 5. The calculated overpressures are significantly lower than the observed over pressures far from the caustic, but show good agreement close to it.

Longitudinal Acceleration Flights

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.

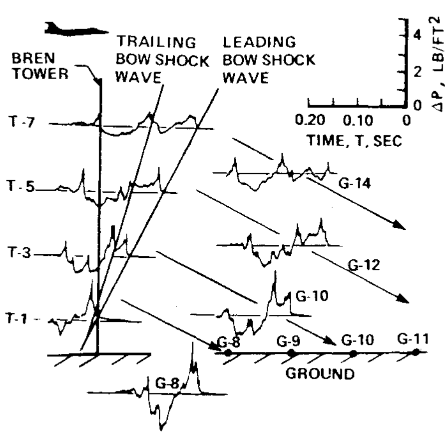

Fig. 6 Measurements near the acceleration caustic.

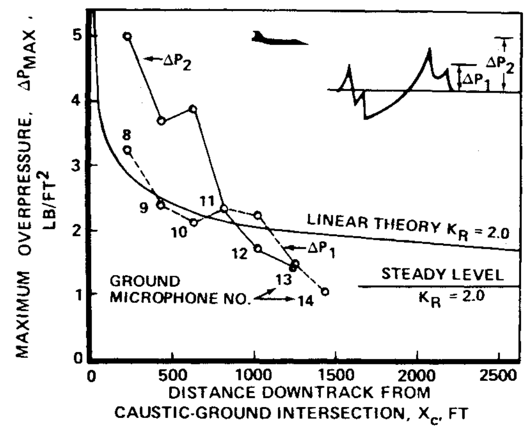

Fig. 7 Overpressure magnification near the acceleration caustic.

Shock Wave Profiles and Signatures

The characteristics of the acceleration caustic are illustrated in Fig. 6 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, nonlinear effects begin to dominate 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 200–500 ft above the caustic nonlinear effects begin to dominate the signature shape and within 100 ft of the caustic 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 illustrating the effect of passing through the caustic. These data also indicate that some acoustic disturbances precede the caustic to the ground.

Amplification of Pressure

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. 7 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.[7] This "linear theory" does include cumulative nonlinear effects but the geometrical acoustics method fails close to the caustic. In addition, 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 (27 and 34).

Effect of Acceleration Magnitude

For the seven cases where the caustic produced by longitudinal acceleration were observed on the tower it was

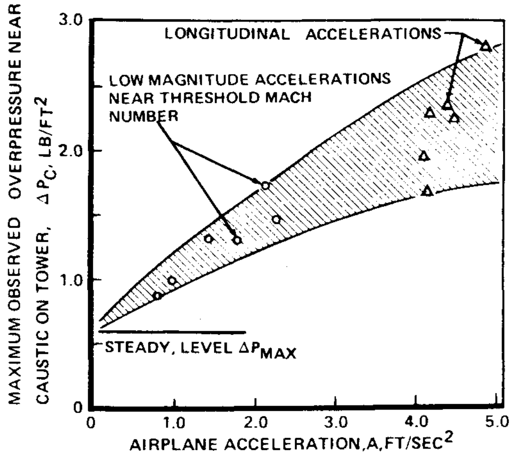

Fig. 8 Comparison of the effect of fast and slow acceleration on caustic intensity.

possible to correlate the observed caustic intensity with the magnitude of the airplane acceleration which produced it. Theoretical ray calculations were used to determine the portion of the flight path which produced the caustic and the acceleration magnitude was calculated over a 6 sec flight path interval from the detailed radar ground speed observations. A relationship between acceleration magnitude and caustic intensity was expected, due to the way the ray trajectories converge as acceleration magnitude increases. A correlation from the measured data is given in Fig. 8. These results indicate a general trend toward increasing caustic intensity with increasing acceleration magnitude.

Additional information on the effect of acceleration magnitude was provided by several of the threshold Mach number flights for which the flight Mach number was greater than the threshold value. Slight changes in the airplane ground speed during flight just above the threshold Mach number can produce caustics. For six flights the predicted caustic location agreed reasonably well with the caustic observed on the tower, and it was possible to calculate an acceleration magnitude associated with the caustic. These results are also shown in Fig. 8. A rather significant increase in caustic intensity with increasing acceleration magnitude is indicated. In each case the acceleration magnitude was calculated over a 3 sec flight path interval over which the airplane ground speed was increasing. The wave folding produced by slight airplane speed changes (10–30 fps) in most cases explained the multiple shock waves observed on the BREN tower.

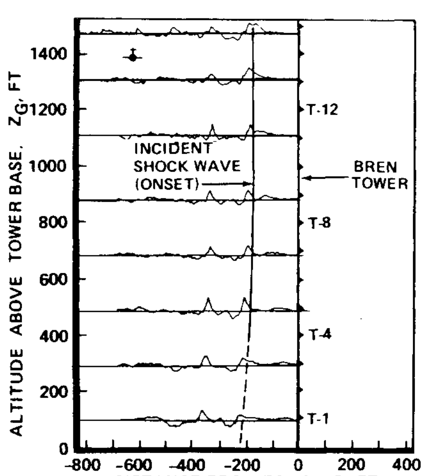

Fig. 9 Shock wave profile and tower pressure signatures near lateral cutoff.

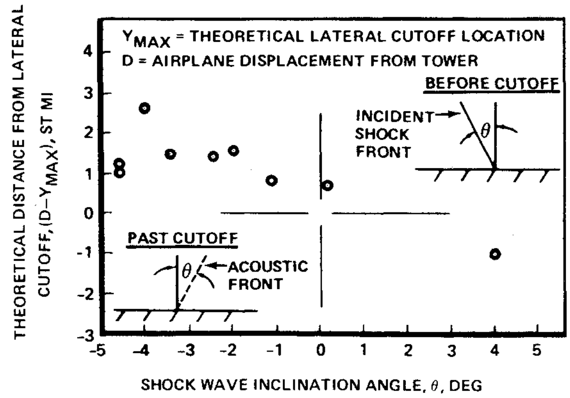

Fig. 10 Comparison of observed lateral cutoff with theory.

Lateral Cutoff 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 (see Fig. 1). 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.

Shock Wave Profiles and Signatures

Several of the nine lateral cutoff flights produced shock waves that were close to cutoff at the BREN tower. The observed pressure signatures and the shock wave profile for one of these cases is illustrated in Fig. 9. The shock front is nearly perpendicular to the ground from midtower to the tower top. The signatures are caustic-like with sharp peaks, but of low intensity.

Location of Lateral Cutoff

Figure 10 gives an indication of the accuracy of the theoretical lateral cutoff location Y_{max} compared to nearness to actual cutoff, θ. The angle θ is the angle of incidence of the incoming shock wave with respect to the vertical at the tower base. It is zero for a shock wave at cutoff. The parameter (D-Y_{max}) is the theoretical lateral cutoff location with respect to the BREN tower. The agreement between the theory and experiment is reasonably good, and these calculations are accurate to about 4000 ft. Since the meteorological conditions along the ray paths associated with boom at the tower are not known precisely, it does not appear possible to achieve better accuracy than indicated in Fig. 10. Thus, the accuracy indicated in Fig. 10 is probably an upper limit for these kinds of calculations.

Overpressure Variation

The data shown in Fig. 11 summarizes the measurements obtained during this phase of the test. Measured overpressures 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 (θ = 0°). For positive angles N-shaped waves were recorded with booms and rumbles occurring shortly beyond cutoff.

A slight increase in overpressure (about 50%) at cutoff relative to those measured just prior to it is evident from these data. The maximum overpressure observed, how-

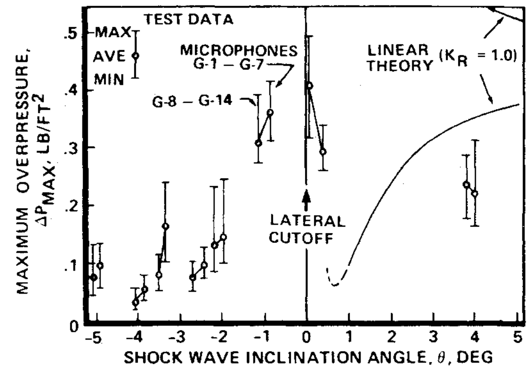

Fig. 11 Overpressure variation near lateral cutoff.

ever, was only 0.50 psf. (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 off-set by a halving of the usual ground reflection effect. Linear theory would predict infinite overpressure at lateral cutoff due to the neglect of higher order effects, but it appears to be reasonably accurate to within about 2–3° of cutoff.

Conclusions

Sonic boom characteristics near the shock wave extremity were more clearly defined by field measurements for several types of flight conditions conducted by NASA Langley Research Center personnel during the 1970 BREN tower sonic boom program. The test program was designed to provide vertical surveys in the vicinity of 1) the shock wave extremity during low altitude near-sonic flight, 2) caustics produced by steady flight near the threshold Mach number, 3) caustics produced by longitudinal accelerations, and 4) the lateral cutoff location during steady flight.

The detailed analysis of the low altitude near-sonic flight test data has indicated that the prevailing meterological conditions influence the vertical extent of attached shock waves produced during near sonic flight. At Mach 0.98 the lower extremity of the shock wave on one flight extended to 1600 ft beneath the airplane, while under different meterological conditions it extended to only about 560 ft. The airplane Mach number has a direct influence on the vertical extent of attached shock waves; for an airplane Mach numbers less than 0.98, the shock waves probably did not extend much more than about 300 ft beneath the airplane.

The observations near caustics are of particular value, since no methods are currently available for predicting realistic pressure signatures at caustics, because of the nonlinear effects that predominate there. Overpressure increases measured at caustics produced during threshold Mach number flight were relatively low, ranging from about 1.0–1.8 times those predicted for flight at a slightly higher Mach number. Caustics were also produced by small, inadvertent changes in the airplane speed during several of the "steady," level threshold Mach number flights. These caustics were slightly stronger, with a maximum amplification of about 3. Measured overpressures at caustics produced by airplane accelerations ranged from 2 to 5 times those which would be observed during steady, level flight at about Mach 1.2. For these caustics, acceleration magnitude appeared to affect the intensity, with the strongest produced by the larger acceleration. This conclusion is also supported by the data measured for some threshold Mach number flights, where small magnitude accelerations produced lower intensity caustics. Pressure signatures were also observed near lateral cutoff which resembled those measured at caustics. These disturbances were of very low intensity, however, less than one-half the intensity beneath the flight path. Pressure signatures near caustics exhibit a U-shaped signature with a longer duration than the incoming N-wave. Linear theory compares favorably with the observations up to a distance of several hundred feet vertically from caustics.

A correlation of the ground reflection coefficient was made as a function of nearness to cutoff. These data indicated a gradual decrease from about 2.0 for an oblique shock wave to near 1.0 when the shock wave becomes perpendicular to the ground at cutoff.

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High-Performance Composite Material Airframe Weight and Cost Estimating Relations

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Estimates of the weight reduction potential of using advanced composite materials in high-performance aircraft airframes are presented. A conventional, all-aluminum airframe is established as the reference configuration for comparison purpose, with the alternate use of other homogeneous metals, viz, titanium and beryllium, also considered. Advanced composites discussed in detail include boron/epoxy, graphite/epoxy, and an organic filament/epoxy. Cost factors are estimated in order to keep the significance of the various weight reduction factors in proper perspective. Conventional sheet and stringer construction will eventually be modified to take advantage of the unique characteristics of composite materials in achieving maximum structural efficiency. Therefore, the influence of advanced construction technology on weight and cost factors is also considered. Numerical examples representing applications to specific vehicle airframes are presented, indicating the significance of the estimated airframe weight savings in terms of vehicle performance increases.

I. Introduction

THE principal application of advanced composites, i.e., those composites which incorporate high-modulus filaments such as boron or graphite, has been and continues to be to airframe structures of high performance manned aircraft. In addition, there is a rapidly increasing interest in the possibility of replacing manned aircraft with unmanned vehicles, e.g., drones and remotely piloted vehicles (RPV), in certain very high-risk missions.[1]

The present paper is limited to the consideration of high-performance airframes. High performance will be defined here as the ability to operate at *g*-levels near the upper limits of pilot tolerance (and above in the case of unmanned vehicles). The effects of aerodynamic heating will not be considered, limiting maximum vehicle speeds to about Mach 2 and below. These limits are sufficiently broad to include a very high percentage of the types of airframe mission requirements being considered in the industry at the present time.

The primary purpose of the present paper is to provide the conceptual designer with quantitative estimates of the weight-savings potential available when considering advanced composites for use in either manned or unmanned vehicle airframes. These estimates have been established by comparing various material properties, possible differences in construction, and the unique aspects of individual airframe subcomponents. They have been substantiated wherever possible by comparing the generalized estimates with results actually achieved in the airframe industry for selected subcomponents of specific vehicles. This substantiation is obviously very valuable, but is necessarily somewhat limited since only scattered experimental results are available for use.

No consideration is given here to the possibility of resizing the entire vehicle because of the reduced airframe weight, although this is always a distinct possibility. Rather, it is assumed that the airframe weight savings will be utilized to increase the range (by carrying more fuel) and/or payload of the given aircraft configuration.

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