Ground Motion from Sonic Booms

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To ascertain the degree of hazard to structures from sonic-boom-induced ground vibrations, seismic measurements were made under NASA support during a series of sonic boom tests in 1967 and 1968. The maximum ground vibration velocity observed was 340 μ/sec at 90 Hz, corresponding to a sonic boom overpressure of 3.5 lb/ft^2. This is less than 1% of the structural damage threshold established experimentally by the U.S. Bureau of Mines and others, of 50,800 μ/sec. It is therefore very unlikely that any structural damage to slabs, foundations, wells, etc., can occur because of sonic booms. Incidental to the study, seismic precursor waves were observed which provide a possible basis for automatic warnings of approaching sonic booms, to reduce their startle effect.

1. Introduction

As part of continuing government programs to study the hazards and annoyances which may be imposed upon the population by sonic booms, Geotech has made an extensive study of the seismic effects associated with sonic booms, supplementing earlier work on the phenomena by others.[1,2] This paper will include a brief introduction to the science of seismology, and will give examples of the results obtained in our field experiments, together with their interpretation.

2. Phenomena and Methods of Seismology

As we all know, sufficiently severe motion of the ground can damage structures, and the degree of damage is related to the severity of the motion. The motion experienced by observers during an earthquake has been estimated for many years in terms of an intensity scale.[3] For example, intensity III can just be clearly felt, and chandeliers are seen to sway; at intensity VI, weak plaster may crack and furniture moves; at intensity IX ordinary masonry is badly damaged and underground pipes are broken; at intensity XII, all structures are destroyed and objects are tossed into the air. A more objective measurement of earthquake severity, known as the magnitude scale[3] has been developed. Earthquake magnitude is related to the logarithm of the energy released and is calculated from ground motions measured by standard seismographs at known distances from the earthquake source. The largest earthquakes are of magnitudes between 8 and 9.

Some human activities, such as blasting, also produce noticeable ground motion. Because of the importance of monitoring and controlling these activities, studies have been conducted by the U.S. Bureau of Mines, the Liberty Mutual Insurance Company, and others, to establish criteria defining the level at which ground motions may damage buildings. Three criteria have been developed. The oldest criterion on which a structural damage threshold was based is the peak acceleration of the ground during passage of seismic waves. Accelerations exceeding 0.1 g (980 mm/sec^2) in the frequency range between 1 and 20 cps were considered to be above the safe range. A newer criterion is the energy ratio, defined as [peak acceleration/frequency]^2. The energy ratio damage threshold is defined as 3 (ft/sec)^2. The latest criterion and the criterion currently recommended by the U.S. Bureau of Mines[4] defines the upper limit of safe ground velocity as 2.0 in./sec; that is, 50,800 μ/sec. This new criterion agrees very well with the earlier "energy ratio" criterion. At this level of ground velocity, damage may begin in the weakest part of a structure; that is, plaster may crack. If the measured ground motion is below this level, courts in many states are likely to reject damage claims.

Seismic energy from either man-made or natural sources travels through the earth in three ways: as compressional, shear, and surface waves. Compressional waves are similar to sound waves in the air and travel with high velocities, ordinarily between 1000 ft/sec and 20,000 ft/sec (about Mach 1 to Mach 20) near the Earth's surface. The higher velocities occur in dense, hard rocks; the lower velocities in low density, softer materials. With shear waves, the ground vibrates at right angles to the direction the energy is traveling. Such

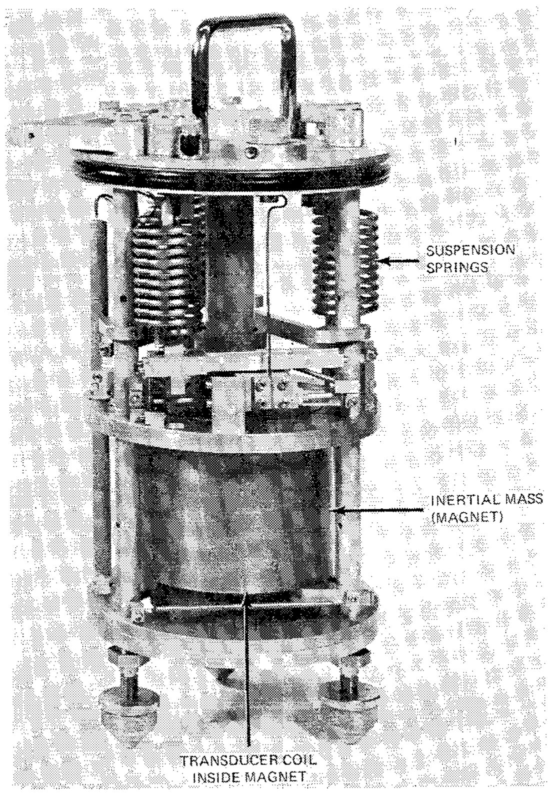

Fig. 1 A modern electromagnetic seismometer.

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waves travel slower than compressional waves, between about Mach 0.6 and Mach 12. Surface waves are of several types, among which are Rayleigh waves. Rayleigh waves produce a motion of the ground surface much like that of waves on the sea,‡ and as with ocean waves, the energy flow is confined to a region quite near the surface. Rayleigh waves travel a little slower than shear waves (between about Mach 0.5 and Mach 11); the exact velocity in a layered medium like the earth is dependent on the frequency of the Rayleigh wave as well as the elastic parameters of the medium.

To measure earth motions accurately, many kinds of seismic instruments have been developed over the past 75 years. Figure 1 shows a sensitive, modern seismometer with its case removed. The seismometer has three principal parts: the inertial mass, the suspension system, and the transducer. By means of the suspension system, consisting of springs, levers, and flexures, the inertial mass is constrained to move in only one direction with respect to the frame. The suspension is soft and without friction. When the instrument is resting on the ground or buried within it, the outer case and frame participate in the motion of the ground, but the inertial mass remains essentially fixed in inertial space. The relative motion between the frame and the inertial mass, which is a magnet, is translated into an electrical signal in the seismometer shown in Fig. 1, by a coil which moves with the seismometer frame. The output voltage of the system is proportional to the relative velocity, and the system response is constant (flat) within ± 1 db between 1 Hz and 100 Hz (cps). This arrangement is typical of modern electromagnetic seismographs.

The seismometer shown in Fig. 1, coupled with suitable amplifiers and recorders, can detect earth motions as small as 10^{-10} m; that is, 1 Å unit or a distance about equal to the diameter of a hydrogen atom. Such sensitivity is ordinarily not required, since natural earth noise is about 10 times this, and the noise in cities may be 1000 times as high because of traffic and other cultural activity.

Figure 2 shows a block diagram of one channel of the portable seismographic instruments used in the sonic boom program. Seismometers operating both in the vertical and horizontal orientations are used to measure all 3 components of ground motion. Data were recorded on a visual recorder and on magnetic tape to permit later processing by computer. Means of electrically calibrating the seismometers were provided. Calibration was performed daily in the field to check small variations in system sensitivity caused, for example, by temperature changes. Field calibration was performed by sending a known amount of electric current through an auxiliary coil, producing a known motion of the inertial mass, which was then registered by the recording apparatus. Such electrical calibration was, in turn, standardized at the laboratory with a precision shake table having optical indicators, the calibration of which was, in turn, traceable to the U.S. Bureau of Standards.

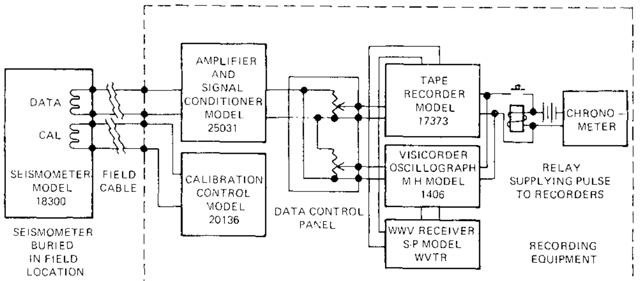


Fig. 2 Block diagram of one seismograph of the mobile equipment.

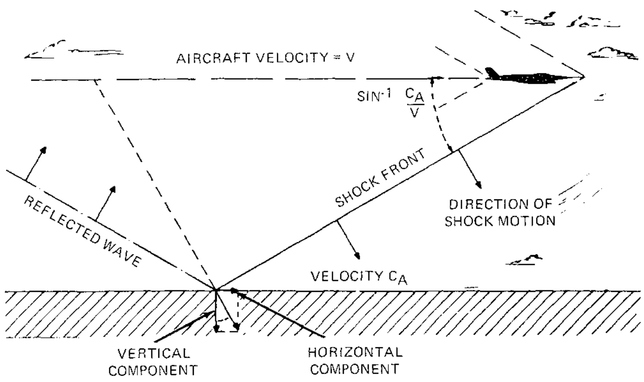


Fig. 3 Vertical section of a shock wave interacting with the ground.

3. Seismic Waves from Sonic Booms

Figure 3 illustrates, in a simplified manner, the conical sonic wave front developed by the shock compression at the nose of a supersonic aircraft, and its interaction with the ground (the tail shock has been omitted for simplicity). Such a shock-generated wave is reflected from the ground like any other acoustic wave, and over 99% of the energy returns to the atmosphere, because of the large density and velocity contrast between earth and air. Acoustic theory indicates that in instances where the density and seismic velocities of the ground are high, as in hard rock, less energy should be coupled into the ground than in instances in which the earth is soft, of low density, and low velocity. Hence, we can expect to find a dependence of the seismic effects of sonic booms upon local geology.

As shown in Fig. 3, the pressure exerted by the front of the sonic boom wave, which has an N-shaped pressure vs time profile[5] produces a moving vertical force and may also generate a horizontal force if the ground is rough or irregular. These forces should be accompanied by corresponding elastic displacements of the ground. Seismic theory indicates that a moving vertical force should also generate a surface wave moving at the same speed as the aircraft, of a frequency determined by the spectrum of the applied force and the vertical velocity distribution in the earth. The amplitude of the surface wave may be especially large if the aircraft speed matches one of the seismic velocities of the local geology.

Secondarily, as the sonic wave travels along the surface, irregularities and variations in density and ground hardness which it encounters may become local sources of seismic waves which radiate in all directions.

Seismic waves traveling forward from the sonic wavefront at a rate faster than the airplane would arrive before the sonic boom. Such precursor waves do indeed exist, as shown by the seismogram in Fig. 4. This seismogram was taken at a large government seismic observatory and the position of the flight trace with respect to the instruments was not known. On the three low-gain traces near the top of the record, and some others, the precursor can be clearly seen to exceed the level of the background noise about 4 sec before the arrival of the sonic boom at the same location, as indicated by the microbarograph.

The forerunner wave may exceed normal background noise by a factor of 10 (20 db) in quiet locations, according to Fig. 4. Further study will be necessary to determine whether it can be reliably distinguished from other seismic noise from sources such as traffic, aircraft, and wind gusts. Nevertheless, the seismic forerunner offers some hope that an auto-

‡ The main difference is that the surface particles revolve in a vertical retrograde orbit in Rayleigh waves, but in a vertical prograde orbit in ocean gravity waves.

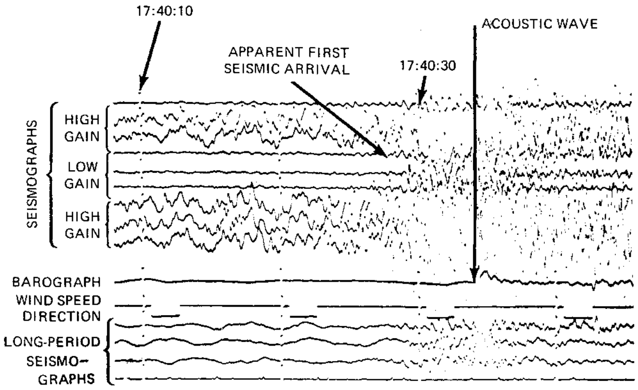


Fig. 4 Observatory seismogram showing precursor waves.

matic warning can be given before the arrival of sonic booms, thereby lessening the startle effect upon people and livestock.

4. Principal Experimental Results

Between October 1966 and March 1967, numerous government supersonic tests were flown at Edwards Air Force Base, Calif. Some additional tests were made at two government seismic observatories: the Tonto Forest observatory in Arizona and the Uinta Basin observatory in Utah. Among the ground-level measurements made by Geotech under NASA Contract, a total of 178 flights were monitored. These flights were made chiefly by B-58, F-104, and SR-71 aircraft; however, 17 overflights were made by an XB-70 aircraft. These are of greatest interest since the XB-70 aircraft most nearly approaches a supersonic transport in size.

Figure 5 shows the location of the three main seismic stations at Edwards Air Force Base (shown as dark spots) with relation to the general flight track of the aircraft (indicated by an arrow). The center station, on the edge of the dry lake bed, included a vertical seismometer, a horizontal in line with the flight track, and a horizontal transverse to the track. The two outlying stations employed vertical seismometers; one was on an area of thicker lake (playa clay) sediments and the other on an outcrop of hard rock (quartz monzonite), giving a comparison of two different geological environments. All seismometers were buried to depths of about 3 ft.

Figure 6 shows a seismogram of a typical F-104 overflight. The aircraft was flying at an altitude of 31,000 ft and a speed of Mach 1.65. The top trace or channel (V1) represents the output from the vertically oriented seismometer and the second

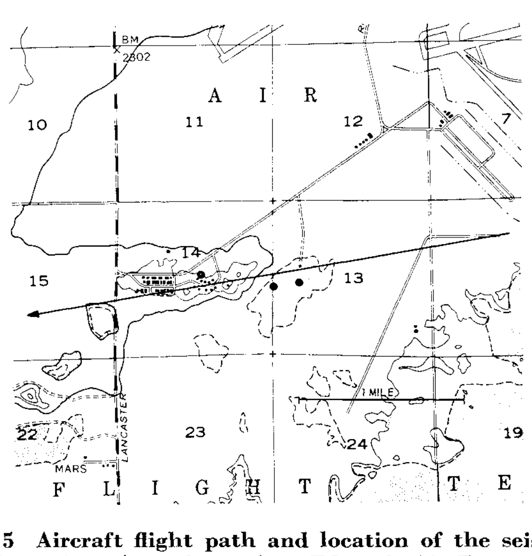


Fig. 5 Aircraft flight path and location of the seismograph stations (round spots) at Edwards Air Force Base, Calif.

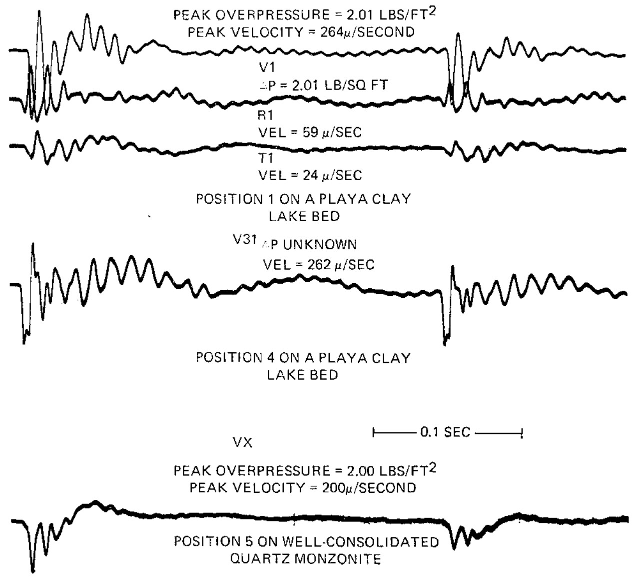


Fig. 6 Sonic boom seismic signatures for mission 13-2 (XB-70) recorded at 3 different positions at Edwards Air Force Base.

and third channels are the radial (R1) and transverse (T1) seismograms, respectively, at the center station. Channel 4 (V31) is the output of the vertical seismograph located nearer the center of the dry lake, and channel 5 (VX) is that of the vertical seismometer situated on the rock outcrop. Channels 4 and 5 have been shifted in time so that all channels can be shown in one illustration. The peak positive air overpressure recorded at each site and the resulting first downward peak of ground velocity are noted for each channel. The precursor waves are present in the magnetic-tape recording but cannot be seen in Fig. 6 because of the low amplification used to display the main peaks without distortion.

Experience has shown that maximum ground velocity always occurs during passage of the pressure peaks of the N wave, and that it is proportional to the peak overpressure in

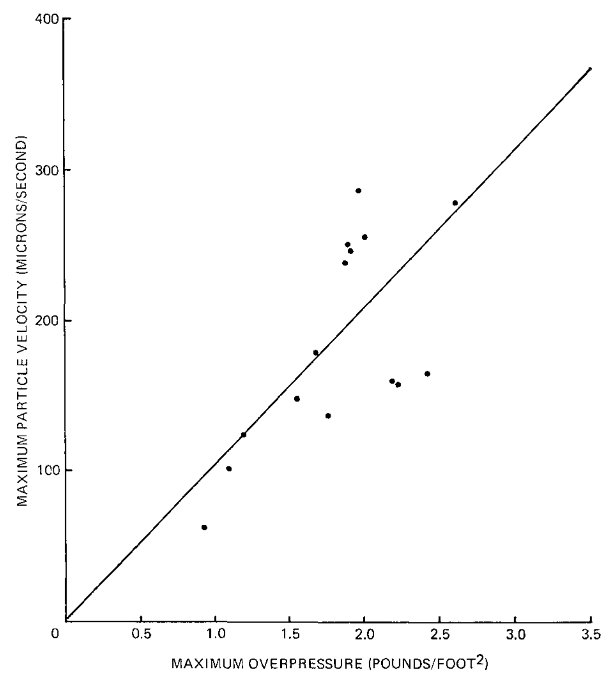
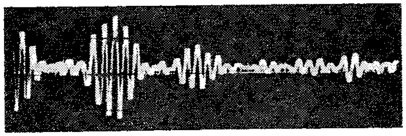
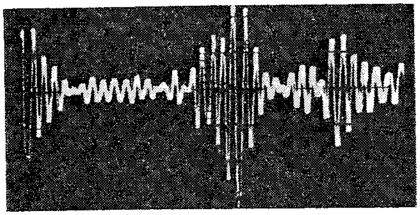


Fig. 7 Relation of maximum overpressure for XB-70 overflights to peak earth particle velocity observed on a vertical seismograph located on a clay lake bed (position 1) at Edwards Air Force Base.



a) Automobile at 30 ft, 30 mph: peaks average 70Hz, 350 μ/sec



b) Semitrailer (20t) at 50 ft, 20 mph: peaks average 70Hz, 800 μ/sec

Fig. 8 Some examples of traffic-generated ground motion.

the N wave, regardless of aircraft type, speed or altitude. The ground motion does depend upon local geology, however; it is greatest on unconsolidated soil-like materials such as the lake bed clay, and is least on hard rock. These findings are in agreement with predictions from the theory of elasticity.[6]

Secondary oscillations of the ground accompany the two major displacements, in some types of ground. These were always observed to be weaker than the two major displacements associated with the N wave. Measurements at a depth of 44 ft showed a ground motion only $\frac{1}{75}$ that at the surface. Evidently, sonic boom effects are confined to a thin layer of earth near the surface.

Figure 7 shows the relation of the maximum overpressure to first peak vertical ground velocity recorded by instruments located on the dry lake bed. These results indicate a linear relationship between maximum positive overpressure and first peak ground velocity for both the clay and the rock. The ground motion for a given overpressure is consistently greater in the lake sediments than in the rock. It has also been found that the horizontal ground motions are substantially less then the vertical.

The values of ground velocity obtained for the limited range of overpressures available are small compared with the most reliable estimates of the damage threshold. The maximum value of ground velocity which has been recorded and analyzed in these tests is 340 μ/sec (at 90 Hz) from an overpressure of 3.5 lb/ft^2. This is less than 1% of the seismic damage threshold criterion now accepted by the U.S. Bureau of Mines.

Further evidence that such values of peak ground vibration velocity are not likely to harm structures attached to the ground is given by a comparison with more familiar sources of vibration. Figure 8 shows two examples of (horizontal-component) vibrations measured in ordinary grassy soil near a paved city street. As we all know, buildings 30–50 ft from a street are not generally considered to be in any danger from traffic vibrations. In the two examples shown in Fig. 8, the vibration intensities are greater than those of the strongest XB-70 sonic booms measured at Edwards Air Force Base, by any criterion.

5. Conclusions

1) The ground motion induced by sonic booms of ordinary intensity (below 3.5 lb/ft^2) probably cannot damage foundations or other structures which are in good condition. The ground motion is even weaker below the surface, and is very unlikely to damage well casings. 2) "Forerunner" seismic waves precede the sonic boom by several seconds at most locations. Automatic sonic boom warning devices utilizing these waves may be feasible.

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