(NASA-CR-142075) LABORATORY STUDY OF SONIC BOOMS AND THEIR SCALING LAWS Final Technical Report (Massachusetts Inst. of Tech.) 10 p HC $3.25 CSCL 20A
N75-17153
Unclas
G3/71 09012

Final Technical Report on Research

Supported by NASA Grant NGR22-009-618

LABORATORY STUDY OF SONIC BOOMS AND THEIR SCALING LAWS

Tau-Yi Toong and Mohsen Sanai

Massachusetts Institute of Technology

Cambridge, Massachusetts

The main objective of this research program is to seek basic understanding of non-linear effects associated with caustics, through laboratory simulation experiments of sonic booms in a ballistic range and a coordinated theoretical study of scaling laws. Two cases of superbooms or enhanced sonic booms at caustics have been studied. The first case, referred to as "acceleration superbooms", is related to the enhanced sonic booms generated during the acceleration maneuvers of supersonic aircrafts. The second case, referred to as "refraction superbooms", involves the superbooms that are generated as a result of atmospheric refraction.

Important theoretical and experimental results obtained in this research program are briefly reported below with complete details to be found in the M.I.T. Doctoral Thesis of Sanai[1]. Most of these results have been presented at several professional meetings and reported in the literature[2,7]; two papers describing the main results have also been submitted for publication in the Journal of the Acoustical Society of America[8,9].

1. Acceleration Superbooms

Acceleration superbooms are studied by firing projectiles of different sizes and shapes at constant supersonic speeds into gaseous media with decreasing sound speed along the line of flight. This results in trajectories with increasing body Mach numbers which simulate the acceleration of supersonic aircrafts.

Theoretical analyses include the development of a computer program which locates the geometrical-acoustics rays and shock fronts for an idealized model of the above experiments[1,5]. The results indicate that a concave shock front is produced which converges and folds over itself as it passes a cusp formed at the junction of two caustic surfaces. (The cusp is usually referred to as an arête or superfocus.) A scaling law for peak overpressures near an arête has been developed[2]. According to this law, the peak overpressure at the arête is dependent on the shape and strength of the shock some time before the arête is reached. Theoretical studies have also been made to examine the effects of refraction introduced in the present simulation experiments[1,6]. They show that the behavior of the superboom generated in the simulation experiments are comparable to that observed in real acceleration maneuvers.

To analyse the flow fields produced in the simulation experiments, signatures from pressure transducers have been studied in conjunction with dual-schlieren pictures obtained simultaneously during each run[1,5,9]. For weaker shocks (shock Mach numbers of about 1.03) generated by

17-caliber bullets at low supersonic speeds, a structure similar to that of a folded shock predicted by the linear theory is observed in the schlieren pictures while for slightly stronger shocks (shock Mach numbers of about 1.05) generated by faster 17-caliber bullets, a concave focusing front is recorded[1,9]. In the case of very strong shocks (shock Mach numbers of about 1.30) generated by 12.7 mm-diameter spheres or conical-nosed bodies at high supersonic speeds, no folding-like structure has been detected in the available schlieren viewing field while both focusing and defocusing (or flattening) of shock concavities have been observed[1,5]. Based on these observations, it has been conjectured[9] that the fold-over hypothesis of the geometrical acoustics theory and the hypothesis of Whitham that concave shocks will straighten out without folding are complementary rather than contradictory and that each applies under certain (and as yet not completely delimited) shock conditions.

Applicability of Whitham's shock-shock theory* to the present experiments have been tested by assuming that the point at which the minimum radius of curvature of the shock concavity, r_{min}, is measured corresponds to the "shock-shock" in Whitham's theory[1]. A reasonable agreement is found for cases where r_{min} is very small: i.e., for cases where the shock-shock geometry of Whitham is approached. For other cases, the agreement is poor with the shock concavity "propagating" at a faster speed along the shock face than that predicted by the shock-shock theory.

*In this theory, discontinuities in shock inclinations and Mach numbers are assumed to exist across a "shock-shock" which propagates along the shock face.

Enhanced overpressures have been detected in the shock concavities on the basis of shock speed calculations from superimposed dual-schlieren pictures[1,5] as well as from direct pressure measurements[1,9]. This enhancement or focusing effect is found to depend on the shock curvature and its nominal strength. With the aid of the Guiraud-Thery scaling law**, a remarkable correlation has been obtained for the focus factors measured in the experiments involving weak shocks (shock Mach numbers of about 1.05) and strong shocks (shock Mach numbers of about 1.30) with the variation of r_{min} (here representing the extent of bending of the front) from 9 cm to 2 cm[1,9]. The results tend to suggest the substantial effects of the shock curvature and nominal strength in the focusing phenomenon.

A largest focus factor of 2.0 has been obtained in the present experiments[1]. (The nominal shock Mach number was about 1.05 for this case.) This value, with appropriate theoretical scaling to account for differences in shock overpressure ratios, suggests that peak magnifications of atmospheric sonic booms due to accelerated flight should be in the range of 6 to 13, which compares favorably with results of field tests[9].

2. Refraction Superbooms

To simulate the refraction superbooms, projectiles are fired at

---

**This law prescribes that the focus factor at corresponding points along a smooth caustic should vary with the nominal shock overpressure ratio as $(\Delta p/p_o)^{-4/5}$ in any two geometrically similar experiments involving weak shocks.

low supersonic speeds into a gaseous medium produced by a slow injection of CO_2 into air through a porous rubber sheet located at the bottom of the test section[1,7,8]. Schlieren observation of the resulting flow fields indicate that the generated shocks are reflected near the sonic cut-off elevation, where the local sound speed equals the body speed, provided that such an altitude exists. The incident shock and its reflected portion join to form a Y-shaped configuration near the cut-off region. This has been compared to the predictions of the linear theory, which indicates that the incident shock is totally reflected at a caustic located at the sonic cut-off elevation and that the reflected shock joins the incident shock to form a cusp at the caustic. The difference between the two shock configurations near the cut-off elevation is believed to be related to the non-linear effects near the caustic.

A remarkable similarity has been found to exist between the triple-shock Y-shaped configuration observed in the present simulation experiments and that produced by an irregular Mach reflection of a shock at a solid surface[1,7]. However, detailed comparisons with several studies of Mach reflection indicate that the similarity is restricted to the shape alone and does not extend to other important flow features such as the shock strength. In particular, the Mach stem produced in the irregular reflection is at least as strong as the incident shock while the strength of the corresponding normal shock portion in the simulation experiments is generally weaker than the leading shock and decreases rapidly as the cut-off elevation is reached. Based on the above comparisons, it has been concluded that the Mach reflection phenomenon alone cannot describe the flow field associated with the refraction superboom experiments.

Dependence of cut-off elevations on the body Mach number has been determined experimentally for the leading and wake shocks[1]. Despite the rather large dispersion that exists about the mean curves, the results tend to indicate that, in general, the leading shock is reflected at an elevation slightly below the theoretical caustic while the wake shock penetrates by a small amount into the theoretical "silent zone" above the caustic before it is reflected.

Variation of the triple-point of the leading shock with body Mach number has also been studied experimentally[1]. The mean curves tend to indicate that the triple-point and cut-off elevations are coincident for shocks of infinitesimal strength, in agreement with the prediction of the linear theory. But, due to nonlinear effects, the triple-point and cut-off elevations do not coincide when real shocks are involved. For this latter case, the reflection at the caustic gives rise to the triple-shock configuration that was mentioned earlier.

Depending on the flow field behind the leading shock, several regions have been identified including a "critical altitude" region where the flow speed behind the leading shock is transonic and where the pressure measurements indicate the occurrence of enhanced shock overpressures[1,7,8]. The experiments also show that the maximum shock intensity occurs very nearly at the point where the incident and the reflected shocks join (i.e., the triple-point), indicating that the presence of the reflected shock may have an appreciable effect on the magnitude of the focus factor.

The largest focus factor detected in the present simulation experiments is 1.7 and leads to an estimate that the constant in the Guiraud-Thery scaling law should have a value of 1.3[8]. This is in agreement with the value that might be inferred from the NASA field test data. Furthermore, it is nearly equal to the previous theoretical estimate of 1.4 given by Thery. While the Guiraud-Thery scaling law remains a topic for further investigation, the fact that both of the experimentally derived values of the constant agree so well with the theoretically predicted one would tend to suggest its validity.

CONCLUDING REMARKS

The results of the present research program have indicated that certain aspects of the problem of enhanced sonic booms or superbooms may be studied by simulating the phenomenon in a ballistic range. In particular, the results obtained from the simulation experiments of acceleration superbooms indicate the presence of a shock concavity and the appearance of a folding-like shock structure in cases where weak shocks (shock Mach numbers of about 1.03) are involved. By noting that in the case of very strong shocks (shock Mach numbers of about 1.30) both focusing and defocusing (or flattening) of shock concavities are observed and that no folding-like structure is detected in the available schlieren viewing area, it is proposed that the fold-over hypothesis of the geometrical acoustics and the hypothesis of Whitham that concave shocks will straighten out without folding are complementary rather than contradictory and that each may apply under certain (but as yet not completely delimited) shock conditions. Also in the same experiments, the existence of enhanced shock overpressures at shock concavities has been established and, in connection with some suitable scaling laws, a range of values is predicted for the magnitude of the focus factor in the case of real flight situation which brackets those obtained from field test measurements.

The results of the simulation experiments of refraction superbooms indicate the formation of a Y-shaped shock configuration as a result of reflection of the leading shock near the sonic cut-off elevation (elevation at which the body speed equals the sound speed). Pressure measurements have indicated the occurrence of enhanced overpressures near the "critical altitude" where the flow speed behind the shock becomes transonic. By applying a suitable scaling law, the peak focus factor to be expected in the case of threshold Mach number flights in the real atmosphere has been predicted which compares favorably to those measured in real flight tests.

PUBLICATIONS AND PRESENTATIONS

1. M. Sanai, "Generation and Propagation of Focused Shock Fronts," Ph.D. Thesis, Mass. Inst. of Tech. (May 1974). (Copy sent to NASA on June 10, 1974).

2. A.D. Pierce, "Maximum Overpressures of Sonic Booms Near the Cusps of Caustics," Noise and Vibration Control Engineering, M.J. Crocker, Ed. (Purdue University Press, 1971) pp. 478-487.

3. M. Sanai, T.Y. Toong, A.D. Pierce and R.F. Salant, "Propagation of Weak Oblique Shocks through a Diffusing Gas Mixture," presented at the 83rd Meeting of the Acoustical Society of America, Buffalo, N.Y. (April 1972).

4. M. Sanai, A.D. Pierce, T.Y. Toong, "Simulation of Acceleration Superboom," presented at the ASA-NBS Symposium on Atmospheric Acoustics and Noise Propagation, held at the National Bureau of Standards, Gaithersburg, Maryland (September 1972).

5. M. Sanai, A.D. Pierce, T.Y. Toong and R. F. Salant, "Acceleration Superbooms: Some Preliminary Results," Proceedings of the Inter-Agency Symposium on University Research in Transportation Noise, Stanford University, Stanford, Calif. (March 1973) Vol.I, pp. 351-368.

6. M. Sanai, "Refraction Effects in the Simulation Experiments of Acceleration Superbooms," Research Report submitted to NASA, Langley Research Center (July 1973).

7. M. Sanai and T.Y. Toong, "Laboratory Investigation of Sonic Boom Focusing," Proceedings of the Second Interagency Symposium on University Research in Transportation Noise, Raleigh, North Carolina (June 1974) Vol. I, pp. 416-431. (Copy sent to NASA on April 18, 1974.)

8. M. Sanai, T.Y. Toong and A.D. Pierce, "Ballistic Range Experiments on the Superboom Generated by Refraction," submitted for publication in the Journal of the Acoustical Society of America (August 1974). (Copy sent to NASA on August 22, 1974.)

9. M. Sanai, T.Y. Toong and A.D. Pierce, "Ballistic Range Experiments on the Superbooms Generated at Increasing Flight Mach Number," submitted for publication in the Journal of the Acoustical Society of America (September 1974). (Copy sent to NASA on September 13, 1974.)

END

DATE

FILMED

APR 11 1975