Effect of SST Operational Maneuvers on Sonic Boom

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An extensive theoretical study has been made of the effect of operational maneuvers on sonic boom. The results indicate that for large transport class airplanes it is possible to perform most normal operational maneuvers without producing pressure signatures that are appreciably stronger than those generated during steady flight. An exception is the case of initial acceleration to cruise, which produces caustics and increased boom strength over a very small ground area. Sensitivity of sonic boom signatures to maneuvers is more pronounced at Mach numbers near but above threshold values. Specific results and a method for computing maneuver signatures from steady flight signatures are given.

Introduction

THE shock waves produced during supersonic flight are influenced by the trajectory of the airplane. Several theoretical and experimental studies have been made of the effect of changes from steady level flight on sonic-boom signatures received at the ground.[1–6] These investigations were all relatively general and were devoted primarily to describing the effect of maneuvers of small supersonic airplanes. Such information is invaluable to the understanding of maneuver effects and has been responsible for the present state of knowledge.

The current work described in this paper is an application of the preceding investigations toward defining the influence on sonic boom of operational maneuvers characteristic of large supersonic airplanes. These airplanes are in the transport class and are not capable of high-maneuver load factors because of structural, inertial, or passenger comfort considerations. The objectives of this study were to investigate the effect of a practical range of maneuver parameters for this class of airplane, to classify these effects, and to derive a generalized method for computing these influences. Four types of maneuvers are considered in this paper so that their individual effects can be discussed separately. Combinations of these, discussed in Ref. 7, will not be reviewed here to allow the maximum space for the review of significant results.

The scale of the phenomenon can be brought into perspective by considering the sketch in Fig. 1. This is a comparison of the sonic-boom "footprint" for a typical acceleration to cruise Mach number, obtained by first ignoring maneuver effects (Fig. 1a) and then by including the maneuver effects (Fig. 1b). It can be seen in this example that the influence of the maneuver is confined mainly to a small area near the caustic locus. The affected area is then a very small percentage of the total area receiving the boom.

This figure is also useful in that it illustrates the basic phenomena and their division into two categories. These two categories are the effects on sonic boom signatures near a caustic and the effects on signatures at the caustic. Current methods based on linear theory are reasonably valid in the vicinity of caustics where nonlinear effects do not dominate the phenomena.[8] At the caustic, however, the nonlinear effects dominate and signatures cannot be computed using only linear considerations. Hence, the discussion is divided

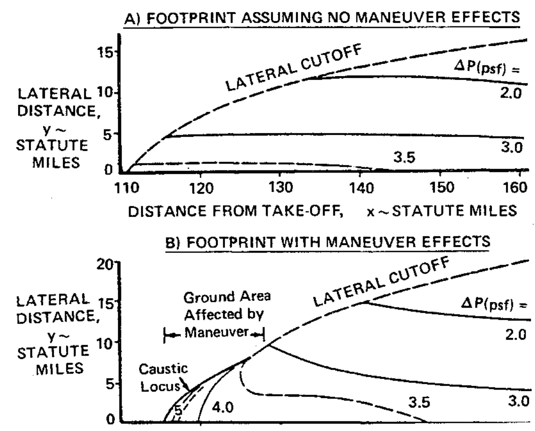

Fig. 1 Influence of maneuvers on sonic boom footprint—acceleration to cruise.

into two parts. The first section contains a summary of the influence on pressure signatures away from the caustic where linear theories are valid. The effect of various single maneuvers are discussed, the influence of nonstandard atmospheric conditions are considered, and a brief summary is given of a general method that can be used to scale steady-flight signatures to obtain maneuver signatures for any airplane configuration. The second section is devoted to a discussion of the caustic phenomenon, the influence of meteorological and flight conditions on caustic location, and the maneuver load factors that are required to produce caustics on the ground.

Maneuver Effects on Pressure Signatures

In this section the effects of longitudinal accelerations, pushovers, and pullups on pressure signatures are summarized for noncaustic-forming maneuvers. The results are independent of airplane configuration and can be applied to any airplane of interest. A generalized method of accounting for the effects of airplane shape, lift, weight, and Mach number through the use of steady, level-flight pressure signatures is briefly outlined.

Maneuver Effects on Ray Paths

Some brief comments about ray paths associated with maneuvers may prove helpful in understanding the maneuver effects. Figure 2 shows ray paths for several typical maneuvers considered in this paper. A ray or path ray is the trajectory in space and time of a point on a shock front. In the case of airplanes accelerating longitudinally, successive rays

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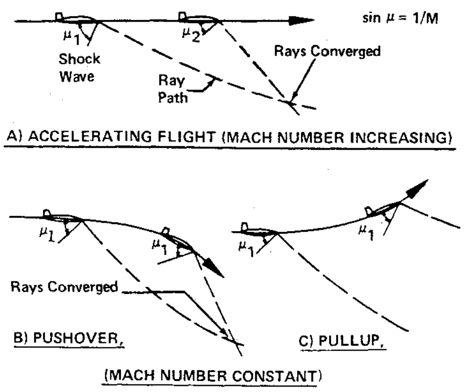

Fig. 2 Typical ray paths for maneuvering airplanes.

along the flight path are emitted at larger angles than previous rays. Adjacent rays, therefore, tend to converge. The convergency of adjacent rays will tend to form stronger shock waves when compared to those formed during steady level flight. If the acceleration and airplane altitude are large enough, the distance between adjacent rays will converge to zero, forming a caustic.

In the case of a constant Mach number pushover, successive rays are emitted at larger angles relative to the horizontal due to the change in flight-path angle. As in the acceleration case, the rays tend to converge. For pushovers of large flight-path curvature, a caustic may be formed. During pullups and decelerations, on the other hand, caustics cannot be formed because of the divergence of successive rays; in these cases lower sonic boom intensities will generally result.

The turn maneuver produces a complex shock wave pattern on the ground. In general, there is a relatively small region of amplified shock strength toward the inside of the turn where rays are converging and a large area of lower intensity boom strength to the outside of the turn. Large radius turns do not produce caustics. More detailed information on the effects of turn maneuvers is contained in Refs. 5 and 7.

Maneuver Effects on Boom Intensities

The effects of longitudinal accelerations on maximum overpressure are given in Fig. 3 for several initial Mach number-altitude combinations for which no caustic occurs. These data have been normalized by the steady flight maximum overpressure, and are for the 1962 U.S. Standard Atmosphere directly beneath the airplane. The maneuver effects increase with decreasing Mach number, increasing altitude and increasing acceleration rate. Longitudinal accelerations begun at Mach 1.2 and 30,000 ft altitude produce relatively strong shock wave amplification. This is because at these flight conditions caustics are produced at the ground for the quite small acceleration magnitude of $0.14g$. A more detailed discussion of caustics produced by acceleration from subsonic to supersonic Mach numbers is given in a later section.

The effects of nonstandard atmospheric conditions are also illustrated in Fig. 3 for $0.1g$ accelerations. The envelope of variation in boom strength caused by different atmospheric conditions is about $\pm 5\%$ above Mach 1.7. At the lower Mach numbers the shock propagation distance through the atmosphere is longer, so that the sensitivity to the atmosphere is greater. Below the threshold Mach number (variable from Mach 1.0 to about 1.3) the shocks do not reach the ground, so no results are shown.

The effects of pushovers ($0.5g$) and pullups ($1.5g$) are summarized in Figs. 4 and 5, respectively, for the various initial climb angle and initial Mach number-altitude combinations noted. Only noncaustic cases are shown. Since all the pushovers begun at Mach 1.2, 30,000 ft, produced caustics in the Standard Atmosphere, data for this flight condition are not shown. As shown in Figs. 4 and 5 the sensitivity to maneuvers increases with increasing altitude, decreasing Mach number, and decreasing climb angle. Here again, there is no effect at Mach numbers below the threshold value since the shock waves do not reach the ground.

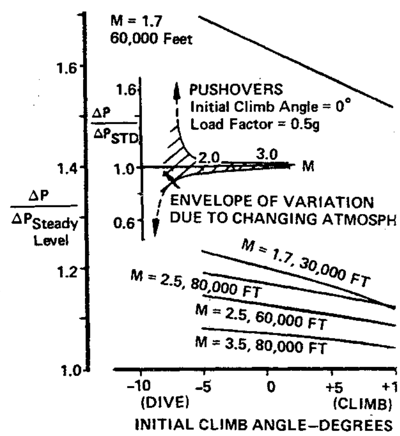

Fig. 4 Effect of pushovers on shock-wave strength.

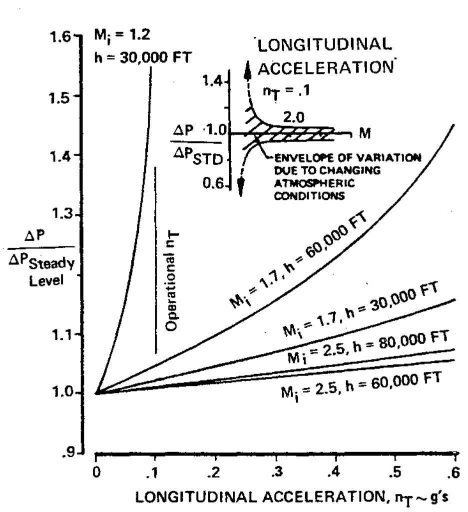

Fig. 3 Effect of longitudinal acceleration on shock-wave strength.

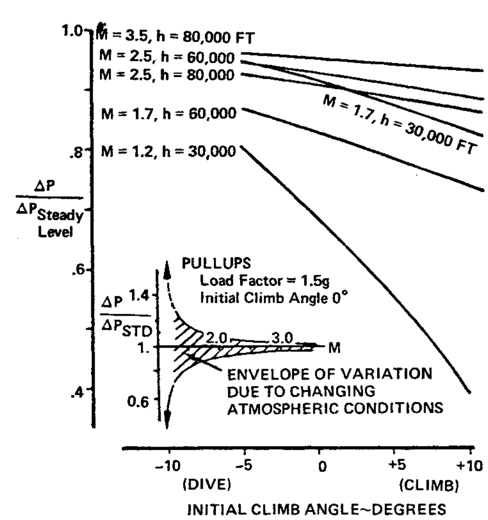

Fig. 5 Effect of pullups on shock-wave strength.

Figures 4 and 5 also show the envelopes of variations caused by varying atmospheric conditions from the Standard Day. In each case atmospheric variations cause less than ±5% variation in shock strength at speeds greater than about Mach 2.0.

It should be stressed that the results shown in this section cannot be extrapolated beyond the ranges shown. Such extrapolations will lead to invalid answers, since physical considerations require finite shock-wave strengths and maximum overpressures. The values of these limits cannot at present be calculated because of limitations in the available theories. Additional data are contained in Ref. 7 illustrating the variation of overpressure with time for maneuvers in this category.

Airplane Shape and Lift Effects

The effect of the change of the lift load factor from steady level flight (1.0*g*) in pushovers and pullups must also be accounted for to obtain valid results. In a pushover the lift load factor is less than 1.0, so that the lift contribution to shock strength is less and, considering only this effect, lower sonic boom intensities result. As noted previously, however, the effect of the pushover maneuver itself is to cause converging rays and higher intensities than during steady level flight. Thus the two effects are opposed to each other. For the pushover cases considered in this paper (0.5*g*), the effect of the converging rays is more important than the change in load factor. A third important effect is the initial airplane climb angle. In some cases, intensities for high climb angles may be less than for steady level flight (see Fig. 4).

A similar situation exists with respect to pullups. The increased lift load factor during a pullup (> 1.0*g*) tends to give higher intensities than for steady, level flight. On the other hand, the pull-up maneuver causes rays to diverge, giving lower intensities than during steady, level flight. Normally the latter effect is more important. A third important effect is the initial airplane climb angle. A pullup initiated from a diving flight path may give stronger intensities than comparable steady level-flight conditions (see Fig. 5).

In addition to the intensity, two other features of sonic boom pressure signatures that are affected by maneuvers are the number of shock waves in a signature (a maneuver may cause shocks to merge or diverge) and the length of the pressure signature. Figure 6 gives some rather extreme calculated maneuver signatures for a longitudinal acceleration, a pushover, and a pullup. Pressure signatures are shown for the SCAT 15-F (an SST concept studied at NASA Langley Research Center). Steady level flight pressure signatures calculated for the same altitude and Mach number as the maneuver are also given to aid in identifying the maneuver effects. Figure 6a illustrates that the longitudinal acceleration results in stronger intensities and only slightly longer time durations compared to steady level flight. It should be noted that this signature occurs very near the caustic and would affect only a very small ground area.

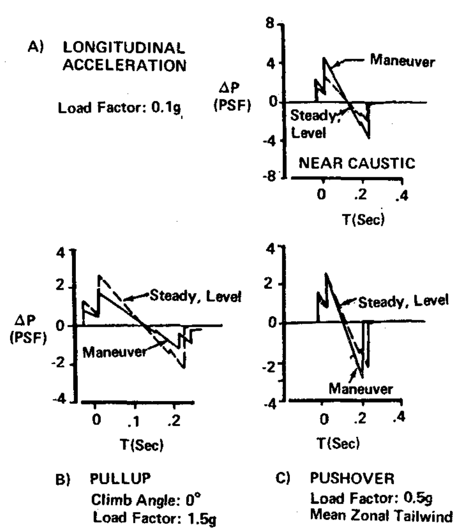

Fig. 6 SCAT 15-F maneuver pressure signatures at Mach. 1.2, 30,000 ft and 500,000 lb weight.

The pullup pressure signature in Fig. 6b shows that the maneuver results in lower intensity shock waves. The effect of the increased wing lift due to the pullup can be seen in the location and intensity of the intermediate shock. The intermediate shock is slightly stronger than maneuver effects alone would give, because of the increased lift, and it is located further forward. Also the tail shock is located further aft and is not decreased as much, because of the increased lift.

The pushover signature, on the other hand, illustrates the opposing effects of decreased lift but amplification due to the ray convergence. The bow shock is stronger because of the maneuver but the intermediate shock is about the same intensity as the steady, level-flight case because of the decreased lift. The tail shock is stronger but has not advanced as far aft, because of the lower lift.

The pressure signatures in Fig. 6 illustrate that the maneuver effects are not independent of the airplane configuration or lift (see Refs. 6 and 7). Thus two different airplanes performing the same maneuver may give completely different maneuver effects compared to steady level flight. In the next section a method for applying the study results to any airplane is indicated.

Application of Scaling Factors to Calculate Maneuver Signatures

In this section a brief description is given of a method for using maneuver scaling factors to compute maneuver pressure signatures from known steady-flight signatures. Maneuver scaling factors are useful since they can be used to calculate the maneuver pressure signatures accurately for any configuration once its steady-flight sonic-boom characteristics are known. These scaling factors can also be used to obtain reasonably accurate quick estimates of the maneuver effects on maximum overpressure. This considerably simplifies the calculation procedure since maneuver effects can be tabulated for various classes of maneuvers independent of any airplane configuration. Such tabulations, a detailed explanation and derivation of the scaling method, and examples are contained in Ref. 7.

To compute a maneuver pressure signature from a steady-flight pressure signature, two scaling factors are required. One scaling factor, K_1, is used to scale the intensity of the steady-flight signature. K_1 is also a fairly accurate measure of the increase in maximum overpressure due to a maneuver. This is given by

$$\Delta P = K_1 \, \Delta P_{(\text{steady level})}$$

The data given in Figs. 3–5 are K_1's. A second scaling factor, K_2 must be used to calculate the complete maneuver pressure signature and to obtain $\Delta P/\Delta P_{(\text{steady level})}$ more accurately. K_2 is called the maneuver "age scaling factor" since it accounts for the shifting of shock locations relative to the steady-flight signature.

In general, the linear theory used for calculating maneuver effects near and away from caustics appears to be reasonably valid when compared to flight test data. Pressure signatures can be calculated for any airplane performing realistic maneuvers in horizontally stratified atmospheres with winds.

Caustics

Operational accelerations through Mach 1.0 to cruise will produce a caustic on the ground. The discussion in this section is therefore concerned primarily with aspects of caustics produced by this maneuver. The nature and geometry of the caustic phenomena and the effects of flight and meteorological variations on the caustic location are presented. Finally, maneuver requirements (load factors) required to form caustics at the ground are given for longitudinal accelerations, pushovers, and turns.

Nature of the Caustic Phenomenon

A caustic, in terms of sonic boom, is a cusp or fold that exists on a shock-wave surface and consists of a single, intensified, sonic-boom signature. A caustic locus is a line which defines the progressive intersection of the caustic with the ground. Figure 1 illustrated such a caustic locus for a typical acceleration to cruise of an SST. As noted before, the maneuver effects are most important within a region about 10 miles wide near the caustic whereas the remainder of the sonic-boom footprint is very similar to the steady-flight case. In the region immediately surrounding the caustic locus, two or more pressure signatures are observed, one of which is somewhat stronger than the steady-flight signature but with nearly the same shape. Very close to the caustic (within about 2000 ft) these two signatures occur almost simultaneously, and at the caustic they are merged.

The development of shock waves during acceleration from subsonic to supersonic Mach numbers is illustrated in Fig. 7. The cusp occurs where the shock wave folds and forms a leading- and trailing-shock system with the caustic occurring at the cusp. For this particular maneuver the trailing shock was produced at the low-supersonic Mach numbers, and the leading shock was produced at the higher Mach numbers. The caustic is the first part of the shock wave to reach the ground. As the acceleration continues, the leading and trailing shocks separate after the cusp is reflected from the ground, until finally the trailing shock is completely refracted, so that only one pressure signature is observed.

The development of the shock wave and pressure signature near the caustic is illustrated in Fig. 8. At the caustic itself the leading and trailing shocks are merged and nonlinear effects predominate. Thus the linear sonic boom theory is invalid since it predicts an infinitely strong shock at a caustic. A typical observed pressure signature at a caustic is shown in Fig. 8. Within a few hundred feet of the caustic the linear theory is capable of predicting the order of magnitude of shock-wave intensities, but the nonlinear effects are still relatively dominant and the absolute values are unreliable. Within a few thousand feet of the caustic the nonlinear effects are less than or equal to the linear effects, so that the linear theory should be reasonably valid.

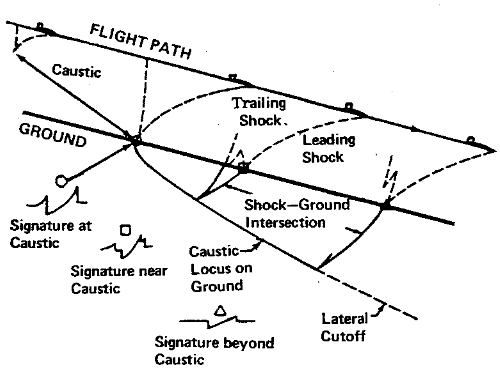

Fig. 7 Development of shock waves during acceleration from subsonic Mach number.

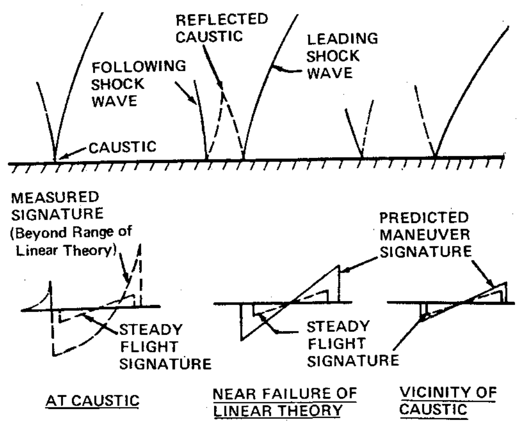

Fig. 8 Signature development of shock wave near caustic.

Figure 9 compares the linear theory with some experimental data from Ref. 5. The shock wave amplification with respect to a reference intensity is plotted vs distance past the caustic intersection with the ground. For the observed data the pressure jumps of the leading shock and the total pressure signature have been plotted with separate symbols. The linear theory is concerned with the leading shock only, since the trailing shock has passed through the caustic and has been significantly influenced by second-order effects. At the caustic the leading and trailing shocks are merged. For the case shown in Fig. 9 the linear theory predicts the amplification reasonably well for the leading shock, but fails within about 200 ft from the caustic where nonlinear effects predominate ("failure of linear theory"). At about 1000 ft from the caustic ("vicinity of caustic"), the linear and nonlinear effects are about equal.

For the case shown in Fig. 1 the caustic would be observed along the caustic locus only, with significantly amplified pressure signatures within about 1000 ft of it. Thus only a very small portion of the ground area would be affected by the caustic.

Meteorological and Flight Effects on Caustic Location for Longitudinal Acceleration

In general the caustic location is sensitive to flight and atmospheric variations. Figure 10 shows the effect of varying meteorological conditions from the 1962 U.S. Standard Atmosphere on the caustic location directly beneath the airplane for two acceleration rates. A headwind and higher temperatures cause the caustic to intersect the ground further

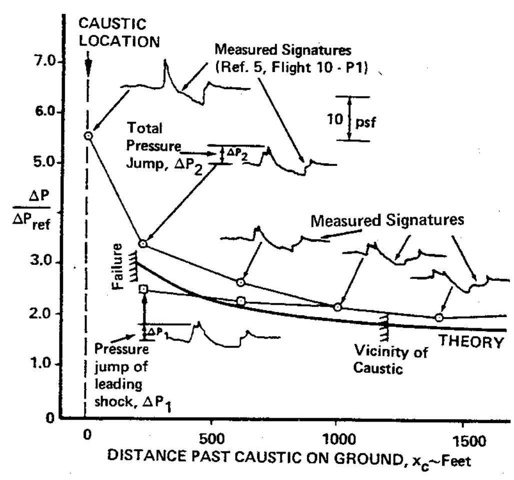

Fig. 9 Measured variation of shock strength near caustic.

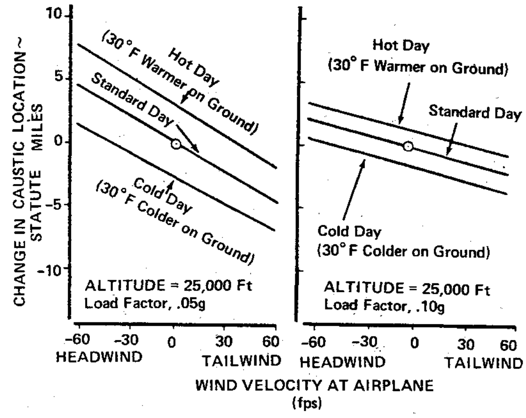

Fig. 10 Meteorological effects on location of caustic due to longitudinal acceleration.

down track, while a tailwind or lower temperatures on the ground cause the caustic to intersect earlier compared to the Standard Day. The atmospheric effects are significantly less important at the higher acceleration rate when starting from subsonic Mach numbers' This is because at the higher acceleration rates the rays associated with the caustic at the ground are produced at a higher airplane Mach number so that their propagation distance through the atmosphere is correspondingly less.

The caustic location due to longitudinal acceleration can be calculated to within a few miles of the observed caustic locations. To illustrate the accuracy of the calculation of caustic locations, the experimental data from Ref. 5 were used as test cases. The observed meteorological and flight data were used. Table 1 summarizes the comparison between calculated and observed caustic locations.

This excellent agreement between theory and experiment must be considered to be an upper limit for these kinds of calculations, since the observed flight and meteorological data were used. In actual practice (i.e., predicting caustic locations) these would not be known as accurately beforehand. It should be possible, however, to place the caustic consistently within a few miles of a desired location, provided that a reasonable degree of flight-path control exists and the average meteorological conditions are known. Figure 10 indicates that for an acceleration of $0.05g$ the point of initial acceleration would have to be varied by approximately ± 10 miles to place the caustic at one desired location for a wide range of meteorological conditions. A group of operational aids for determining the effects of meteorological and flight variations on caustic locations is given in Ref. 9. These were developed for field use during sonic boom flight tests, but are typical of the type of operational flight control data that could be derived for daily use.

Table 1 Comparison of calculated and observed caustic locations—Longitudinal Acceleration[a]

Flight number	Airplane altitude (ft)	Acceleration n_T (g's)	Initial mach number	Calculated caustic location from start of accel. (stat. mile)	Observed caustic location (stat. mile)	Error (stat. mile)
1	36,400	0.088	1.11	23.65	23.93	−0.27
7	36,150	0.074	1.11	23.93	24.78	−0.85
8	36,400	0.066	1.11	24.75	24.45	+0.30
9	36,150	0.065	1.10	25.61	25.18	+0.43
10	36,450	0.069	1.115	24.03	23.80	+0.23

[a] Experimental Data from Ref. 5.

Maneuver Requirements to Form Caustics

In considering possible constraints on supersonic maneuvers and/or operation, the formation of caustics at the ground is of primary interest. In general, caustics are to be avoided operationally since shock waves near caustics have been observed to be significantly more intense than shock waves during steady, level flight (3, 4, 5). To determine permissible maneuver load factors for no caustics at the ground, the ray-tube area expression given by Hayes, Haefeli, and Kulsrud[8] was analyzed in detail. Since the ray-tube area expression includes the effects of maneuvers, the equation was used to determine load factor and acceleration magnitudes required to give caustics (zero ray-tube area) at the ground for several simple maneuvers, including longitudinal acceleration, pushovers, and circular turns. Given a particular airplane altitude, Mach number, atmosphere, and maneuver, there is a particular load factor that will just give a caustic at the ground.

Figure 11 gives the critical (or minimum) acceleration load factor, n_T, required for a caustic to occur at the ground directly beneath the airplane during longitudinal accelerations in the 1962 U.S. Standard Atmosphere. Operationally, caustics can be produced only by acceleration beginning from Mach numbers below about 1.3 since the thrust load factors required for caustics starting from higher initial Mach numbers are very high and could not be produced by an SST, for instance.

Acceleration through Mach 1, however, will produce a caustic at the ground if the acceleration is continued above the threshold Mach number. The data given in Fig. 11 apply directly beneath the airplane only.

Critical lift load factors n_L required for a caustic at the ground directly beneath the airplane during pushovers in the 1962 U.S. Standard Atmosphere with no wind are given in Fig. 12. Again, caustics are most easily produced at the low supersonic Mach numbers. At speeds greater than about Mach 2, caustics are impossible to form operationally, for an SST, because of the load factor constraint on commercial flight. For passenger comfort the lift load factor will be restricted to greater than $0.5g$ in pushovers, while the structural lift load factor minimum is about $-0.5g$. A typical flight profile (Mach number-altitude variation) is also given in Fig. 12 for reference. For the operational minimum of $0.5g$ load factor, caustics could be produced only at Mach numbers between 1.5 and the threshold value.

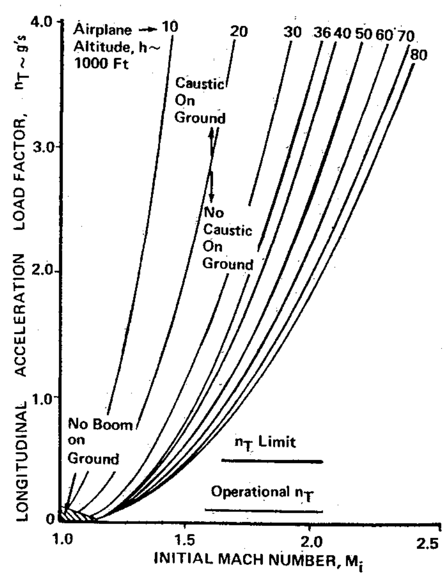

Fig. 11 Longitudinal acceleration requirements for caustic formation on the ground.

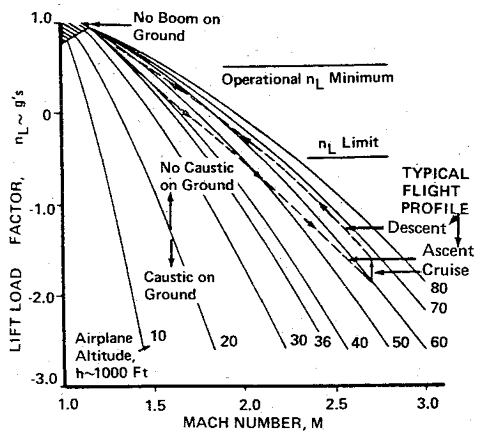

Fig. 12 Pushover requirements for caustic formation on the ground.

Critical airplane bank angles in degrees ϕ_a required for caustics to occur at the ground during constant altitude circular turns in the 1962 U.S. Standard Atmosphere are given in Fig. 13. For a lift load factor of 1.5 ($\phi_a = 48.2°$) caustics at the ground are possible for all Mach numbers up to and higher than Mach 2.7. These caustics occur well to one side of the flight path, near lateral cut-off.

Figures 11–13 show that, in general, caustics are most easily formed at the low-supersonic Mach numbers and that, at the higher Mach numbers during cruise, operational and structural load-factor constraints prohibit caustic-forming maneuvers. Caustics produced by turns, however, can be formed at all Mach numbers up to about Mach 2.7.

Conclusions

The comprehensive study of maneuver effects on sonic boom has shown that the maneuver effects are not necessarily significant for large supersonic airplanes, because of the normal operating characteristics (Mach number, altitude, and maneuver-load limits). The maneuver effects are most significant at the low-supersonic Mach numbers where it is possible to produce caustics within permissible load limits. Thus it may be necessary to place constraints on maneuvers between the threshold Mach number and, say, Mach 1.5 to ensure the avoidance of caustics and significant maneuver effects. Load-factor maneuver requirements to produce caustics at the ground were presented for this purpose. Thus, it would be possible to perform normal SST-type operations without producing caustics over significant ground areas.

The most important maneuver in normal SST-type operations is the transition from subsonic to supersonic flight where the acceleration through Mach 1 produces a caustic on the ground. The location of intensified shock waves on the ground, however, occurs over a very small ground area and can be placed with reasonable accuracy in a specific location using modern methods of flight-path control.

Methods have been devised to calculate detailed pressure signatures near caustics, but the signature at the caustic cannot be calculated using present linear theories. Theoretical predictions to date seem to be reasonably accurate. Methods have also been derived to predict with good accuracy the location of caustics on the ground due to any maneuver.

Some general conclusions can be made about the effects of maneuvers on pressure signatures. For instance, longitudinal accelerations result in slightly longer pressure signatures with stronger shock waves. During pullups the pressure signature increases in length and the shock waves are weaker compared to steady level flight. The opposite is true, in general, for pushover maneuvers. The airplane climb angle has an important effect on shock wave strength during pullups and pushovers. These effects are small for operational maneuvers except at the low-supersonic Mach numbers. A method for computing maneuver signatures starting from steady-flight signatures has been devised. This simplifies such calculations, since only the maneuver and atmosphere need be considered and the results applied to the steady flight signature for any configuration.

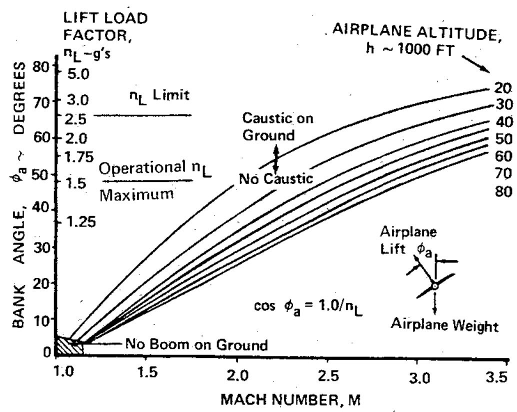

Fig. 13 Turn requirements for caustic formation on the ground.

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