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GROUND MEASUREMENTS OF AIRPLANE SHOCK-WAVE NOISE AT MACH NUMBERS TO 2.0 AND AT ALTITUDES TO 60,000 FEET

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SUMMARY

The intensity of shock-wave noise at the ground resulting from flights at Mach numbers to 2.0 and altitudes to 60,000 feet was measured. Measurements near the ground track for flights of a supersonic fighter and one flight of a supersonic bomber are presented.

Level cruising flight at an altitude of 60,000 feet and a Mach number of 2.0 produced sonic booms which were considered to be tolerable, and it is reasonable to expect that cruising flight at higher altitudes will produce booms of tolerable intensity for airplanes of the size and weight of the test airplanes. The measured variation of sonic-boom intensity with altitude was in good agreement with the variation calculated by an equation given in NASA Technical Note D-48.

The effect of Mach number on the ground overpressure is small between Mach numbers of 1.4 and 2.0, a result in agreement with the theory. No amplification of the shock-wave overpressures due to refraction effects was apparent near the cutoff Mach number.

A method for estimating the effect of flight-path angle on cutoff Mach number is shown. Experimental results indicate agreement with the method, since a climb maneuver produced booms of a much decreased intensity as compared with the intensity of those measured in level flight at about the same altitude and Mach number.

Comparison of sound pressure levels for the fighter and bomber airplanes indicated little effect of either airplane size or weight at an altitude of 40,000 feet.

INTRODUCTION

Military organizations in this country are presently aware of the problem of shock-wave noise accompanying supersonic flight. People in some communities have heard sonic booms and occasionally damage has been done to buildings in spite of efforts to prohibit supersonic flight of military aircraft near populated areas.

Although the sonic boom is familiar to some localities, the probable future introduction of commercial supersonic travel will necessarily be accompanied by disturbances over large areas occurring at regular and, in a few locations, frequent intervals. The maximum tolerable intensity of these disturbances is already recognized as an important consideration in the operation and, therefore, in the design of supersonic transports. (See, for example, ref. 1.) There appears to be an immediate need for accurate knowledge of the ground overpressures to be expected for the climb and descent phases of a flight plan typical of future supersonic transports and for measurements of the magnitude and lateral spread of sonic-boom disturbances caused by cruising flight at Mach numbers to 3.0 and altitudes to 80,000 feet.

The intensity of sonic booms for a wide range of flight conditions can be estimated by a theoretical method presented in references 2 and 3. This theory has been experimentally verified by flight tests between 200 and 45,000 feet and at Mach numbers to 1.45 in the investigations of references 4, 5, and 6 but has not been verified in the range of speeds and altitudes that may be expected for future supersonic-transport operation. This paper presents data from an investigation of sonic-boom overpressures resulting from level flights at Mach numbers from 1.2 to 2.0 and at altitudes from 30,000 to 60,000 feet; these flight conditions are more nearly comparable with the operating conditions for economical cruising flight of future supersonic-transport aircraft. In addition, the present investigation includes measurements of sonic-boom overpressure obtained for climbing flight and the effects of airplane size and weight obtained from comparison flights of a supersonic bomber and a supersonic fighter. Although the investigation included measurements to determine the lateral spread of the noise disturbances, only the data obtained near the ground track of the airplane are presented in this paper.

SYMBOLS

d	equivalent-body diameter, ft
K_1	ground-reflection factor, $\frac{\Delta p_f + \Delta p_r}{\Delta p_f}$
K_2	airplane body-shape factor
l	airplane length, ft

M airplane Mach number

M_L cutoff Mach number for level flight

M_γ cutoff Mach number

p_a ambient pressure at altitude, lb/sq ft

p_o ambient pressure at ground level, lb/sq ft

Δp_f pressure rise across shock wave in free air, lb/sq ft

Δp_o pressure rise across shock wave at ground level, lb/sq ft

Δp_r pressure rise across reflected shock wave, lb/sq ft

y perpendicular distance from measuring station to flight path, ft

γ flight-path angle

APPARATUS AND METHODS

The tests were made in the vicinity of NASA Wallops Station. A ground radar station was used to direct the airplane ground track within 1 or 2 miles of the measuring station. The terrain in the vicinity of the measuring station is generally open and the elevation is near sea level. The tests were conducted in a manner similar to those of reference 6. Some differences in the sound equipment, radar tracking equipment, and flight technique are explained and a brief description of the airplanes used in these tests is given.

Test Airplanes

Photographs of the test airplanes are presented as figures 1 and 2. The supersonic fighter shown in figure 1 weighed about 38,000 pounds at takeoff but averaged about 30,000 pounds for most of the flights. The wing area of the airplane is 452 square feet and the length is 58.8 feet. The major portion of the present investigation was made with the fighter airplane.

The supersonic bomber shown in figure 2 was flown for comparison purposes to determine the effects of airplane size and weight on sonic-boom intensity. This airplane is designed to operate at approximately the same range of altitude and speed as the fighter of figure 1. The airplane weight was about 140,000 pounds for the test flight. The wing area is 1,545 square feet and the airplane length is 97 feet. The flight was made with an external pod attached to the bottom of the fuselage. The pod is not shown in figure 2.

Sound Equipment

Noise-pressure measurements were obtained with the aid of commercially available condenser-type microphones and an inductance-type pressure pickup. The microphones had a usable frequency range from 5 to 10,000 cps and the pressure pickup had a flat frequency response from 0 to 175 cps. The signals from both types of instruments were fed into an FM tape recorder having a flat frequency response from 0 to 10,000 cps. Two microphones and a pressure pickup were located at the measuring station. One microphone and the pressure pickup were mounted in a plywood board to measure the ground pressures. The other microphone was attached to a mast 30 feet above ground level. The latter microphone detected the free-air pressure as well as the reflected component.

In addition to obtaining the measured noise pressure, the operators and observers at the measuring station recorded their reactions to the booms and also, when possible, observed the reaction of other persons in the vicinity.

Radar Tracking for Flight Control

Ground tracks and altitude-distance paths were plotted automatically at 1-second intervals by the use of FPS-16 and SCR-584 Model II radars located at the NASA Wallops Station. All the flights were in a northerly direction over the Atlantic Ocean and were terminated near Wallops Station. The ground-track positions are believed to be accurate within about ±1/2 mile and altitudes are believed to be accurate within about ±500 feet.

For each flight, a zone along the airplane track from which disturbances would bracket the measuring station was predetermined by calculations. Flight control of the aircraft by radio communication with the pilot was used to insure that the desired flight conditions were reached prior to entering the test zones. An indication of the reliability of estimating the location of the test zone was determined by comparisons of observed arrival time with the prediction of the arrival time of the sonic boom at the measuring station. The tests indicated excellent agreement with the predicted arrival times; for example, in many instances the times checked within 2 seconds for a total travel time of the shock wave of 2 minutes. Flight Mach number was determined for several positions on each ground track by radio communication with the pilot. Since the Mach numbers were obtained from the pilot's readings of the airplane Mach meter, Mach numbers are believed to be accurate within about ±0.02.

Atmospheric Soundings

Rawinsonde atmospheric soundings were obtained in the morning and in the afternoon of each day on which tests were made. The soundings were made up to 60,000 feet. Plots of soundings, which were made on days of occurrence of extremes of pressure and extreme average gradients of speed of sound, temperature, and wind components for the tests, are shown in figures 3 and 4. Standard ICAO atmospheric conditions (ref. 7) are included in figure 3 for comparison. These soundings were used in the determination of the ray paths (path of travel of a segment of the shock-wave disturbance from the airplane).

RESULTS AND DISCUSSION

The magnitude of the first peak overpressure on the ground Δp_o, resulting from passage of the airplane bow shock wave, was measured from time histories obtained with the microphone and related sound equipment. A typical time history is shown in figure 5. The theoretical variations of overpressure with altitude, Mach number, and airplane shape and size were calculated from the following equation which was presented in reference 8:

$$\Delta p_o = K_1 K_2 \frac{\sqrt{p_a p_o}}{y^{3/4}} \left(M^2 - 1\right)^{1/8} \left(\frac{d}{l}\right) l^{3/4} \tag{1}$$

This equation is based on the volume-effect theory of references 2 and 3. The measured overpressures, with a few exceptions, are those obtained at ground level on the plywood reflection surface located near the flight track. In a few instances free-air microphone data were read and corrected to ground pressure by multiplying the measured values by 1.8. This number represents the average measured value of K_1, the ground-reflection factor.

Most of the data are from flights of the supersonic fighter, but data from one flight of the supersonic bomber were also obtained to determine the effect of airplane size and weight.

A list of the flight conditions for the data presented is given in table I. The data obtained in the flight test to determine the lateral spread of the noise disturbances are only from the ground-track measuring station and, therefore, are not intended to show the effect of lateral distance in this report. These ground-track data are used to supplement the measurements for altitude effect. Comments of observers classifying the noise level as either objectionable or tolerable are included in the table. Some information on the tolerable level of sonic-boom overpressure was also presented in references 6 and 8. Although the maximum level judged to be tolerable by the observers in these tests and in the tests of references 6 and 8 was about 1.0 lb/sq ft, it is believed that the maximum tolerance level will vary with the individual - that is, his preoccupation and conditioning to noise.

Effect of Altitude

A summary of the measured ground overpressure obtained from flights of the supersonic fighter at Mach numbers from 1.2 to 2.0 and altitudes from 30,000 to 60,000 feet is shown in figure 6. The measured variations of overpressure with altitude are compared with the theoretical variations. The measurement at 60,000 feet was obtained at a Mach number of 2.0, and the data at the lower altitudes were obtained at various Mach numbers from 1.2 to about 2.0. The two theoretical curves indicate the range of overpressures predicted for Mach numbers between 1.2 and 2.0. The data are seen to be in good agreement with theory in spite of changes in weather conditions for the various days on which the data were gathered. (The extremes of the weather conditions prevailing during these tests were presented in figs. 3 and 4.) Some of the scatter of the data is probably due to weather effects, but no corrections for weather effects were applied to the test data.

The results of the tests indicate that level cruising flight at 60,000 feet is well above the altitudes at which objectionable sonic booms are created at speeds up to a Mach number of 2.0. The agreement of the test results with the theory of references 2 and 3 seems to warrant the prediction that flight operation at altitudes above 60,000 feet would produce sonic booms of less intensity than those measured for flights at 60,000 feet in the present tests.

Effect of Clouds

Flight data obtained on an overcast day, at an altitude of 58,000 feet and a Mach number of 1.87, are shown in figure 6 as the solid symbol. This value of overpressure is approximately the same as that obtained at 60,000 feet and a Mach number of 2.0 on a clear day. The effect of cloud cover is, therefore, seen to be small and not significant when compared with the scatter of the data.

Effect of Mach Number

The variation of ground noise pressure with Mach number was measured in several flights on the same day at altitudes varying from 43,000 to 47,500 feet. The results, shown in figure 7, indicate that there was little effect of Mach number between Mach numbers of 1.4 and 2.0. The scatter of the data was in fact greater than the theoretical effect of Mach number shown for comparison in the figure. A contribution to the magnitude of scatter could have been caused by the fact that the flights were several hours apart. The theoretical curves are based on equation (1), which does not account for atmospheric refraction, and show variation down to a Mach number of 1.0. However, because of refraction of the atmosphere a cutoff Mach number occurs near a Mach number of 1.2 for most of the present tests. This cutoff Mach number varies with altitude and weather conditions and is affected by temperature and wind gradients in a manner shown in reference 3. From the results shown in figure 7, the effect of Mach number is small as long as the Mach number is well above the cutoff Mach number. This agreement with the theory of reference 2 indicates that it is reasonable to predict only a 26-percent increase in sonic-boom overpressure between Mach numbers of 1.5 and 3.0.

In figure 8, data are shown which are believed to be an accurate measure of the effect of Mach number near the cutoff Mach number. Since these data were obtained at about 15-minute intervals in the morning and afternoon of one day, the data are believed to be more nearly comparable because of constant atmospheric conditions.

A theoretical method is described in section 4 of the appendix in reference 3 which predicts a focusing effect of refraction that causes an increase of the sonic-boom intensity over that calculated for a homogenous atmosphere by a factor greater than 5 at the cutoff Mach number. Such effect would have great significance in the operation of supersonic aircraft. The data of figure 8 indicate that the sonic-boom intensity decreased as Mach number was decreased to the cutoff Mach number and the maximum value of Δp_o obtained was only about 40 percent greater than that predicted by equation (1). This maximum measured intensity was, however, larger than that predicted from equation (1) by an amount somewhat larger than the data scatter. This result may be in some way related to the focusing effect of refraction but the large intensification (at the cutoff Mach number) indicated by the theoretical method in reference 3 was not detected.

For the flights near the cutoff Mach number, the ray paths were known to have been just grazing the ground. These ray paths represent the propagation path of a segment of the shock wave. The shock wave front is perpendicular to the ray path, and for the grazing ray path the shock front is, therefore, vertical near the ground. The shock fronts were known to be vertical from examination of the records from the free-air microphone and the microphone mounted on the ground board. In addition to arrival times of the bow wave being the same for both microphones, no reflected wave was seen on the free-air microphone trace; this indicated a shock wave perpendicular to the ground. The intensity measured by the free-air microphone was the same as that measured by the ground microphone.

The cutoff Mach number, predicted from the rawinsonde data and by use of the method of reference 3, was 1.22 for both the morning and afternoon flights and agrees with the measured cutoff Mach numbers within about ±0.03.

Effect of Flight-Path Angle

Level-flight operation at the cutoff Mach number is characterized by a ray path just grazing the ground. This situation can also be realized in climbing or descending flight at Mach numbers respectively above and below the cutoff Mach number for level flight. It is believed that flight-path-angle changes are equivalent to changes in the Mach angle as far as propagation direction is concerned. On this basis, the change in cutoff Mach number may be expressed by the following relation:

$$M_\gamma = \frac{1}{\sin\left(\sin^{-1}\frac{1}{M_L} - \gamma\right)} \tag{2}$$

The variation of cutoff Mach number, obtained by use of equation (2), with flight path angle is shown in figure 9 for flight in the standard ICAO atmosphere (ref. 7) at various altitudes. It can be seen from figure 9 that an airplane having a large climb-angle capability may be operated at relatively high Mach numbers with no sonic-boom problem. Conversely, descending flight requires a decreased Mach number if sonic booms are to be avoided on the ground.

In order to determine experimentally whether cutoff Mach number is affected in the manner indicated by equation (2), the effect of climb angle on sonic-boom intensity was investigated by making two tests, one in level flight followed a short time later by one that included a pull-up and climb maneuver. The Mach number was 1.4 for the level-flight test but varied between 1.4 and 1.34 in the climb maneuver. The flight paths for the two tests, taken from the radar plot board, are shown in figure 10. Ray paths, for several positions in each test, were computed from the rawinsonde data presented in figure 11. It can be seen in figure 10 that level flight produced a ray path that was more nearly perpendicular to the ground at the measuring station than was the ray path for the climb maneuver. The climb maneuver was, in fact, purposely made at a combination of flight-path angle and Mach number close to the condition at which a cutoff of the sonic boom would be produced by atmospheric refraction. The computed ray path for the climb maneuver just grazed the ground at the measuring station and the boom intensity was greatly reduced in comparison with the boom produced in level flight. The measured overpressure for level flight was 0.56 lb/sq ft and for the climb maneuver was 0.07 lb/sq ft. Although there was a small difference in altitude and Mach number for the positions in the level flight and the climb maneuver from which the ray paths emanated, the main effect was believed to be caused by flight-path angle in a manner similar to the Mach number effect near cutoff, indicated in figure 8. The flight-path angle and Mach number in the climb maneuver are shown plotted in figure 9 in relation to the variation of cutoff Mach number with flight-path angle computed for atmospheric conditions existing at the time of the flight. The measurement shows good agreement with the calculated curve; from this experimental result it appears that the method of estimating the effect of flight-path angle on cutoff Mach number is essentially correct.

Effect of Airplane Size and Weight

The effect of airplane size and weight on the measured ground overpressure was investigated by flying the supersonic fighter (fig. 1) and supersonic bomber (fig. 2) over the test range on the same day. These flights were made about one hour apart and, therefore, in nearly the same weather conditions. The measured ground overpressures for the flights at a Mach number of 1.5 near 40,000 feet are presented in figure 12. The theoretical curves were again determined by using the method of reference 2. The method is based on airplane volume rather than lift. The supersonic fighter has a fineness ratio of 7.75, and the equivalent-body-shape factor (ref. 8) for the calculations in figure 12 was determined to be 0.558. The supersonic bomber has a fineness ratio of about 8.5 and the equivalent-body-shape factor is about 0.6. The data obtained show good agreement with the volume theory. The supersonic bomber outweighed the fighter by a factor of about 4.0, and the results indicate that the sound intensities are little affected by either the airplane size differences or the weight differences at the test altitude.

CONCLUSIONS

Measurements of the ground shock-wave noise pressures during flight tests of a supersonic fighter and a supersonic bomber in the Mach number range from 1.2 to 2.0 and at altitudes from 30,000 to 60,000 feet indicate the following conclusions:

1. Good agreement of the variation with altitude was obtained between measured and calculated values of ground pressure near the flight track for the wide range of atmospheric conditions encountered.

2. Level cruising flight at an altitude of 60,000 feet at a Mach number of 2.0 produced sonic booms which were considered to be tolerable.

3. The effect of Mach number on the ground overpressure is small in the Mach number range from 1.4 to 2.0. The experimental result is in good agreement with the theory.

4. No amplification of the shock-wave overpressures due to refraction effects was apparent near the cutoff Mach number.

5. The climb maneuver produced booms of a much decreased intensity as compared with those produced in level flight at about the same altitude and Mach number. A method of calculating the effect of flight-path angle on cutoff Mach number is presented which shows good agreement with the experimental results.

6. The differences in the measured ground noise pressures due to airplane size and weight were minor at the test altitude of 40,000 feet, and the measured pressures were in good agreement with the calculated values based on volume effects only.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Field, Va., December 1, 1959.

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TABLE I.- LOG OF FLIGHTS FOR SONIC-BOOM INVESTIGATION

Date	Variable investigated	Mach number	Altitude, feet	Flight-path angle, deg	Lateral distance, nautical miles	Overpressure, Δp_o, lb/sq ft	Boom objectionable	Boom tolerable	Number of booms
6/17/59	Altitude	1.5	42,500	0	0.3	0.87		x	2
6/18/59	Altitude	1.5	40,000	-5	.2	1.12		x	2
6/18/59	Altitude	1.53	54,600	0	.5	.41		x	2
6/18/59	Altitude	1.20	31,000	0	1.2	1.14		x	2
6/18/59	Altitude	1.44	30,000	0	.5	1.51	x		2 or 3
6/26/59	Mach number	1.42	47,500	1	.2	.57		x	5
6/26/59	Mach number	2.00	46,000	2	1.9	.83		x	1 or 2
6/26/59	Mach number	1.71	43,000	5	.2	.80		x	2
6/26/59	Mach number	1.40	45,000	0	1.0	.92	x		2
7/1/59	Lateral spread	1.40	46,000	2	.4	.99	x		2 or 3
7/6/59	Lateral spread	1.87	58,000	3	.2	.40		x	2
7/6/59	Lateral spread	1.40	46,600	1.4	1.8	.70	x		1 or 2
7/17/59	Lateral spread	2.00	60,000	3	.2	.49		x	1
7/20/59	Lateral spread	2.01	48,500	1	.4	.76	x		1 or 2
7/20/59	Lateral spread	1.25	42,000	0	.2	.79	x		2
7/23/59	Mach number near cutoff	1.21	41,400	0	.5	.04		x	2
7/23/59	Mach number near cutoff	1.25	41,400	0	.1	1.12		x	2
7/23/59	Mach number near cutoff	1.23	42,000	1	1.2	0		x	------
7/23/59	Mach number near cutoff	1.35	42,200	1	.8	1.15	x		2
7/23/59	Mach number near cutoff	1.30	41,800	1	.7	.42		x	2
7/23/59	Mach number near cutoff	1.22	42,500	.5	.4	.02		x	2
7/23/59	Mach number near cutoff	1.27	42,700	0	.8	.10		x	2
7/29/59	Climb angle	1.40	43,000	3		.56		x	2
7/29/59	Climb angle	1.40 to 1.34	------	10		.07		x	3 or 4
8/6/59	Airplane size and weight	1.45	39,100	0	1.9E.	1.24	x		2
8/6/59	Airplane size and weight	1.50	40,100	.5	.5W.	1.10	x		

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Figure 1.- Supersonic fighter used in the investigation.

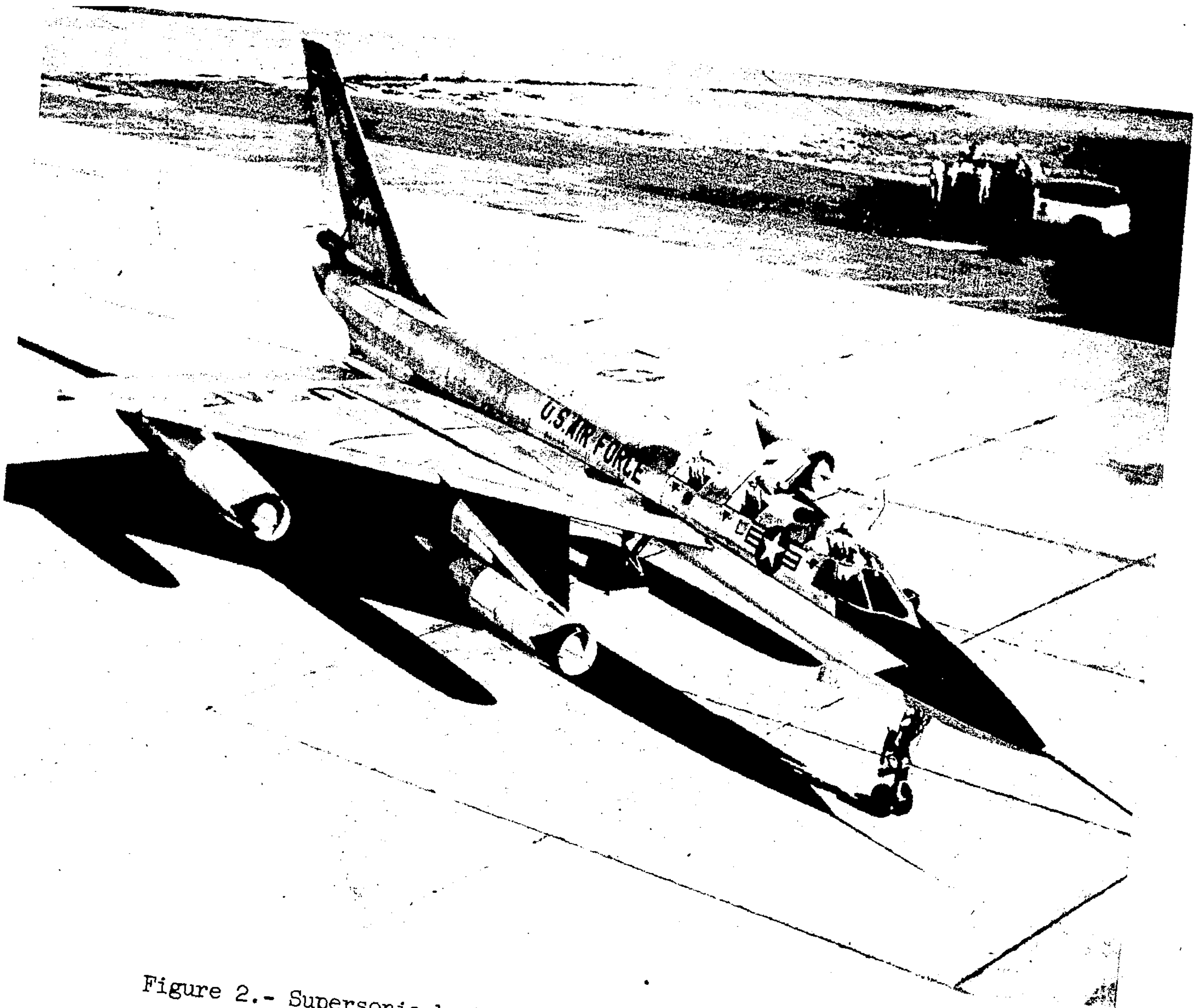

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Figure 2.- Supersonic bomber used for one flight test. L-59-5857.1

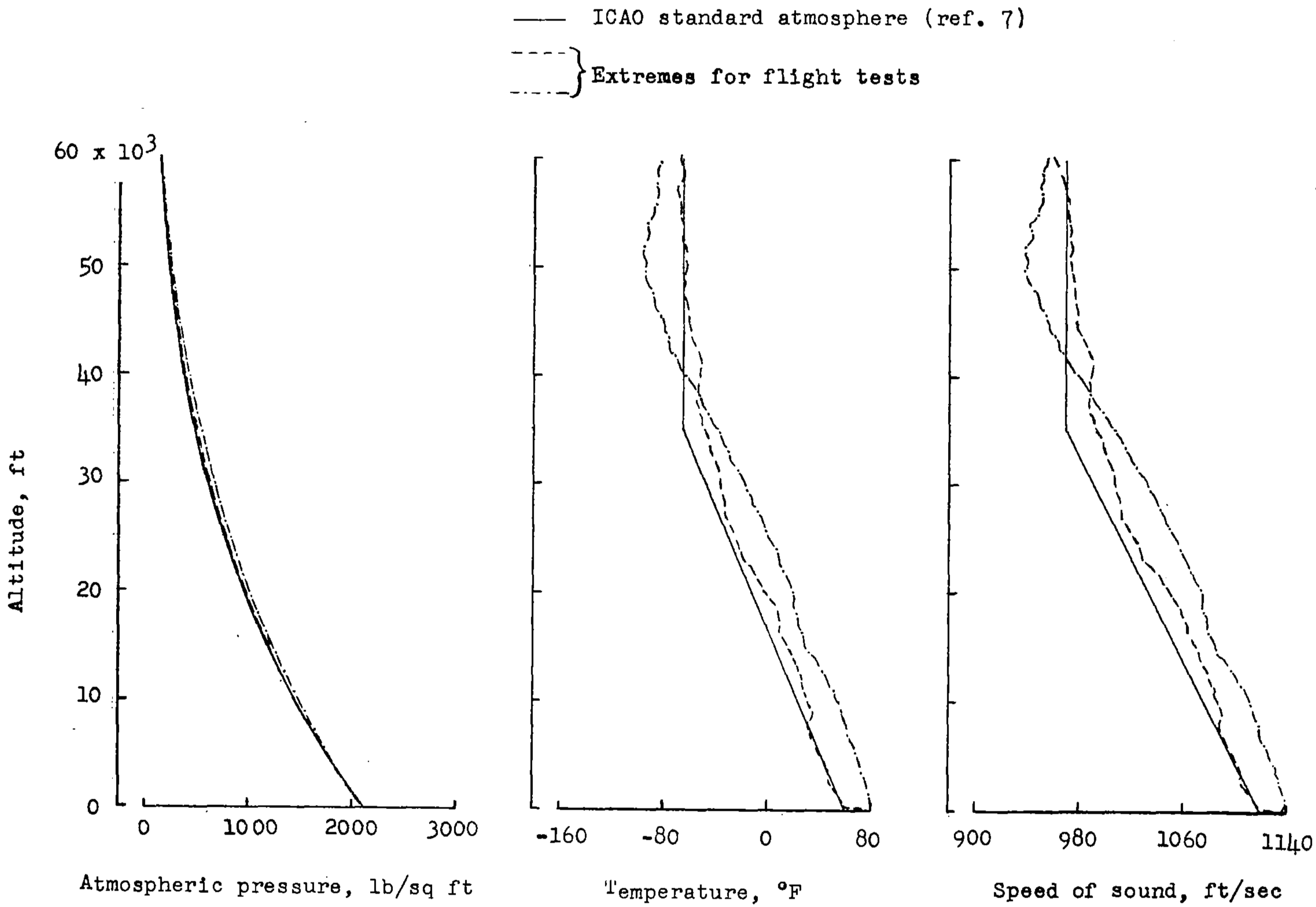
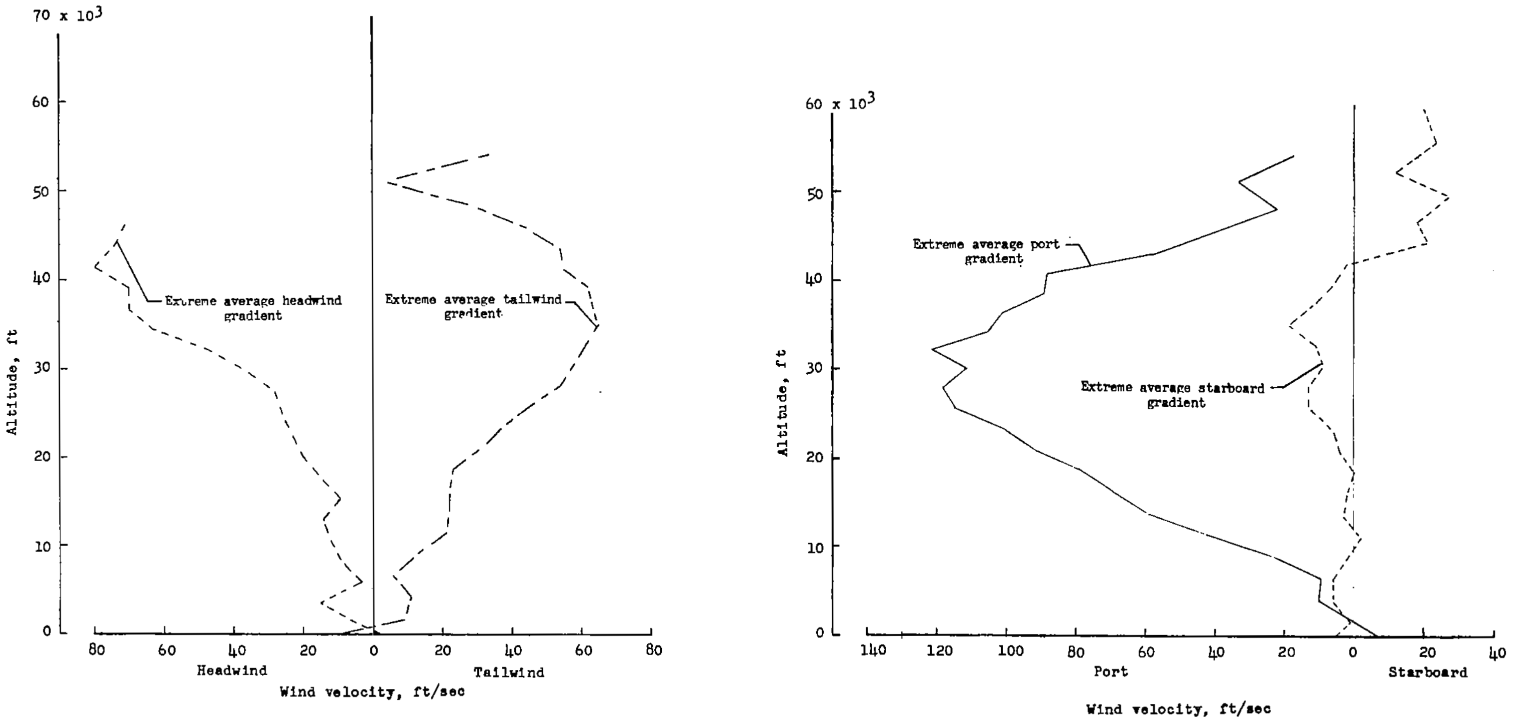


Figure 3.- Profiles of atmospheric soundings on days of occurrence of the extremes of atmospheric pressure and extreme average gradients of temperature and speed of sound.



(a) Components along flight paths.

(b) Components perpendicular to flight paths.

Figure 4.- Profiles of wind soundings on days of occurrence of extreme average gradients along and perpendicular to the flight track.

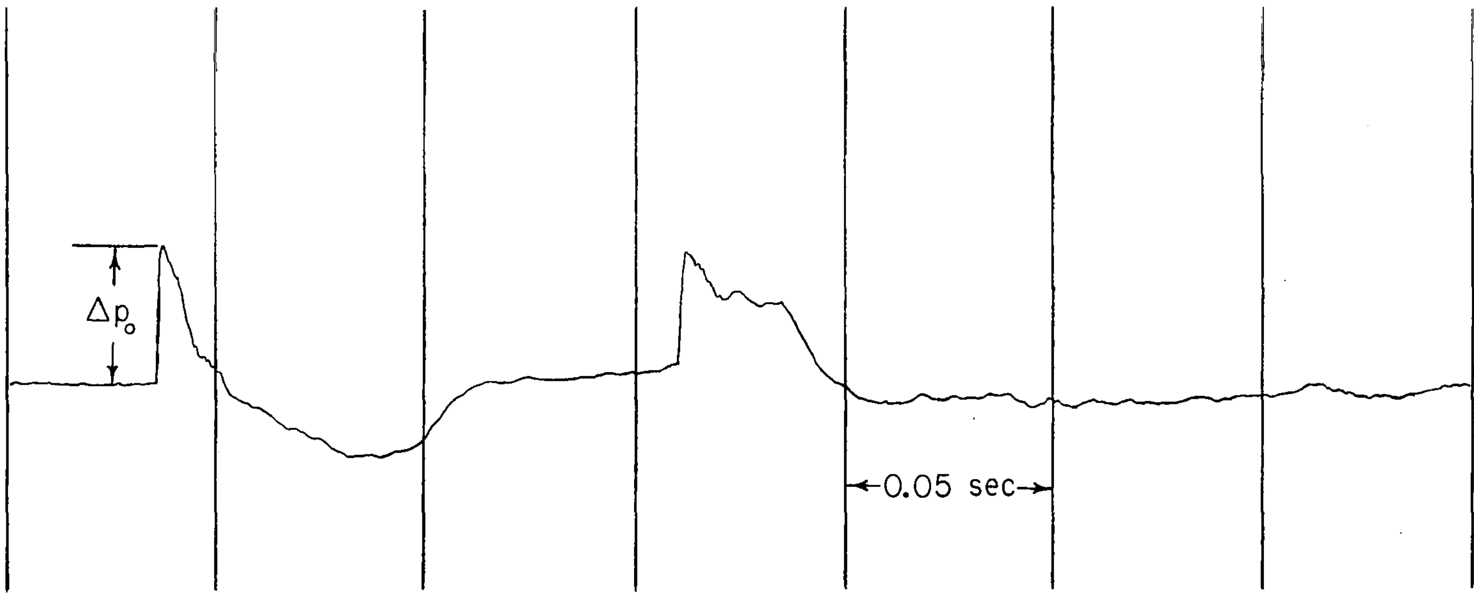


Figure 5.- Time history of pressure as obtained by microphone mounted flush with plywood reflection board.

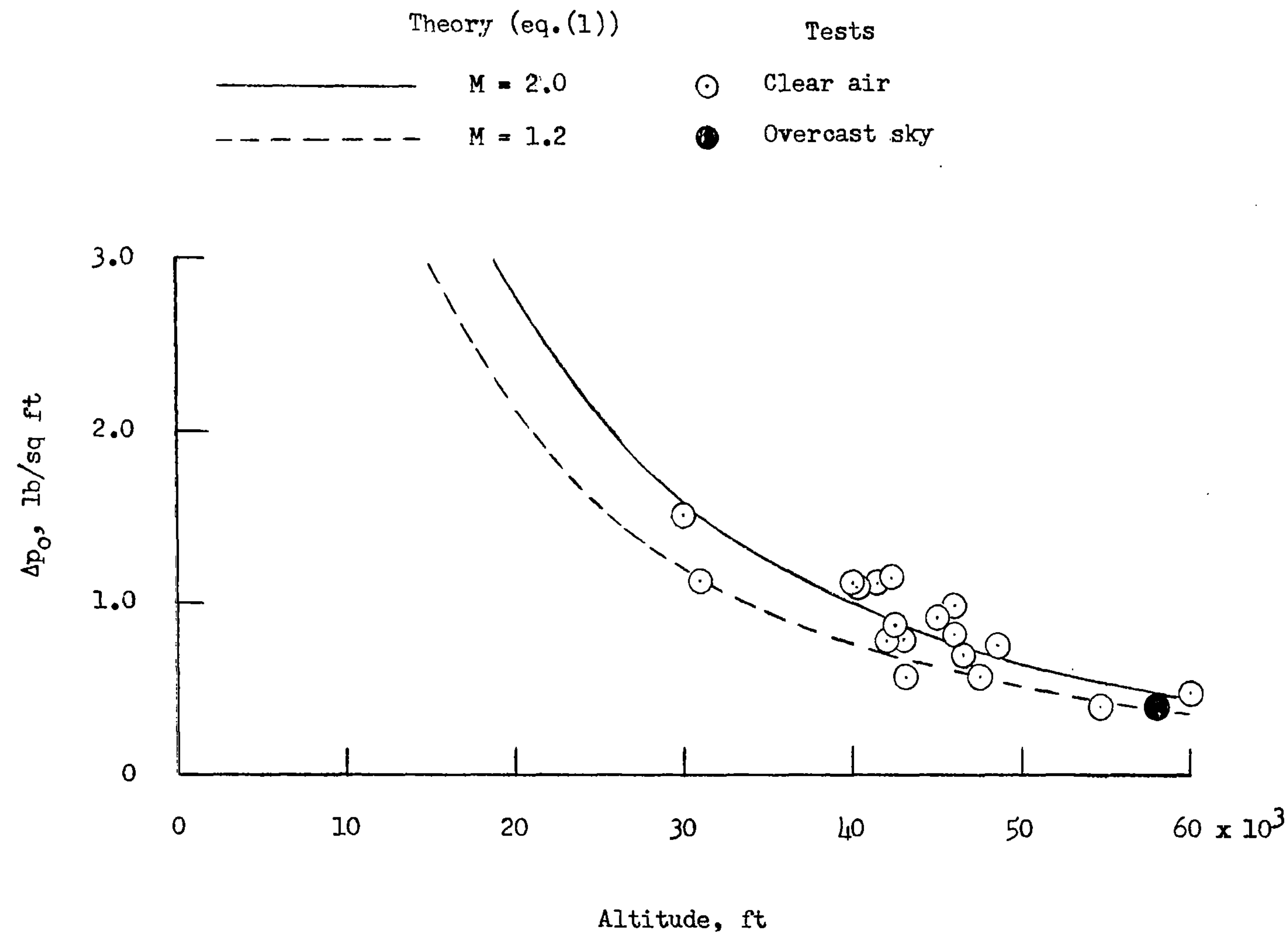


Figure 6.- Measured and calculated variation with altitude of the ground noise pressures near the flight track. Level flights on several different days were made at Mach numbers from 1.2 to 2.0.

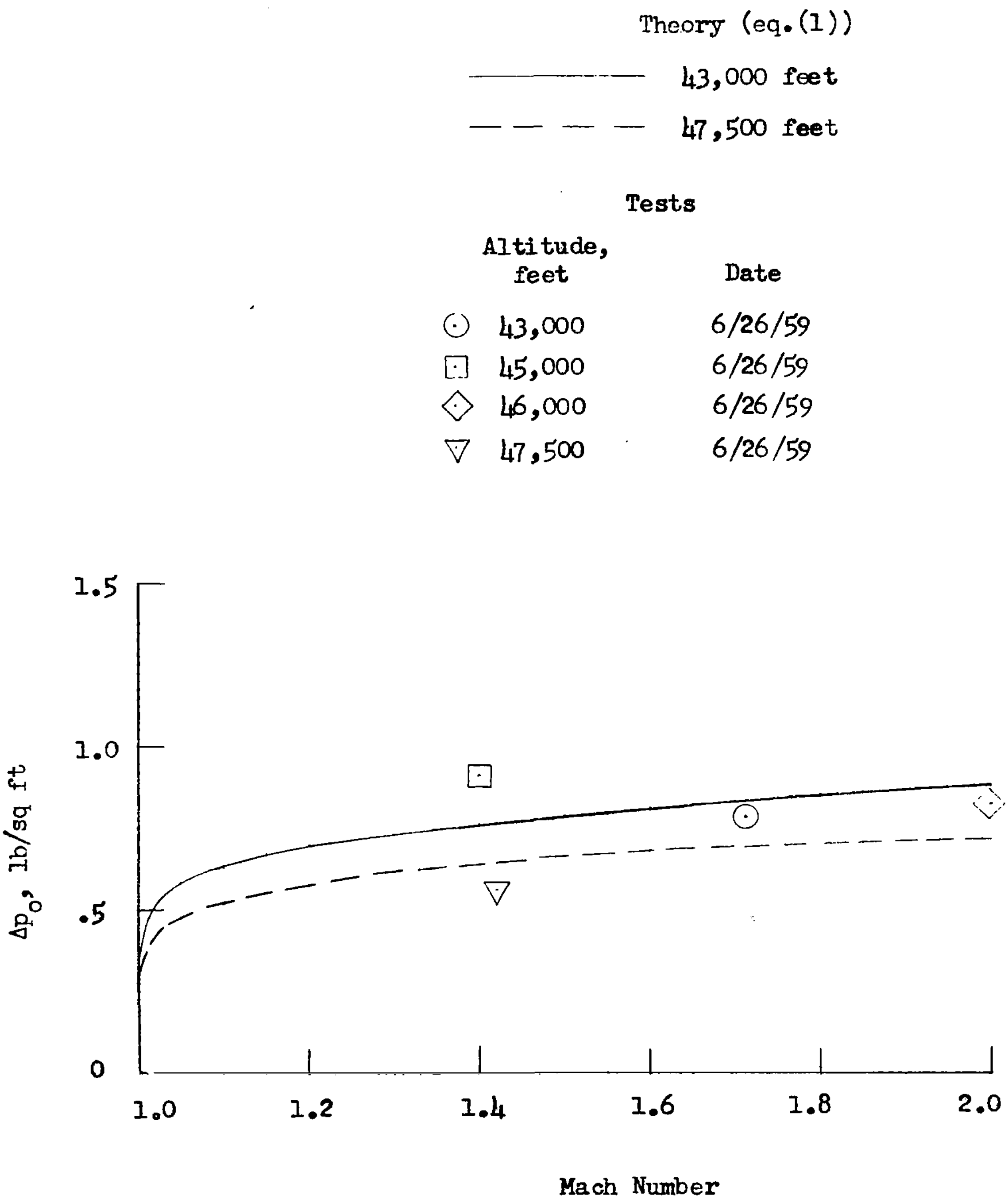


Figure 7.- Measured and calculated variation of ground noise pressure with flight Mach number.

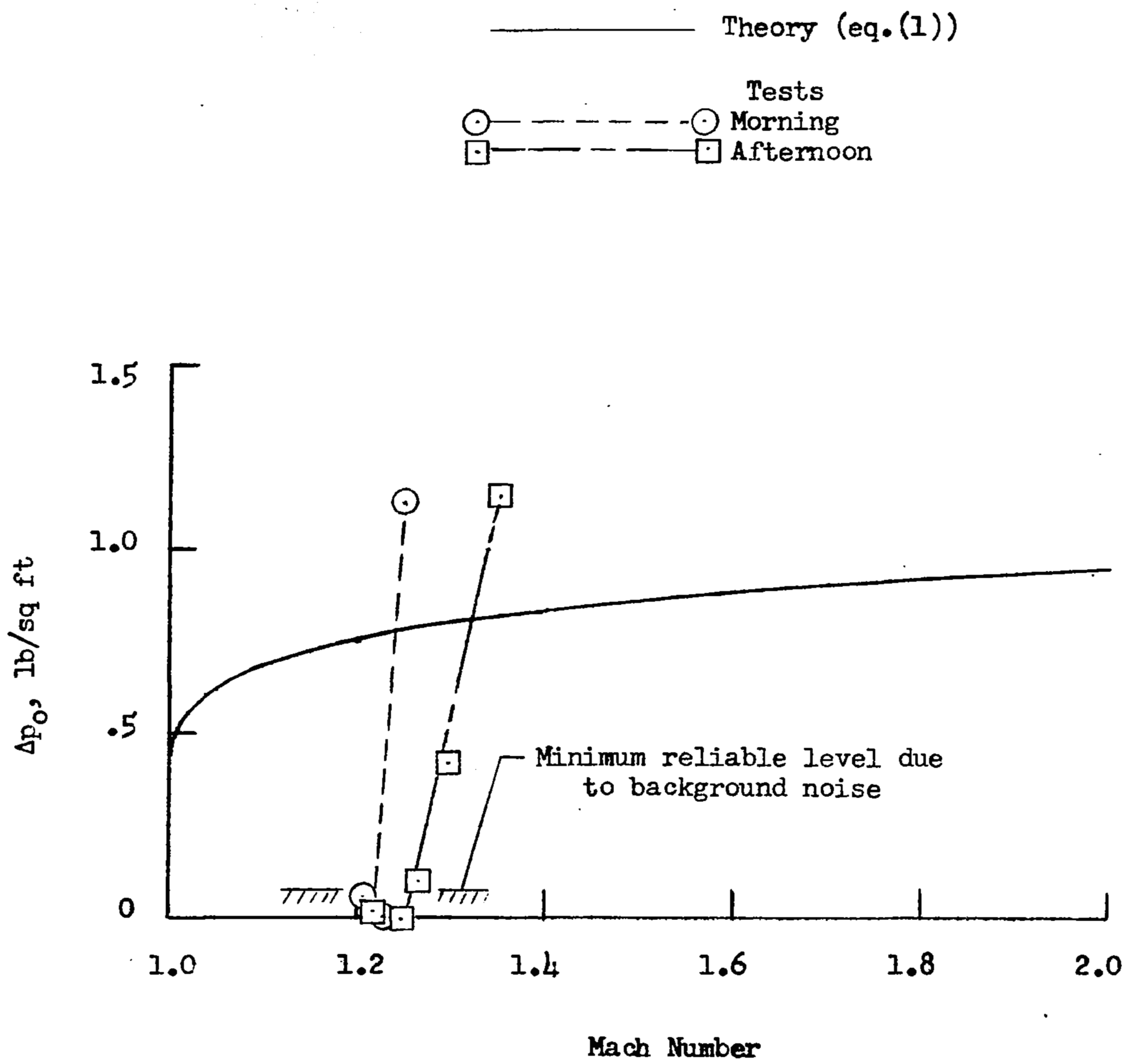


Figure 8.- Measured and calculated variation of ground noise pressure with flight Mach number near cutoff. Data were obtained on the same day at an altitude of about 42,000 feet.

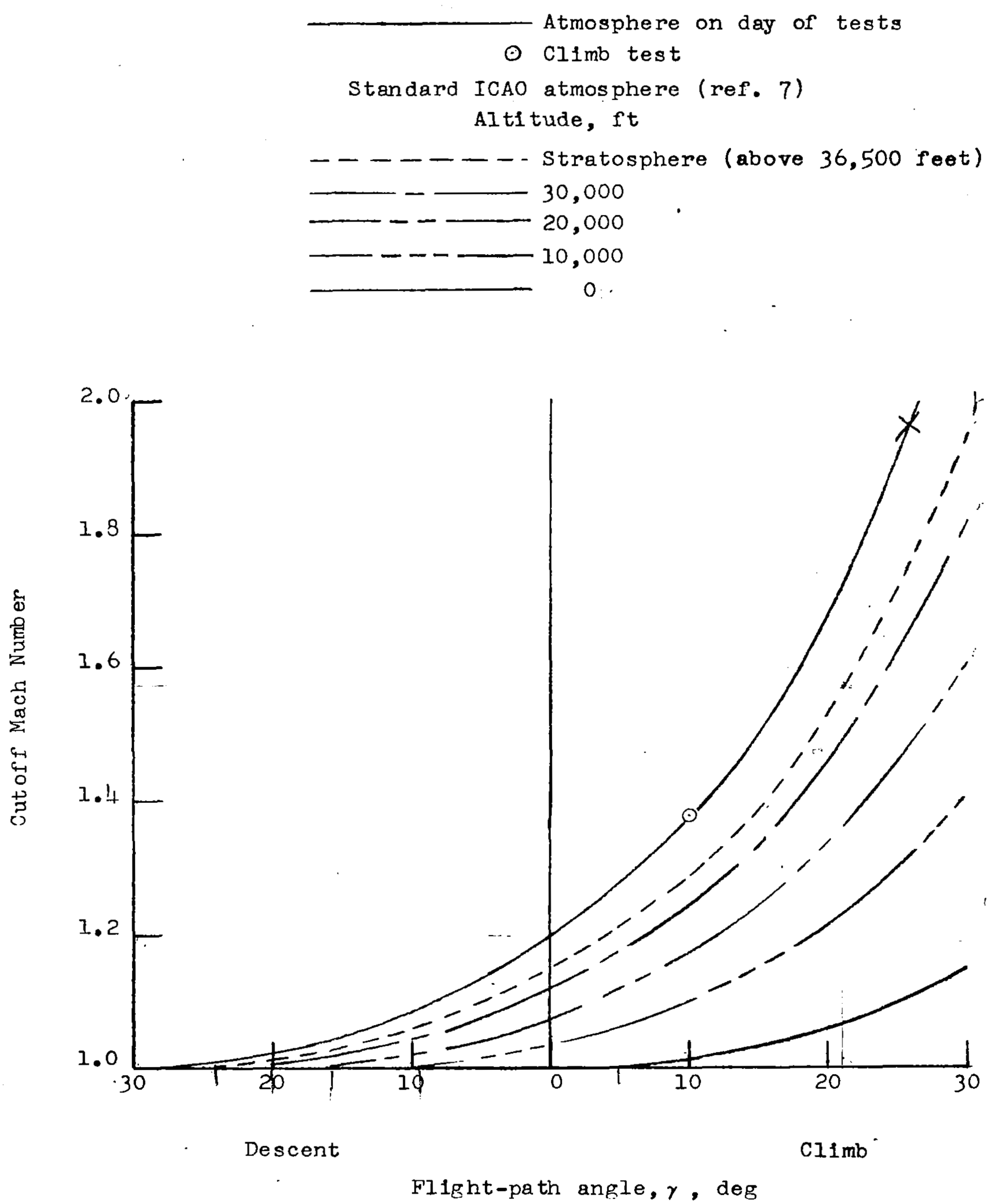


Figure 9.- Calculated effect of flight-path angle on cutoff Mach number for flight in standard ICAO atmosphere and in atmosphere on day of climb-effect tests.

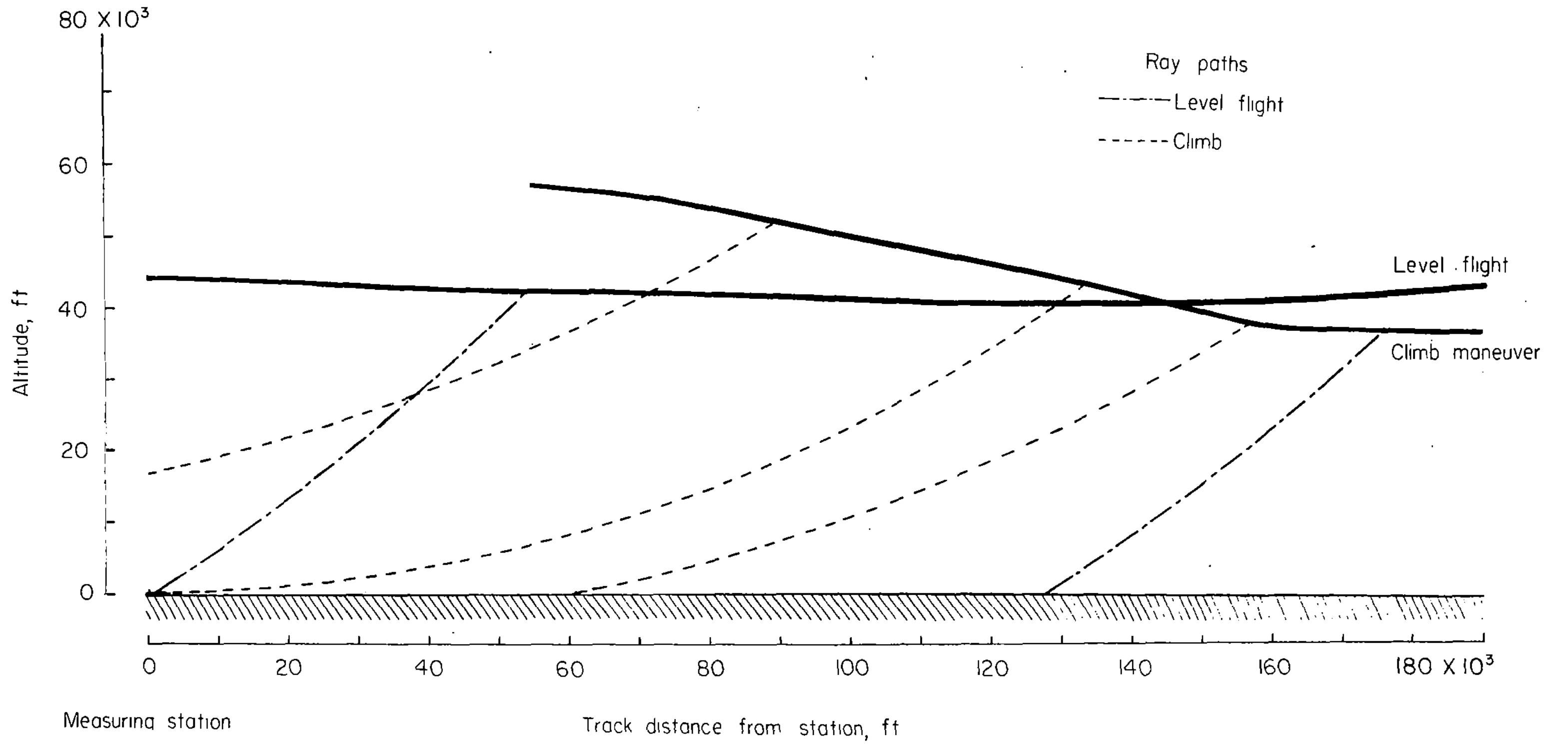
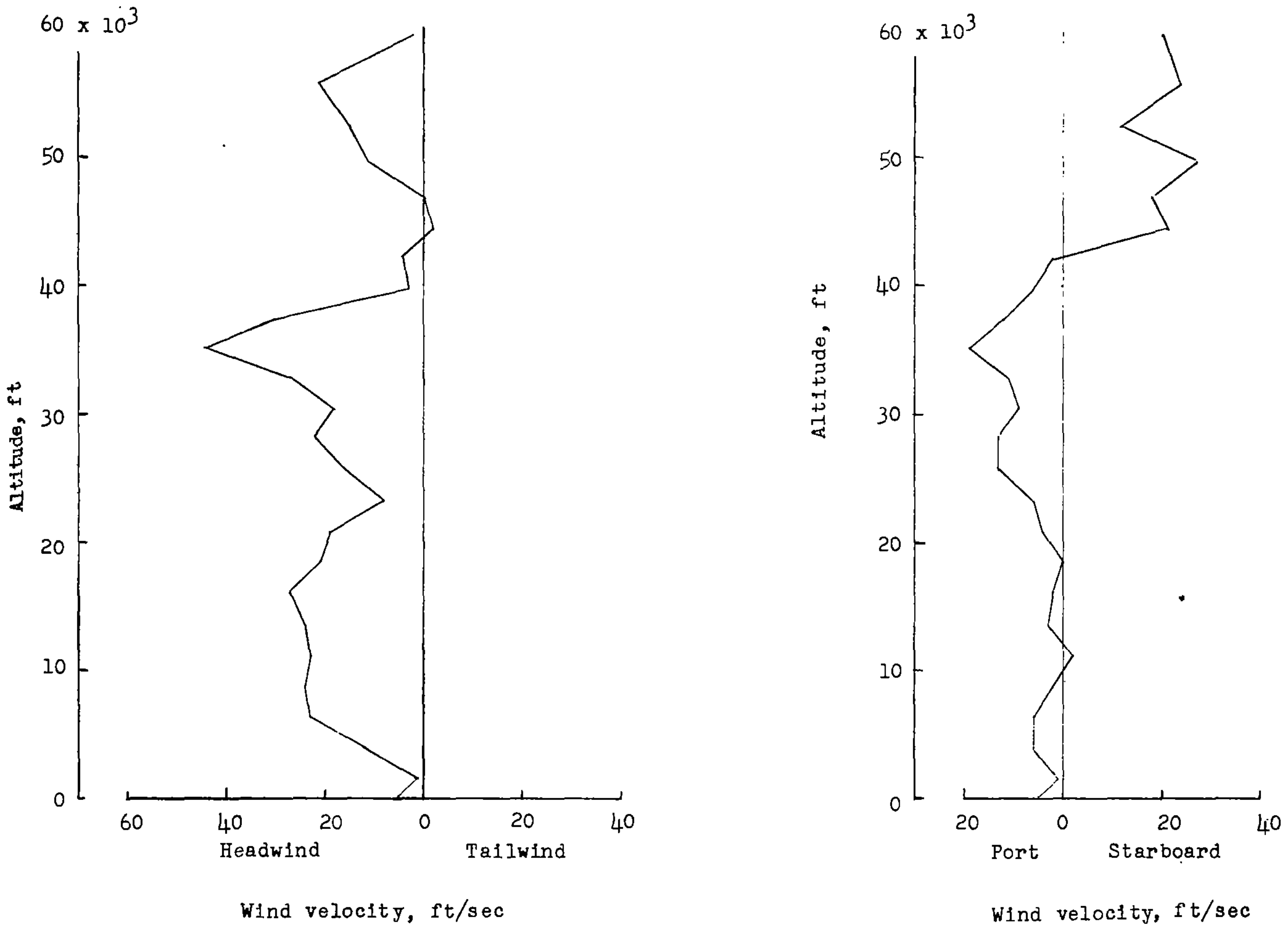


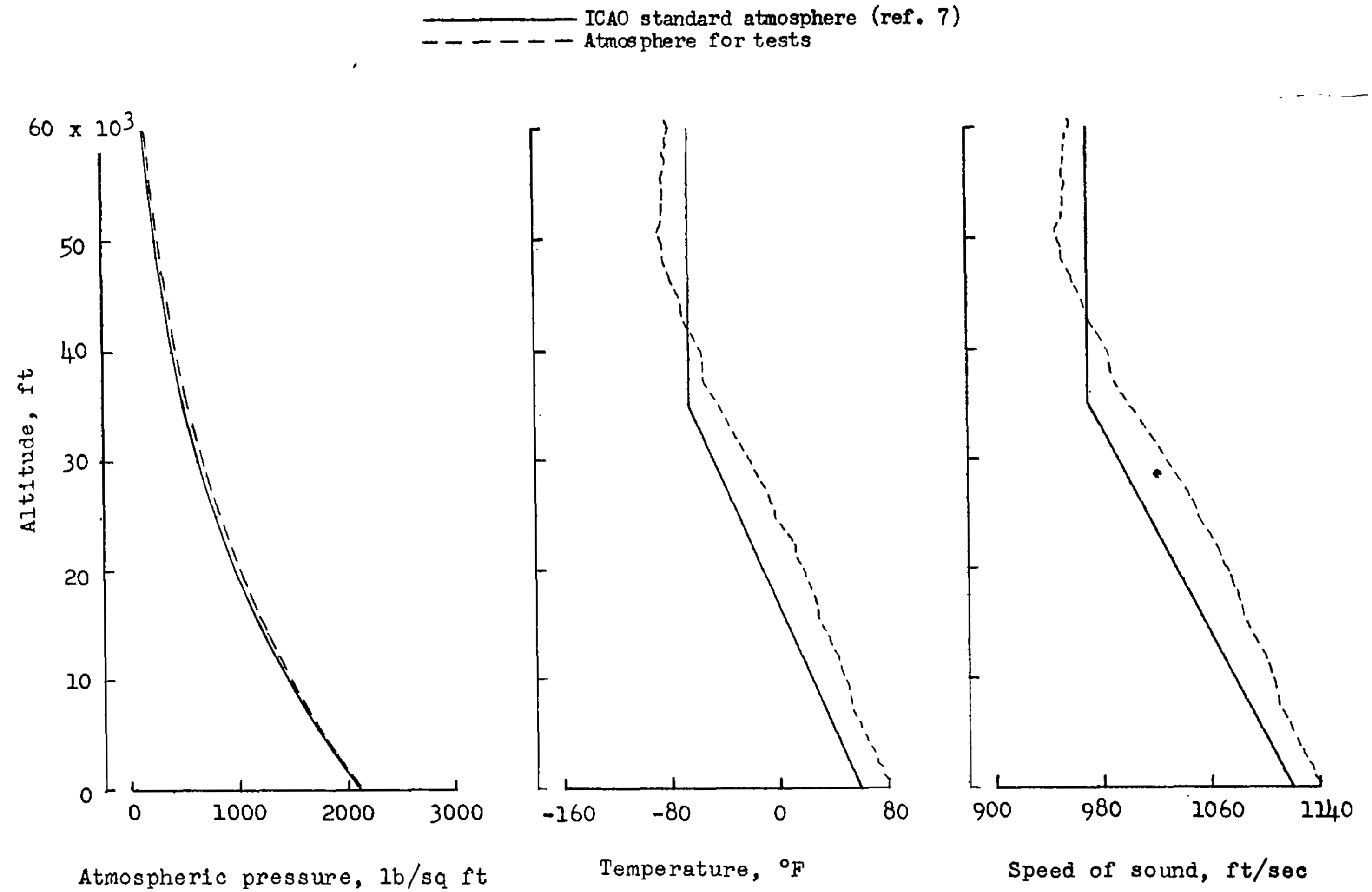
Figure 10.- Flight paths and shock-wave paths (or ray paths) for level flight and a climb maneuver made to investigate the effect of climb angle on sonic-boom intensity.



(a) Wind components along flight path.

(b) Wind components perpendicular to flight path.

Figure 11.- Rawinsonde data for the level-flight test and the climb maneuver shown in figure 10.



(c) Pressure, temperature, and speed-of-sound variation with altitude compared with the standard ICAO atmosphere.

Figure 11.- Concluded.

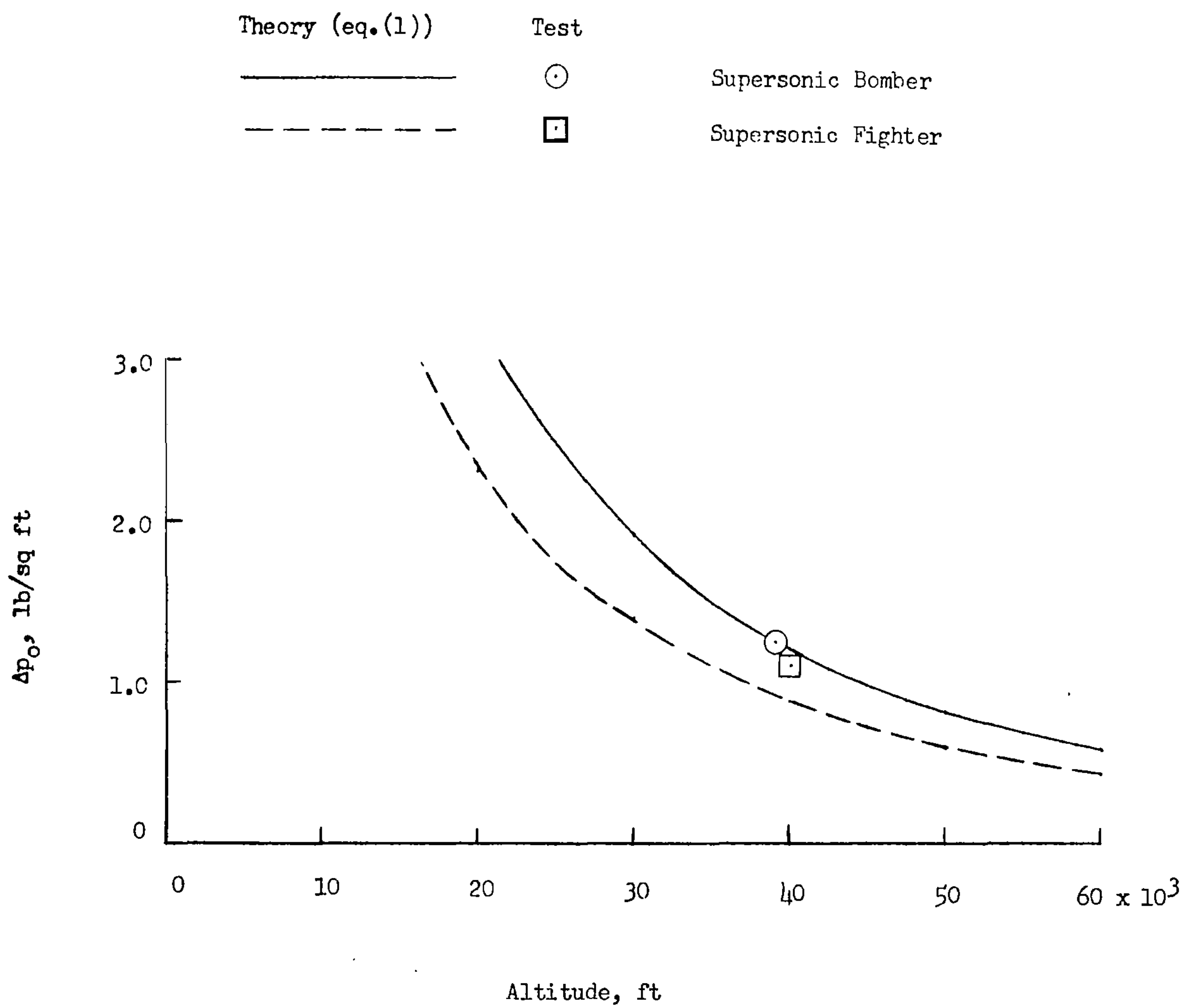


Figure 12.- Comparison of measured and calculated ground noise pressures for the supersonic fighter with measurements and calculations for the supersonic bomber. Flights were made at a Mach number of 1.5 near 40,000 feet.