NOTES AND CORRESPONDENCE

Atmospheric Focusing of Sonic Booms¹

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Supersonic booms have become an everyday occurrence in many parts of the country. Mostly they are an annoyance we must learn to live with if we wish to maintain an effective Air Force. On some occasions, however, these booms from supersonic flights have broken windows and cracked ceilings. Preliminary studies of the problem showed that if supersonic flights were conducted only above 30,000-ft altitudes, most of the damage would be avoided. Still, on rare occasions, windows have been broken from flights which were made according to rules found safe by field experiment.

Sonic boom wave geometry and source function parameters have been described by Wilson (1962). He also gives a qualitative summary of atmospheric temperature and wind effects on boom propagation. A calculation has been derived by Reed and Adams (1962) to show that atmospheric factors can focus conical boom waves and that certain flight conditions, heretofore thought safe, can cause wave focusing, and damaging pressure wave situations seem probable. Sound refraction plays an important role in boom wave focusing as it does in explosion wave focusing. Atmospheric sound ray paths shown by Cox *et al.* (1954) are used to follow a boom to ground through a horizontally stratified atmosphere. These calculations have been programmed in 709/7090 Fortran for computers at Sandia Laboratory. Computing simplifications suggested by Pack (1958) should be used for hand calculation or solution on some models of electronic computers.

Computer output shows proportional distribution of acoustic source energy at ground level from the areal spread of incident rays. If a source strength can be specified then ground level boom pressure amplitude can be predicted.

A series of calculations for hypothetical flights showed that some flights crosswind or quartering downwind through a strong wind field can give a focused wave on the ground. One case for a simple

linear atmospheric structure with constant wind direction is illustrated in Fig. 1, which shows curves for ray emission angle Φ ($\Phi=0^\circ$ is downward directed normal to aircraft axis) versus normal distance from course y for different flight headings relative to the wind. This shows, for crosswind and quarter tailwind flight, that

$$d\Phi/dy \rightarrow \infty \quad \text{as} \quad \Phi \rightarrow 90^\circ$$

which should give large boom wave overpressures. The energy emitted over a finite angle around the airplane axis is concentrated to land on a very narrow strip of ground. A real caustic (sometimes called cusp or sharp focus) has not resulted from calculations with sample atmospheric models; that is, calculated $d\Phi/dy$ has not been found actually to reverse sign. Also, computation was not carried beyond $\Phi=90^\circ$, where conditions above flight level might further affect focusing. However, the degree of convergence found in many calculated examples is probably adequate to explain most cases of damaging boom waves from high-altitude flight.

It has been determined by these calculations that whenever a ray emitted horizontally, $\Phi=90^\circ$, from a flight is refracted to hit ground, it will be part of a strongly converged and compressed section of wave. The fact allows a much simplified method for establishing the likelihood of creating potentially damaging focused waves.

A diagram for developing initial sound velocity for the $\Phi=90^\circ$ ray is shown in Fig. 2. Sound velocity is the sum of wind plus sound speed determined by local air temperature. The law of cosines is applied to show that

$$V_{90} = \{C^2 + W^2 - 2CW M^{-1} [\cos(D-H) - (M^2 - 1)^{1/2} \sin(D-H)]\}^{1/2}, \quad (1)$$

where D is direction from which wind is blowing and H is true heading toward which flight is made. This ray will reach ground, provided there are no intermediate high-velocity layers, whenever V_{90} exceeds ground-level similarly directed sound velocity. It will

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FIG. 1. Calculated sound ray y -coordinate (normal to course) at ground level versus emission angle around the aircraft axis (0° directed downward) for various flight headings relative to wind at altitude. Relative boom intensity depends on curve slope; $dy/d\Phi=0$ gives strong focused boom.

FIG. 2. Plan view of initial geometry for horizontal emitted ray along V . This ray strikes ground in convergent region when sound velocity V exceeds ground level sound speed.

land about as far from the ground course as the aircraft is above ground, i.e., 8 mi to leeward of the track of a 40,000-ft flight. In practice, highly variable surface winds should probably not be depended upon to keep foci from striking; accordingly, surface sound speed, C_0 , may be used to determine occasions when $V_{90} > C_0$, and foci may be generated.

An evaluation of Eq 1 for minimum flight level wind speed for horizontal emitted rays to reach ground and give boom focusing in an ARDC model atmosphere (U. S. Air Force, 1960) has been made. This allows construction of the "safety-gram" in Fig. 3 for different flight altitudes, Mach numbers, and wind-minus-heading angle differences. When flight plan conditions indicate a case which falls above the appropriate curve, a damaging ground-level boom may result. When a case falls below the curve, the boom may or may not be heard, dependent upon cutoff conditions shown by Wilson (1962), but no focus will occur. When focusing is indicated, the flight plan should be changed to an altitude having different winds. In extreme cases for flights crossing strong jet streams, an alternate route may be required to avoid adverse disturbances. If marginal safety is shown, either a safety factor should

FIG. 3. Determination of boom focusing in standard atmosphere temperatures for various flight altitudes, headings, and Mach numbers, and wind speeds and direction. Flight plan points falling above curves may cause focused boom waves; those which fall below curves may be heard but would not cause damage.

be used or an exact machine calculation made to investigate further the effect of the nonstandard conditions known, or forecast, to exist at flight time.

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