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SOUND PRESSURES AND CORRELATIONS OF NOISE ON THE FUSELAGE OF A JET AIRCRAFT IN FLIGHT

By Russell D. Shattuck

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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SUMMARY

Tests were conducted at altitudes of 10,000, 20,000, and 30,000 feet at speeds of Mach 0.4, 0.6, and 0.8. It was found that the sound pressure levels on the aft fuselage of a jet aircraft in flight can be estimated using an equation involving the true airspeed and the free air density. The cross-correlation coefficient over a spacing of 2.5 feet was generalized with Strouhal number. The spectrum of the noise in flight is comparatively flat up to 10,000 cycles per second.

INTRODUCTION

The experimental examination of both boundary-layer and jet-engine noise has been carried on quite thoroughly on the ground, but noise studies under flight conditions have not been extensive. The very near noise field was examined in flight by Fakan and Mull (ref. 1) and Ribner (ref. 2) and on the ground by Howes, et al. (ref. 3). The far noise field of an aircraft in flight as observed from the ground was studied and reported by Greatrex and Brown (ref. 4). Fluctuating pressures on the forward fuselage and on the wing of an aircraft in flight were studied by Mull and Algranti (ref. 5).

The purpose of the present tests was to provide generalized expressions in terms of flight conditions for the noise pressure and the correlation of the pressure fluctuations on a fuselage. The pressures and their correlations are of great interest to aircraft structural designers. These tests were concerned with the pressure fluctuations as seen by the aircraft fuselage in close proximity to a jet engine in flight. This region can neither be described as the near nor the far noise field of the engine; however, it is a problem area in structural design.

In order to be able to compare these results with those of others, some measurements were made of the boundary-layer velocity profile.

The pressure-fluctuation measurements reported here were made with a pattern of nine microphones spaced in the skin of the aft fuselage of a B-57B aircraft in a general direction of 45° from the axis of the starboard engine. Measurements were made on the ground at zero velocity and at altitudes of 10,000, 20,000, and 30,000 feet at Mach numbers of 0.4, 0.6, and 0.8.

SYMBOLS

a	speed of sound, ft/sec
e_1, e_2	time-varying electrical signal from microphones 1 and 2, volts
f	frequency, cps
L	spacing between microphones, ft
N_S	Strouhal number, fL/V
p	pressure, lb/sq ft
q	dynamic pressure, lb/sq ft
R	correlation coefficient, $\dfrac{\left[\overline{e_1 e_2}\right]}{\sqrt{\overline{e_1^2}}\sqrt{\overline{e_2^2}}}$
r_1, r_2	distance from a source to microphones 1 and 2, ft
SPL	sound pressure level, db (re 0.0002 dynes/cm^2)
V	true airspeed, ft/sec
V_{cal}	indicated airspeed corrected for installation errors, ft/sec
ρ	density of air, slugs/cu ft
ρ_e	air density at pressure altitude, slugs/cu ft
ρ_{sl}	air density at sea level, slugs/cu ft

APPARATUS

A B-57B aircraft was chosen for these tests, since this aircraft has wing-mounted engines so located as to make the aft end of the fuselage correspond roughly to the 45° direction from the engine. Accordingly, taking into account the mechanical and structural considerations in the aircraft, the microphone array was positioned as closely as possible to this maximum noise direction.

To obtain the acoustic data, nine microphones were installed flush with the outer surface of fuselage in a longitudinal linear array of 2.65 feet. The microphones used were conventional Altec-Lansing type M-14 condenser microphones using 21BR-150 microphone capsules. The power for each microphone was supplied through individual filter and metering packages using 400-volt and 28-volt direct-current supplies on the aircraft.

The closeup photographs (figs. 1) show the outside and inside of the aircraft with several of the microphones installed and with blank plugs in the places of the remainder of the microphones. These plugs were inserted when a microphone was removed for other purposes. Detailed locating dimensions are given in figure 2.

The outputs of the nine microphones were recorded on an Ampex model 800, 14-channel flight recorder.

Microphone sensitivity-level calibrations were made at the beginning of each flight by placing a small loudspeaker-type acoustic calibrator over each microphone and tape-recording a reference sound signal level.

The frequency response of the recorder and playback system was checked and found to be linear from 40 to 12,500 cycles per second within approximately ±1.5 decibels on all channels of interest. The response of each of the microphones is within ±1.5 decibels of the average response of the group from 30 to 10,000 cycles per second. The net response correction for the recorder plus the microphone is given in figure 3.

Data published by the microphone manufacturer (ref. 6) show a pressure-altitude coefficient of about +1 decibel per 10,000 feet and a temperature coefficient of -0.04 decibel per degree Centigrade. The level adjustments that have been made to the data are given in table I under "Net level correction." The temperature correction was based on the calibrated air temperature.

The correlations of the pressure fluctuations were determined on a specialized analog computer called a correlation computer. This computer is capable of measuring the correlation coefficient for any two

alternating-current signals up to about 20,000 cycles per second at a relative time delay that can be adjusted from about 2 milliseconds lead to 8 milliseconds lag. The computer is thoroughly described by Carlson in reference 7.

The cross-correlation coefficient is defined as

$$R = \frac{\overline{e_1 e_2}}{\sqrt{\overline{e_1^2}}\,\sqrt{\overline{e_2^2}}}$$

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where e_1 and e_2 are the time-varying electrical signals from a pair of microphones spaced a distance for which the cross-correlation coefficient is desired. The cross-correlation coefficient of a single frequency source as measured by two spaced receivers is the cosine of the phase-angle difference between the signals at the two receivers. The phase angle is $2\pi f(r_2 - r_1)/a$. The correlation of random sounds such as jet or boundary-layer noise is essentially the "togetherness" of the two signals.

A total-pressure probe and a static-pressure tap were installed to measure the boundary-layer velocity profile. The first two microphone stations were used for this test. The orientation of the wall static tap and the total-pressure probe is shown in figure 4.

TEST METHODS

Microphones were calibrated before each flight using the following procedure:

(1) One or two hours before takeoff, power was applied and the microphones and tape recorder were allowed to warm up.

(2) After about one-half hour the microphones were removed from their mounts in the aircraft skin; and, using the acoustic calibrator, a reference sound level was recorded on each microphone channel.

(3) After calibration, the microphones were replaced in their mounts.

Power remained on the system until the end of the flight except for a 15-minute period during which the airplane was moved out of the hanger for preflight checks.

In flight, upon establishing the required altitude and Mach number, the recorder was started and the acoustic data from the microphones were

simultaneously recorded on individual tape channels. Engine and flight conditions were recorded from voice comments on the aircraft intercom system using a spare channel of the tape recorder.

The analysis of the tapes for level and spectra was accomplished directly from the playback of the 14 channel tapes. Since the correlation computer is a two-channel machine, it was necessary to transcribe the desired pairs of channels onto two-channel tapes from the 14-channel flight data.

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RESULTS AND DISCUSSION

Flight Conditions

The principal conclusions in this report are based on the conditions of flight given in table II.

Boundary Layer

The velocity profile was measured at the forward end of the microphone pattern outward to a maximum distance of about 0.6 foot from the skin. The results of these measurements are given in figure 5. The measurements indicate a boundary-layer thickness of approximately 1.0 foot. The boundary-layer thickness is not exactly defined because of the momentum loss behind the wing due to the drag of the wing. This loss makes the true value of the local free-stream velocity rather obscure. Data reported by Silverstein and Katzoff (ref. 8) indicate that a considerable loss in free-stream total pressure should be encountered at the location of these measurements. However, an attempt to evaluate these losses using the data of reference 8 did not contribute toward defining the boundary layer more precisely.

The wing interference causes additional problems when noise measurements are made in this area. First, the altered "free-stream" velocity into which the jet exhausts is no longer simply the aircraft forward velocity. Secondly, the fluctuating pressures in the boundary layer are usually found to be related to the free-stream dynamic pressure, but in the current tests the "free-stream" dynamic pressure may not be that which corresponds to the aircraft velocity.

Sound Pressure Level

The fluctuating pressure levels measured in the various flights as well as the sound pressures measured on the ground are presented in table III. The sound pressure levels measured on the aircraft skin on

the ground have an average of 135.3±2 decibels at the engine power setting of 99.2 percent. (Only the engine nearest the microphone pattern was operated for these data.)

The fluctuating pressure levels observed in flight range from a low of 121 decibels at the lowest speed and highest altitude to a high of 135 decibels at the highest speed and lowest altitude. The range of pressure levels is about 8 decibels for the different speeds at each altitude.

The overall sound pressure level is nearly a linear function of calibrated airspeed, as shown in figure 6. If considered as a function of $q = \rho V_{cal}^2/2$, overall sound pressure level is reasonably well represented by

$$SPL = 20 \log q + 73$$

A curve showing this function is given in figure 7, where it can be compared with the observed data. An estimate of the pressure fluctuation level can be made using the relation suggested by Ribner (ref. 2):

$$SPL = 104.6 + 40 \log_{10} \left(\frac{V}{100}\right) + 20 \log_{10} \left(\frac{\rho_e}{\rho_{sl}}\right)$$

A comparison of this equation and the measurements reported here is presented in table IV. It appears that these data would more nearly match Ribner's estimate if his constant were changed from 104.6 to 100.6. This discrepancy might be due to the difference between the free-stream velocity and the actual local velocity existing behind the wing.

Ribner's equation predicts the levels should change about 3 decibels with each altitude step tested. This is substantiated in figure 8.

The relation suggested by Ribner reduces to the one stated previously with a different constant. In other words, Ribner gives

$$SPL = 20 \log q + 83$$

with q based on true airspeed. Using the suggested constant of 100.6 instead of the original 104.6, it becomes

$$SPL = 20 \log q + 79$$

A comparison of figures 6 and 8 shows that a considerable improvement in generalizing is made if calibrated airspeed is used rather than true airspeed.

Another way to consider the overall sound pressure levels is commonly used in boundary-layer studies. This is a representation of the ratio of sound pressure to free-stream dynamic pressure against Mach number. Figure 9 shows this function.

Spectra, Flight

The noise spectra in flight fall into two distinct categories, as shown in figure 10. Figure 10(a) is typical of any flight condition under which the engine power setting is just that required to overcome drag. Figure 10(b) shows the spectrum that is typical of conditions under which there is power in excess of that required to overcome drag, such as in a climb or in acceleration.

The level-flight constant-speed spectrum is essentially continuous, but the "excess-power" case shows a sharp rise in level near 400 cycles per second. The exact frequency of this discontinuity is indicated to be a function of the amount of excess power for the particular flight conditions. If the excess is large, the discontinuity occurs at the 500- or 630-cps band, whereas a small power excess displaces the discontinuity toward the 200-cps band.

At an altitude of 20,000 feet, an 85-percent engine power setting is required to maintain a constant Mach number of 0.55. When the power is increased from idle (64 percent) to maximum (99 percent), the overall noise level increases 2.0±0.5 decibels over the entire measurement span of 2.65 feet. Some individual bands increased 5 decibels.

Spectra, Ground

The spectrum as observed on the ground is given in figure 11. This is a simple average of the sound pressure levels for each microphone in each third octave. Below 100 cycles per second there is little difference between ground and flight data, but the higher frequencies become much less dominant once the aircraft is in flight.

Correlation Coefficient

The measured correlation coefficients are given in detail in figure 12. Disregarding that part of the curves between zero and about 0.5 foot, it is evident that, for any one Mach number, the curves are similar except for a scale factor. Comparing the curves at any one frequency and different Mach numbers also shows a similarity except for a scale factor. These facts indicate that a generalization might be possible using Strouhal number ($N_S = fL/V_{cal}$).

Calculations of Strouhal number at a number of frequencies and Mach numbers were made, and the results are given in figure 13(a). This shows that Strouhal number is a reasonably good generalizing relation. The spread is still appreciable, but some of this may be assigned to the uncertainty in true stream velocity because of the wing interference.

The values of Strouhal number corresponding to the zero crossings of figure 12 are shown in figure 13(b) for the three Mach numbers tested. An approximate curve is shown for the correlation coefficients.

It is noted on all curves that, for Strouhal numbers greater than 0.2, the first maximum negative value of the correlation coefficient is less than the following positive value. The reason for this is obscure at present but may be due to the presence of higher correlated sounds such as the engine.

The presence of engine noise could also account for the fact that the generalized correlation between Strouhal number and correlation coefficient falls down below $N_S = 0.2$.

Using the generalized correlation coefficient given in figure 13(b), the correlation coefficient for 1000 cycles per second was computed at two Mach numbers. The computed coefficient and the measured coefficient are given in figure 14. It is seen that, in order to resolve the values of the correlation coefficient at 1000 cycles per second, a microphone spacing interval of less than 0.1 foot is needed. Since the least interval in this test was about 0.3 foot, the curves for the higher-frequency correlation coefficients are somewhat misleading.

SUMMARY OF RESULTS

Four major observations are substantiated by these tests:

1. The overall sound pressure level on the skin, even in the direction of maximum engine intensity, is largely controlled by the boundary layer and is given by

$$SPL = 20 \log \left(\frac{\rho V_{cal}^2}{2}\right) + 78$$

2. The one-third-octave noise spectrum is nearly flat in level flight, but shows a slight rise in the higher frequencies on the ground.

3. There is definite and appreciable correlation in third-octave bands at distances of a few feet.

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4. The correlation coefficient is generalized through the use of Strouhal number over several zero crossings.

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio, June 12, 1961

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4. Greatrex, F. B., and Brown, D. M.: Progress in Jet Engine Noise Reduction. Rolls-Royce Ltd. (England).

5. Mull, Harold R., and Algranti, Joseph S.: Flight Measurement of Wall-Pressure Fluctuations and Boundary-Layer Turbulence. NASA TN D-280, 1960.

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7. Carlson, Edward R., Conger, Channing C., Laurence, James C., Meyn, Erwin H., and Yocke, Raymond A.: Special Electronic Equipment for the Analysis of Statistical Data. Proc. IRE, vol. 47, no. 5, pt. 1, May 1959, pp. 956-962.

8. Silverstein, A., and Katzoff, S.: A Simplified Method for Determining Wing Profile Drag in Flight. Jour. Aero. Sci., vol. 7, no. 7, May 1940, pp. 295-301.

TABLE I. - MICROPHONE SENSITIVITY CORRECTION

Altitude, ft	10,000			20,000			30,000		
Mach number	0.39	0.60	0.76	0.41	0.60	0.81	0.49	0.61	0.80
Altitude sensitivity correction, db	1.0	1.0	1.0	2.0	2.0	2.0	3.0	3.0	3.0
Temperature sensitivity correction, db (calibrated air temperature)	.6	.3	-.1	1.3	.9	.5	1.9	1.8	1.4
Net level correction, db	-1.6	-1.3	-0.9	-3.3	-2.9	-2.5	-4.9	-4.8	-4.4

TABLE II. - FLIGHT CONDITIONS

Pressure altitude, ft	Mach number	Power setting	Calibrated airspeed, ft/sec	True airspeed, ft/sec	Calibrated air temp., °C	True air temp., °C
Flight 4						
10,000	0.39	0.870	371	423	6	-2
	.60	.875	565	649	15	-2
	.76	.945	717	826	25	-3
20,000	0.41	0.805	329	427	-10	-20
	.60	.852	464	633	0	-17
	.81	.965	633	852	9	-22
30,000	0.49	0.805	312	501	-25	-37
	.61	.845	388	612	-22	-39
	.80	.920	520	804	-14	-42
Ground run						
780	0	0.992	0	0	22	22

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TABLE III. - SOUND PRESSURE LEVELS (RMS VALUES CORRECTED FOR MICROPHONE TEMPERATURE AND ALTITUDE ERRORS)

	Flight 1		Flight 2		Ground run
Altitude, ft	20,000	30,000	20,000	30,000	Ground
Mach number	0.8	0.8	0.8	0.8	0
Position	Sound pressure level, db				
1	132.5	130.0	129.5	124.5	134.5
2	-----	-----	132.5	125.5	135.5
3	130.5	128.5	130.5	127.5	135.5
4	131.5	128.5	131.5	128.5	-----
5	130.0	133.5	130.5	127.5	133.5
6	129.5	133.5	-----	125.5	135.5
8	132.0	129.5	132.5	129.5	135.5
9	132.0	132.0	131.5	128.5	135.5
10	134.5	133.0	132.5	129.5	136.5
Average	131.6	131.1	131.4	127.4	135.3

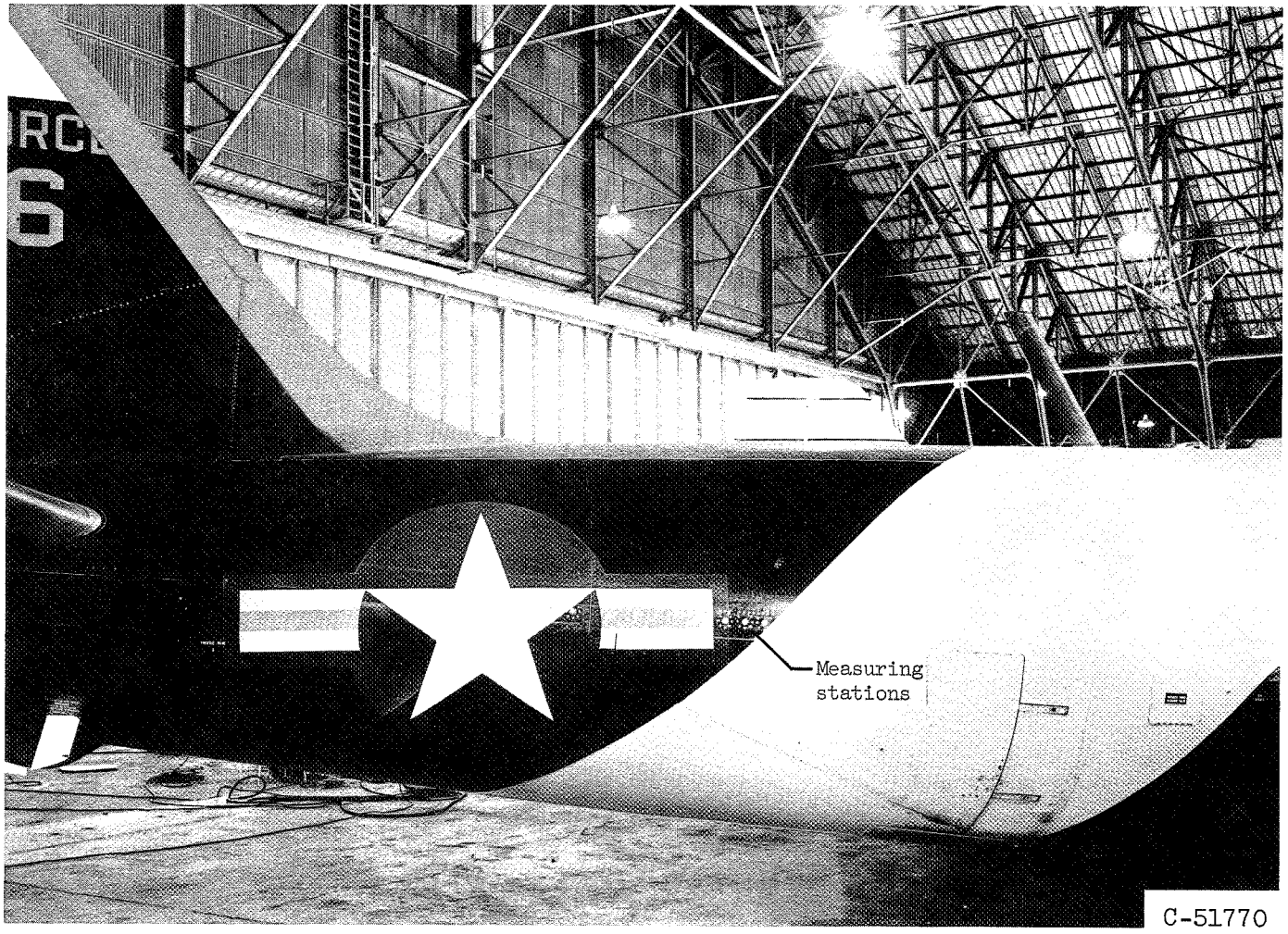
Flight 4

Altitude, ft	10,000			20,000			30,000		
Mach number	0.39	0.60	0.76	0.41	0.60	0.81	0.49	0.61	0.80
Position	Sound pressure level, db								
1	124.5	130.5	133.5	124.0	128.0	131.5	122.0	124.5	127.5
2	126.0	132.5	135.5	122.5	128.0	132.5	119.5	123.0	128.0
3	125.0	130.0	133.3	123.0	127.5	132.0	122.5	125.0	127.5
4	125.5	130.5	133.5	123.5	128.0	132.5	122.0	126.0	127.5
5	123.0	128.5	131.5	120.5	124.5	130.0	119.0	121.5	125.0
6	124.0	129.0	127.5	122.0	125.5	131.0	120.5	122.5	126.5
8	124.0	129.0	132.5	122.0	126.5	131.5	120.5	123.5	127.5
9	124.5	129.0	132.5	122.0	126.5	131.0	120.5	122.5	127.0
10	125.0	129.5	133.5	123.0	127.5	133.0	122.0	125.5	129.0
Average	124.6	129.8	132.6	122.5	126.9	131.7	121.0	123.8	127.3

TABLE IV. - COMPARISON OF CALCULATED AND MEASURED SOUND PRESSURE LEVELS (FLIGHT 4)

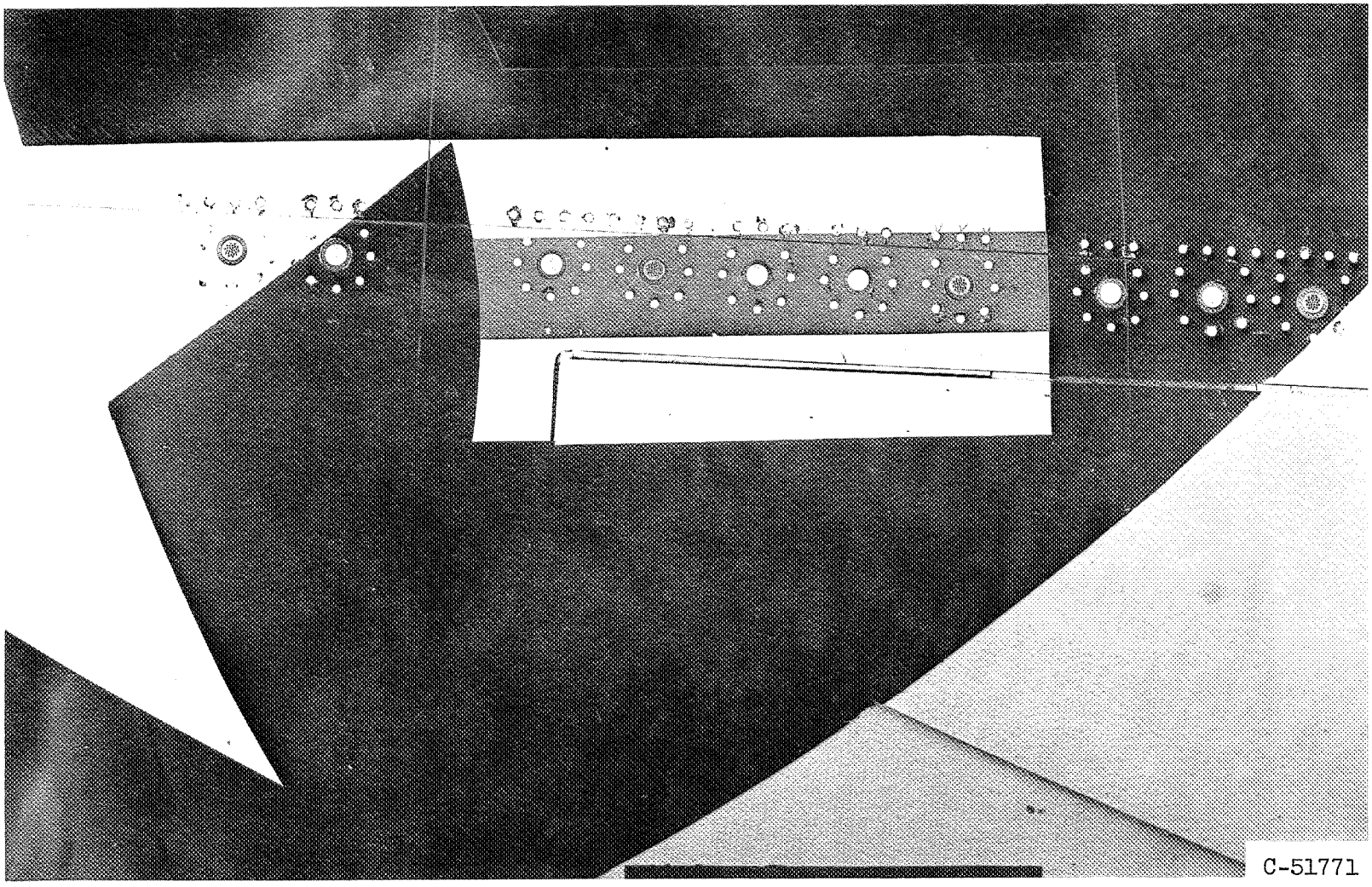
Pressure altitude, ft	Mach number	Sound pressure level, db	
		Calculated[a]	Measured
10,000	0.39	127.4	124.6
	.60	134.8	129.8
	.76	138.9	132.6
20,000	0.41	124.6	122.5
	.60	130.9	126.9
	.81	136.2	131.7
30,000	0.49	123.8	121.0
	.61	127.4	123.8
	.80	132.2	127.3

[a]Using Ribner's equation (ref. 2).



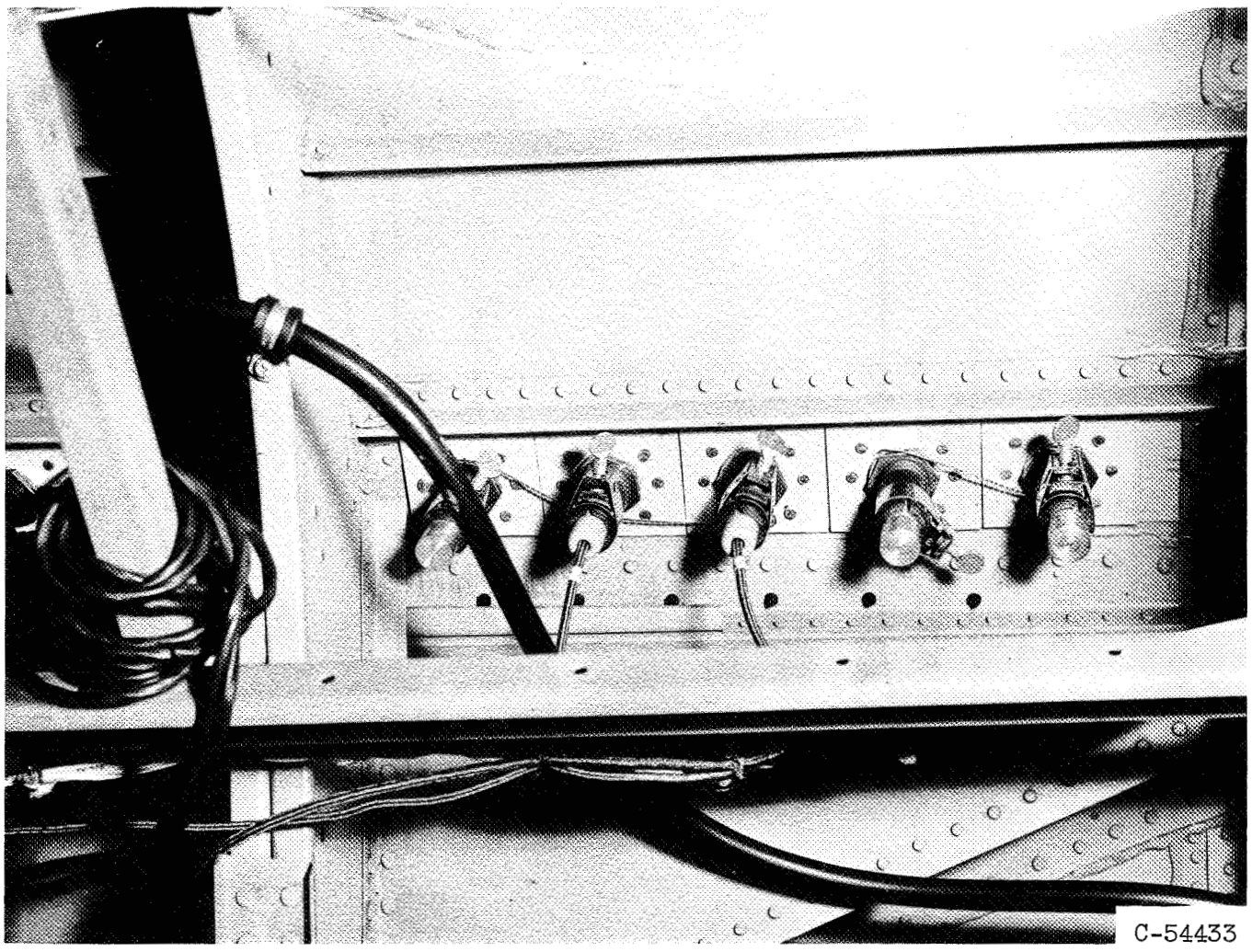
(a) Location of stations on aircraft.

Figure 1. - Measuring stations on aft end of B-57B aircraft.



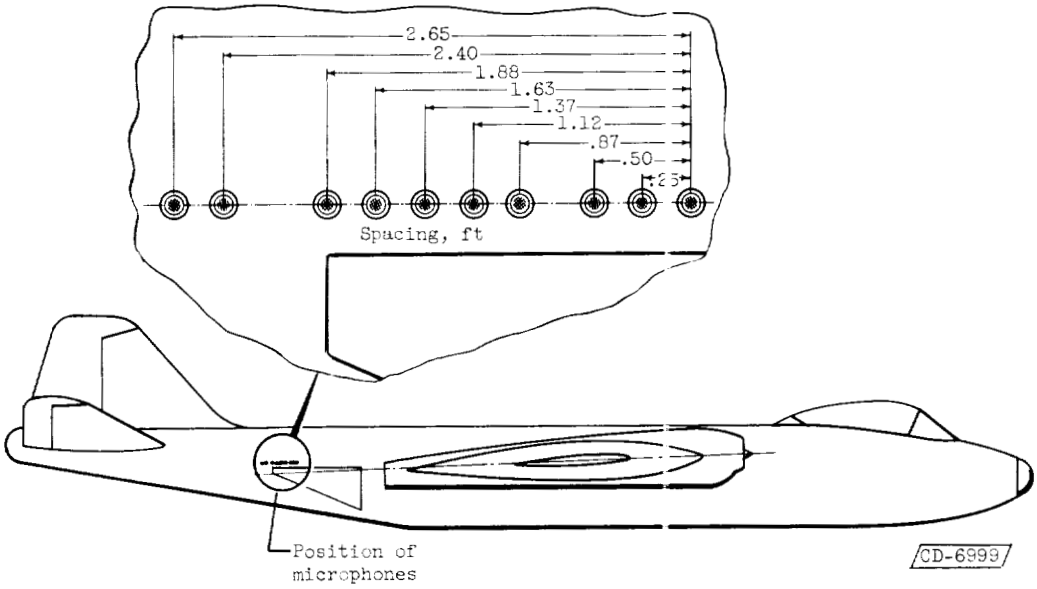
(b) Closeup of the ten measuring stations from outside fuselage.

Figure 1. - Continued. Measuring stations on aft end of B-57B aircraft.

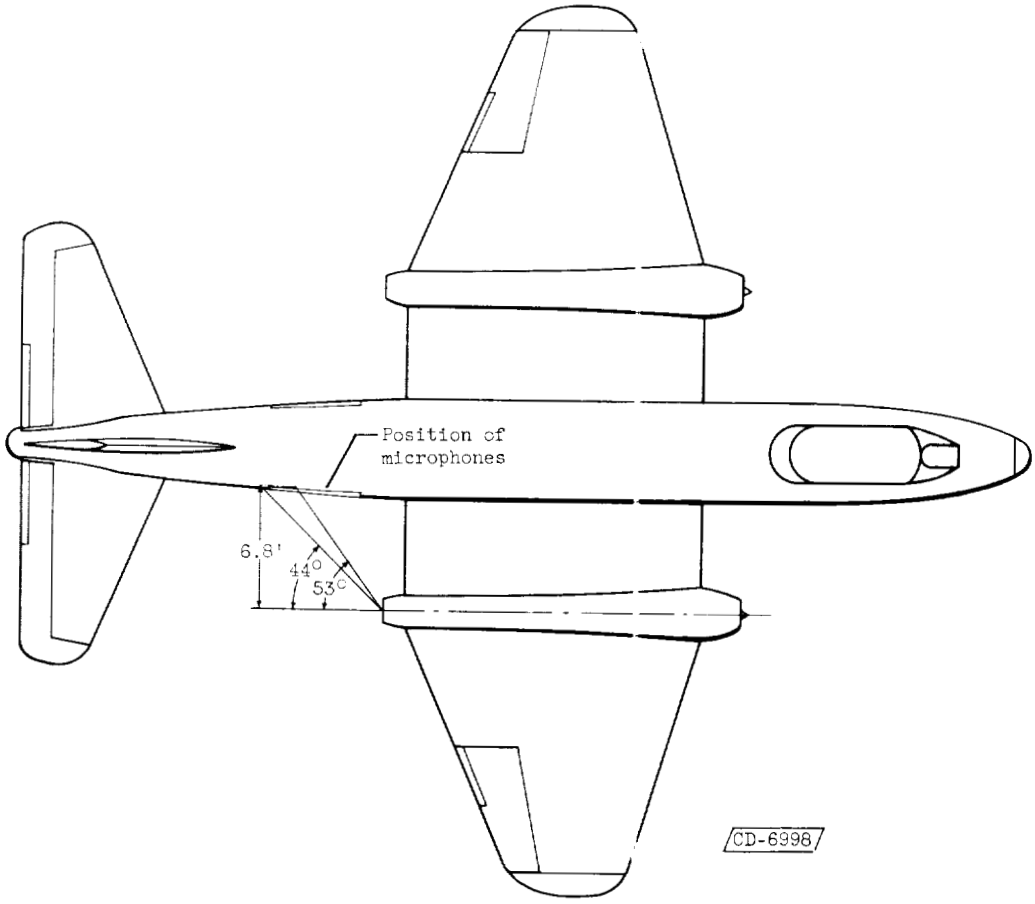


(c) Closeup showing mounting details inside fuselage.

Figure 1. - Concluded. Measuring stations on aft end of B-57B aircraft.



(a) Side view showing arrangement of measuring stations on aircraft skin.



(b) Top view showing location of measuring stations with respect to engine.

Figure 2. - Location and arrangement of microphones.

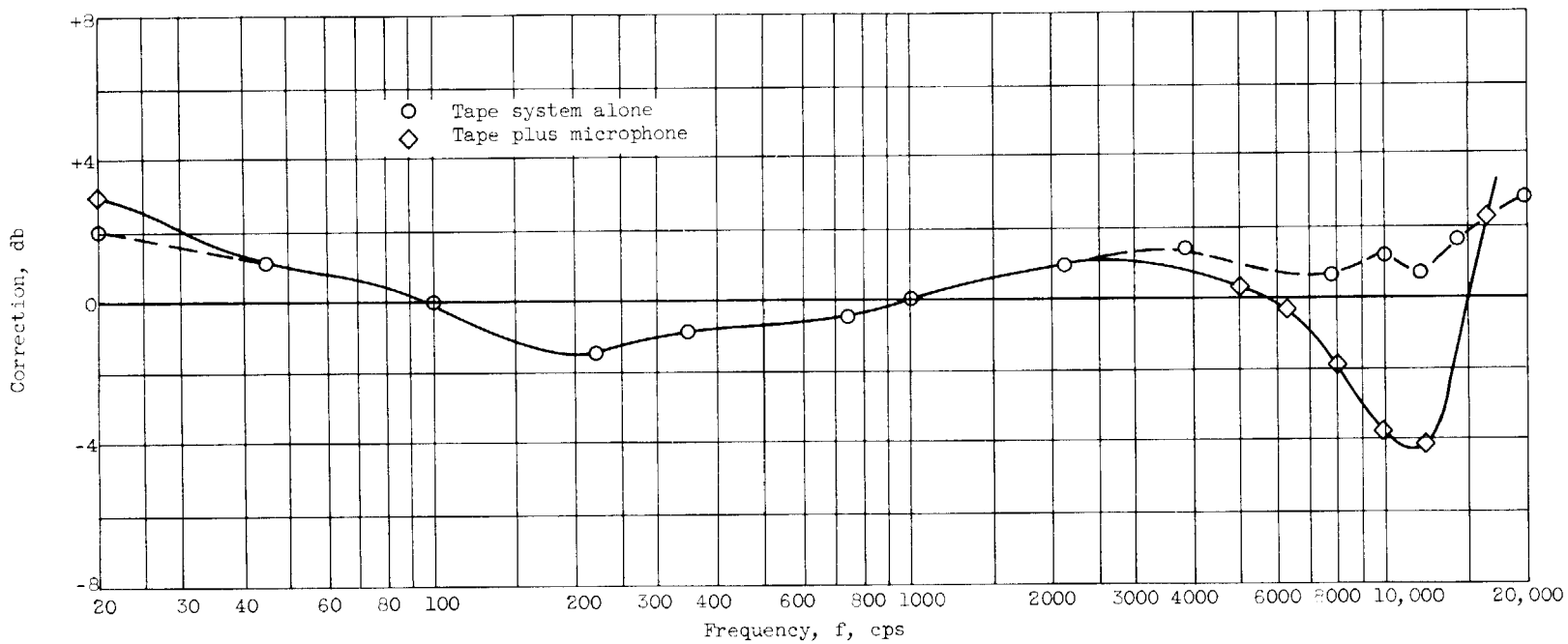


Figure 3. - Microphone and tape system record and playback response correction.

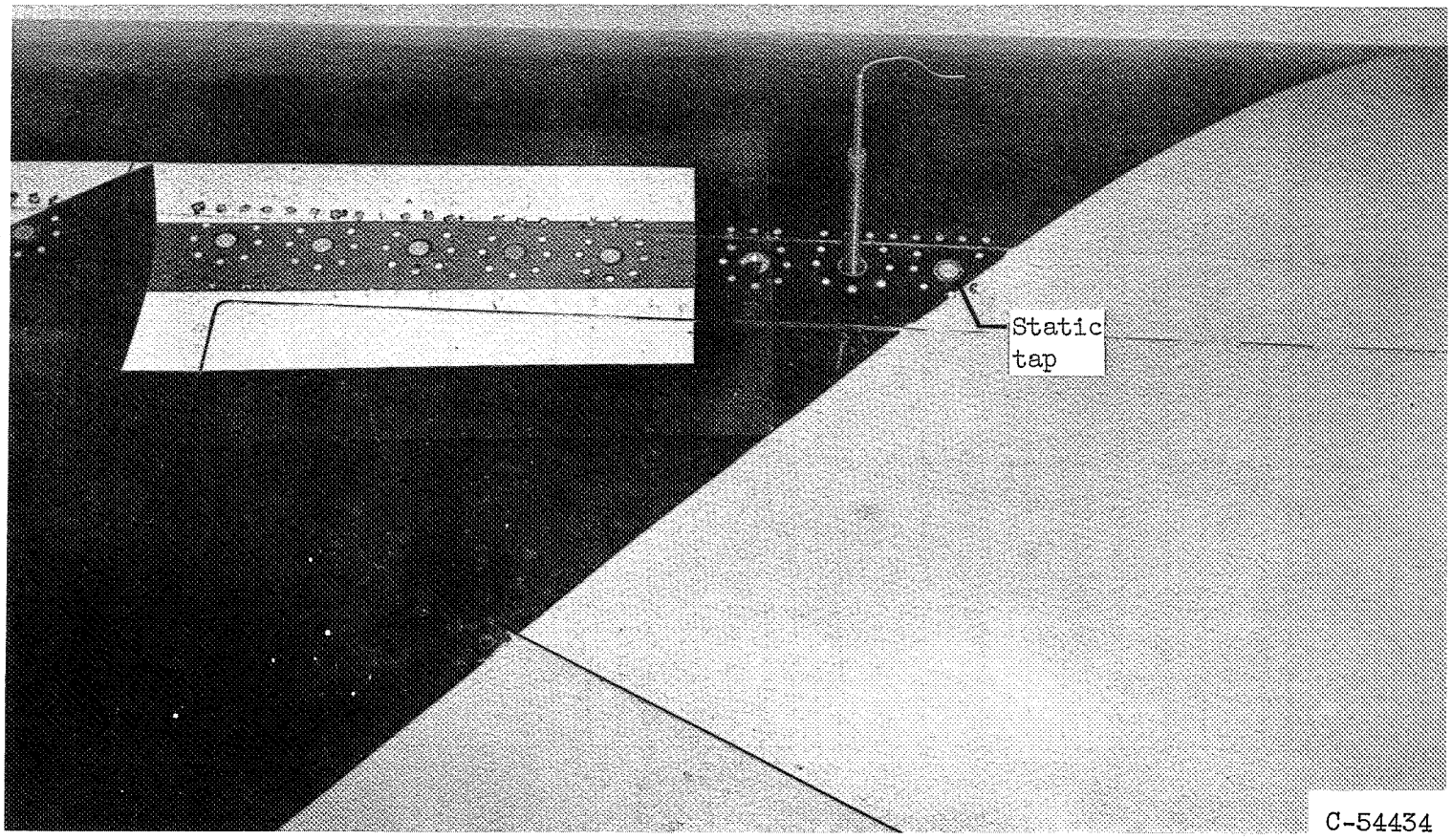


Figure 4. - Total- and static-pressure probes installed in microphone positions.

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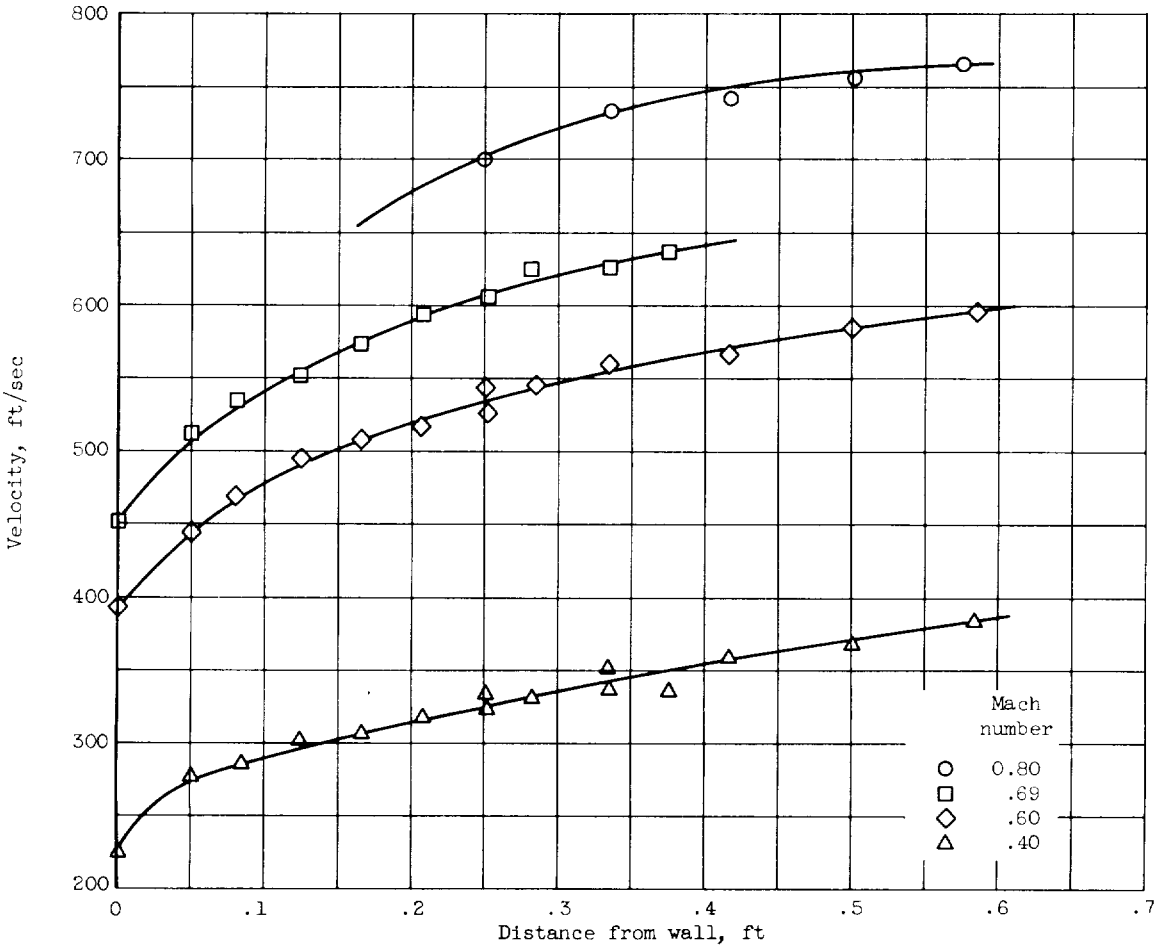
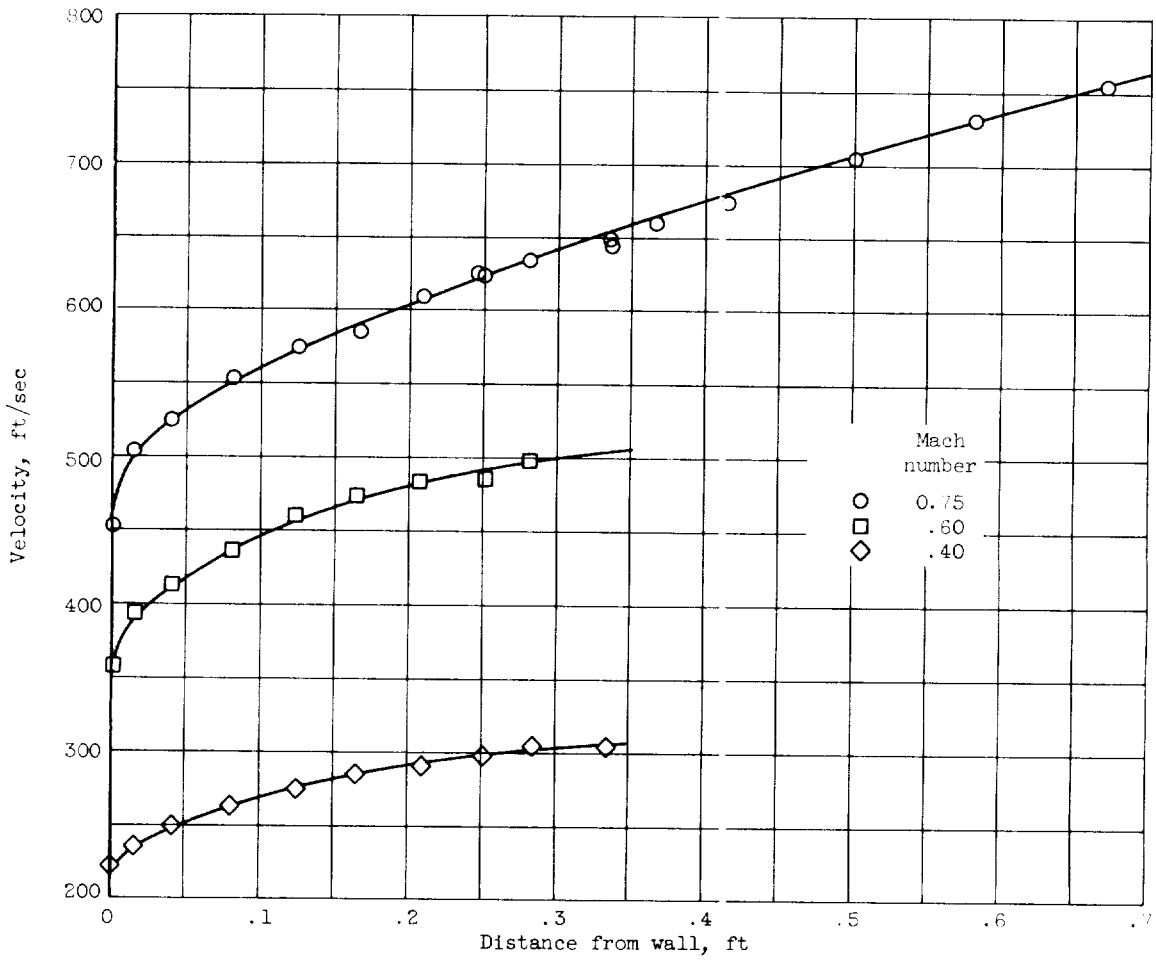


(a) Altitude, 10,000 feet.

Figure 5. - Variation of air velocity with distance from fuselage wall.



(b) Altitude, 20,000 feet.

Figure 5. - Continued. Variation of air velocity with distance from fuselage wall.

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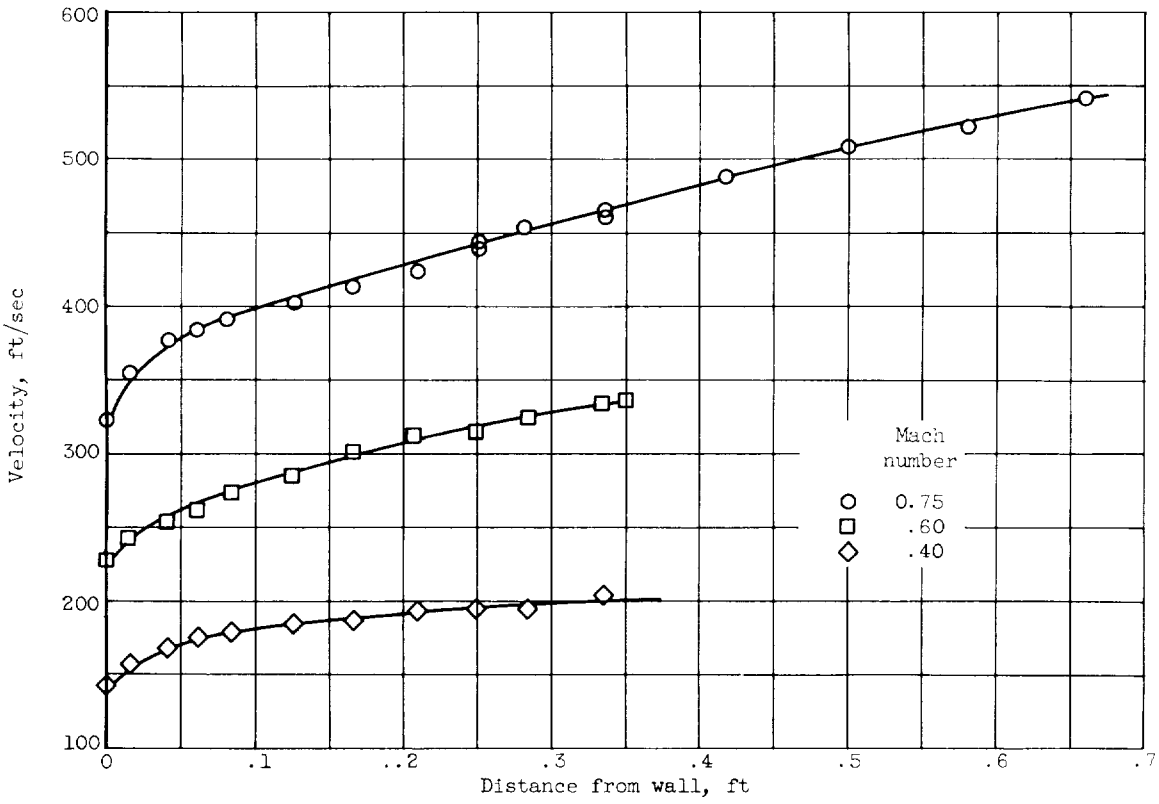


(c) Altitude, 30,000 feet.

Figure 5. - Concluded. Variation of air velocity with distance from fuselage wall.

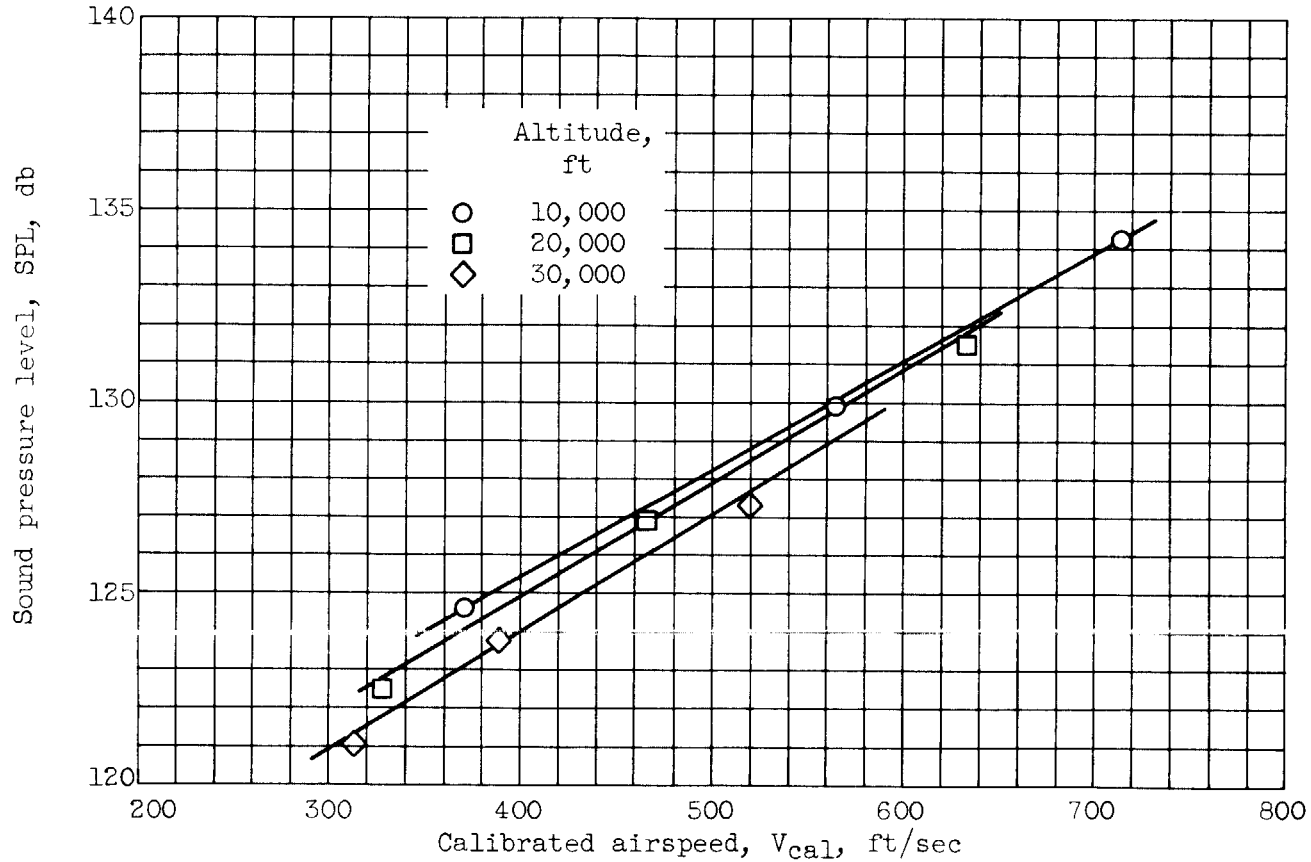


Figure 6. - Variation of overall sound pressure level with calibrated airspeed.

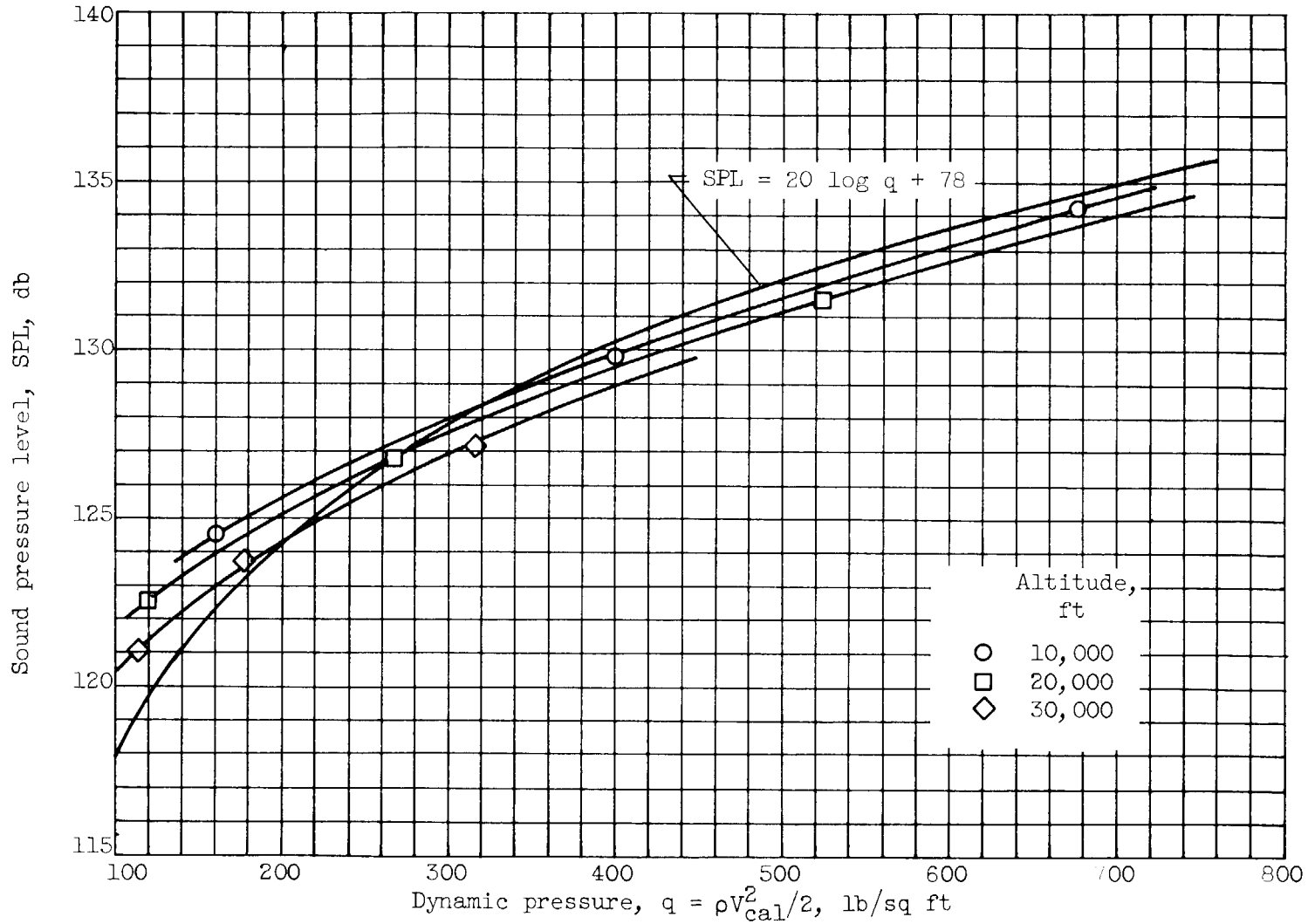


Figure 7. - Variation of sound pressure level with dynamic pressure.

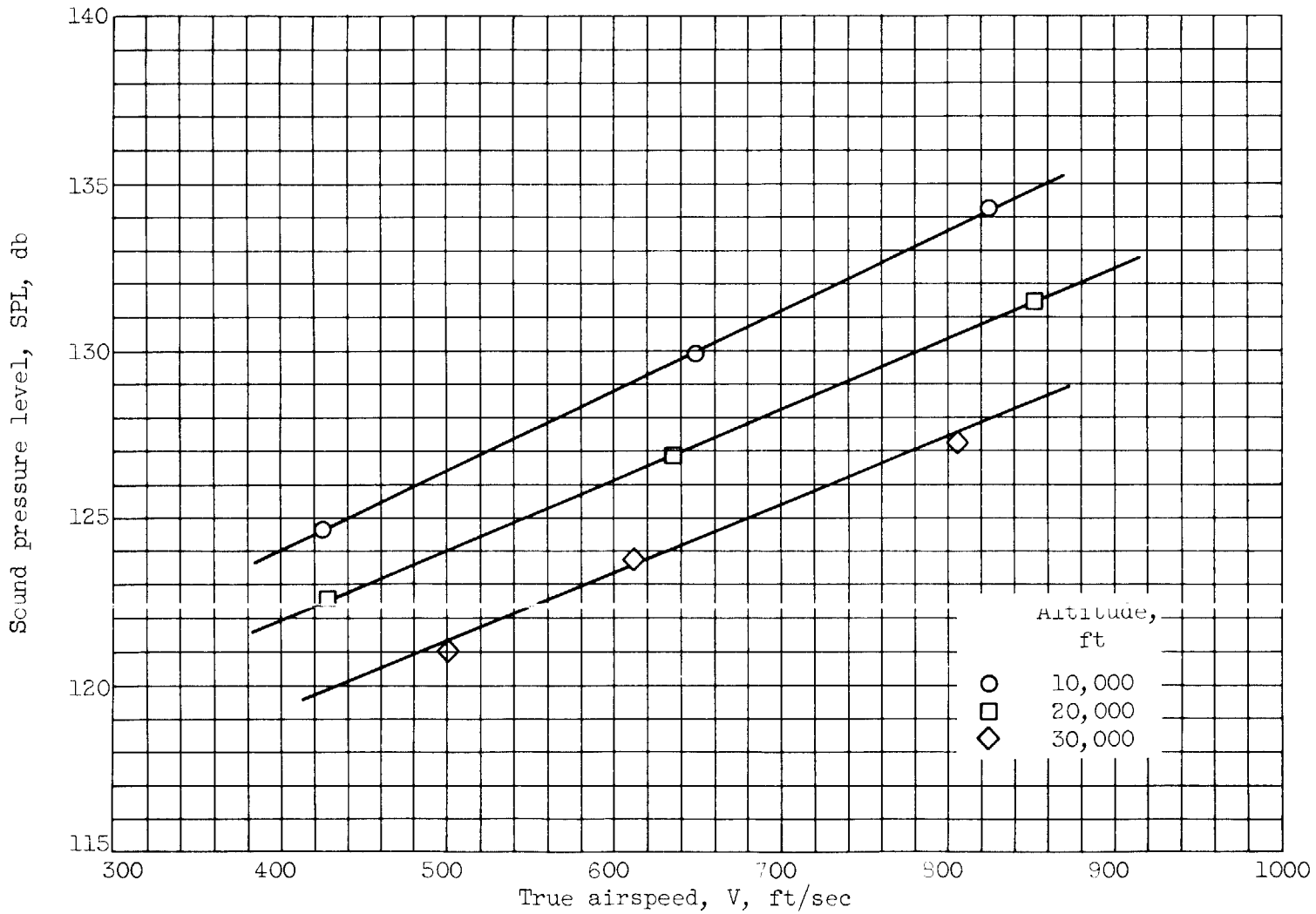


Figure 8. - Variation of overall sound pressure level with true airspeed.

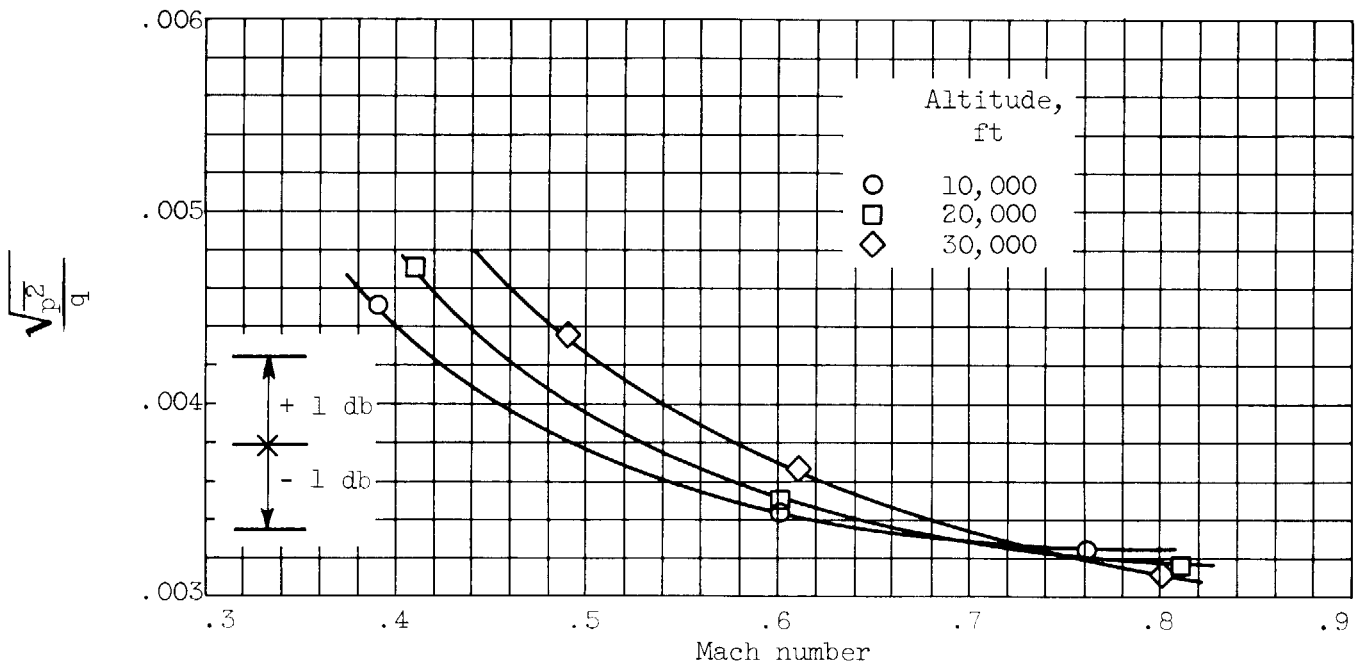
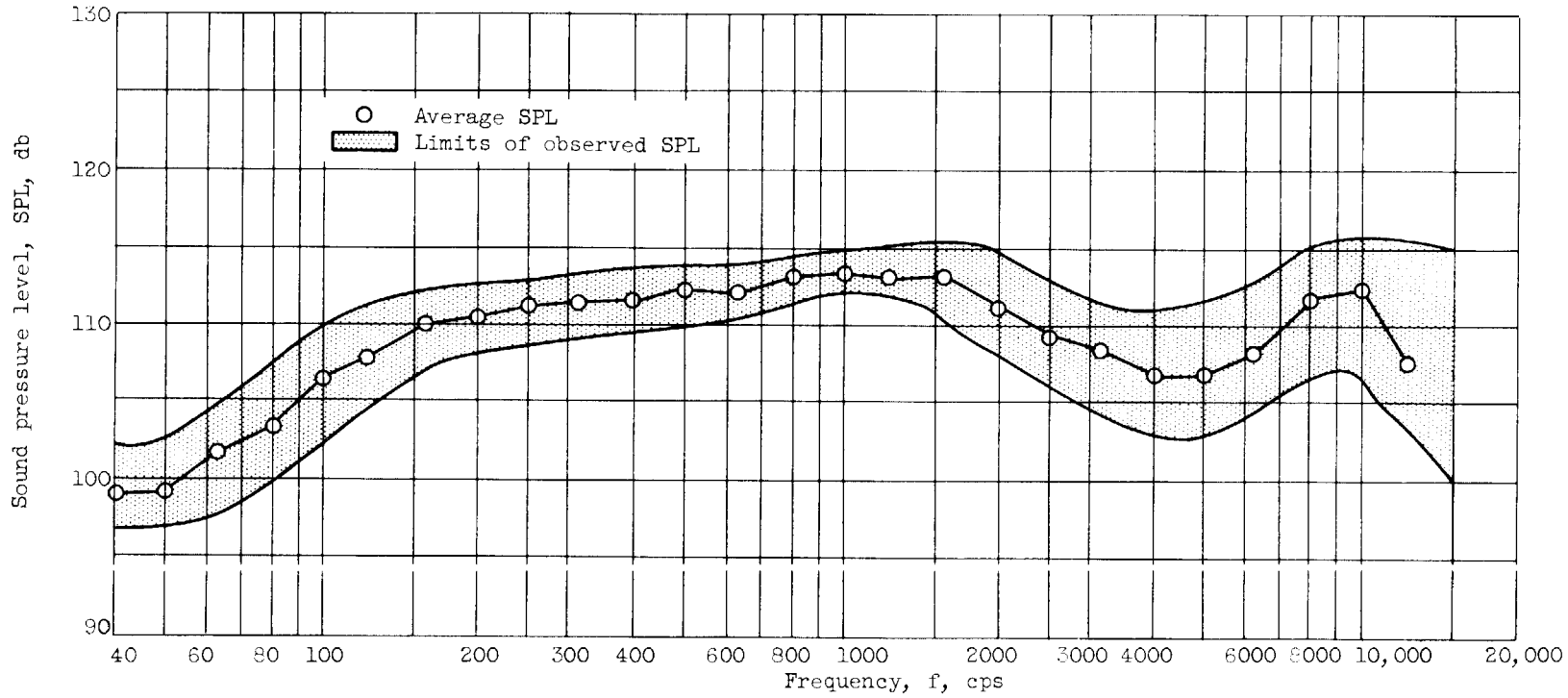
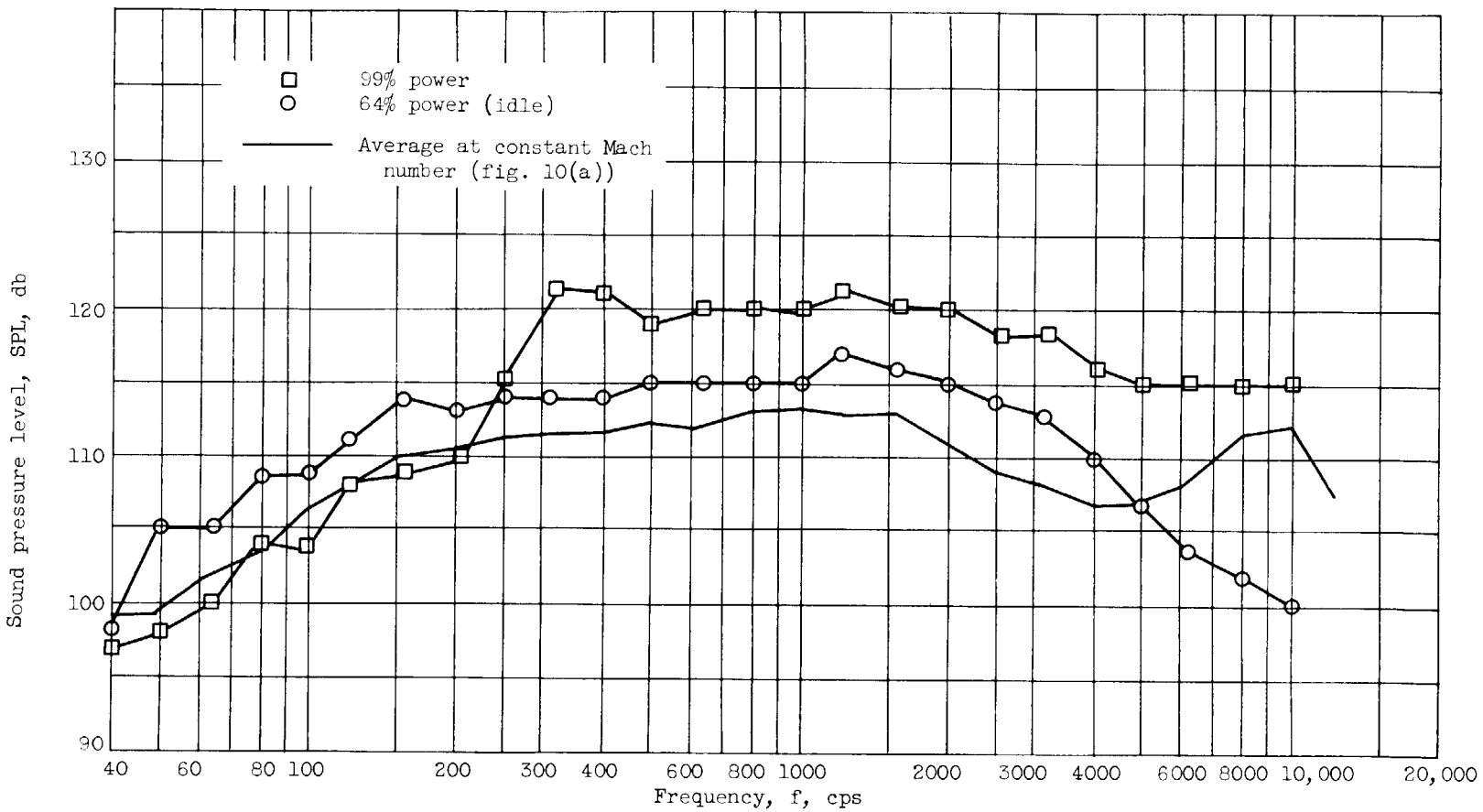


Figure 9. - Variation of ratio of sound pressure to dynamic pressure with Mach number.



(a) Average and range of sound pressure levels in one-third-octave bands, all altitudes, and constant Mach number.

Figure 10. - Flight noise spectra.



(b) Effect of excess power. One-third-octave bands, Mach 0.55, 20,000-foot altitude.

Figure 10. - Concluded. Flight noise spectra.

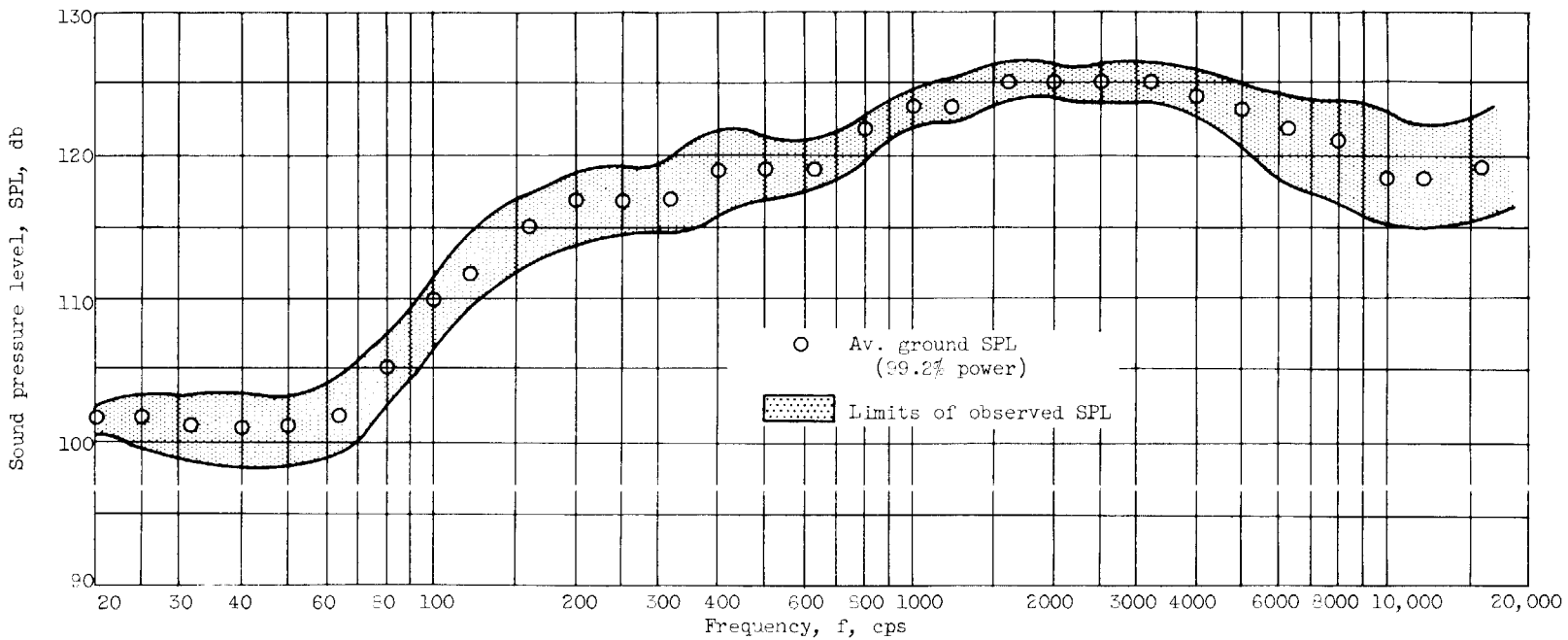


Figure 11. - Ground noise spectra. Average and range of sound pressure level in one-third-octave-bands.

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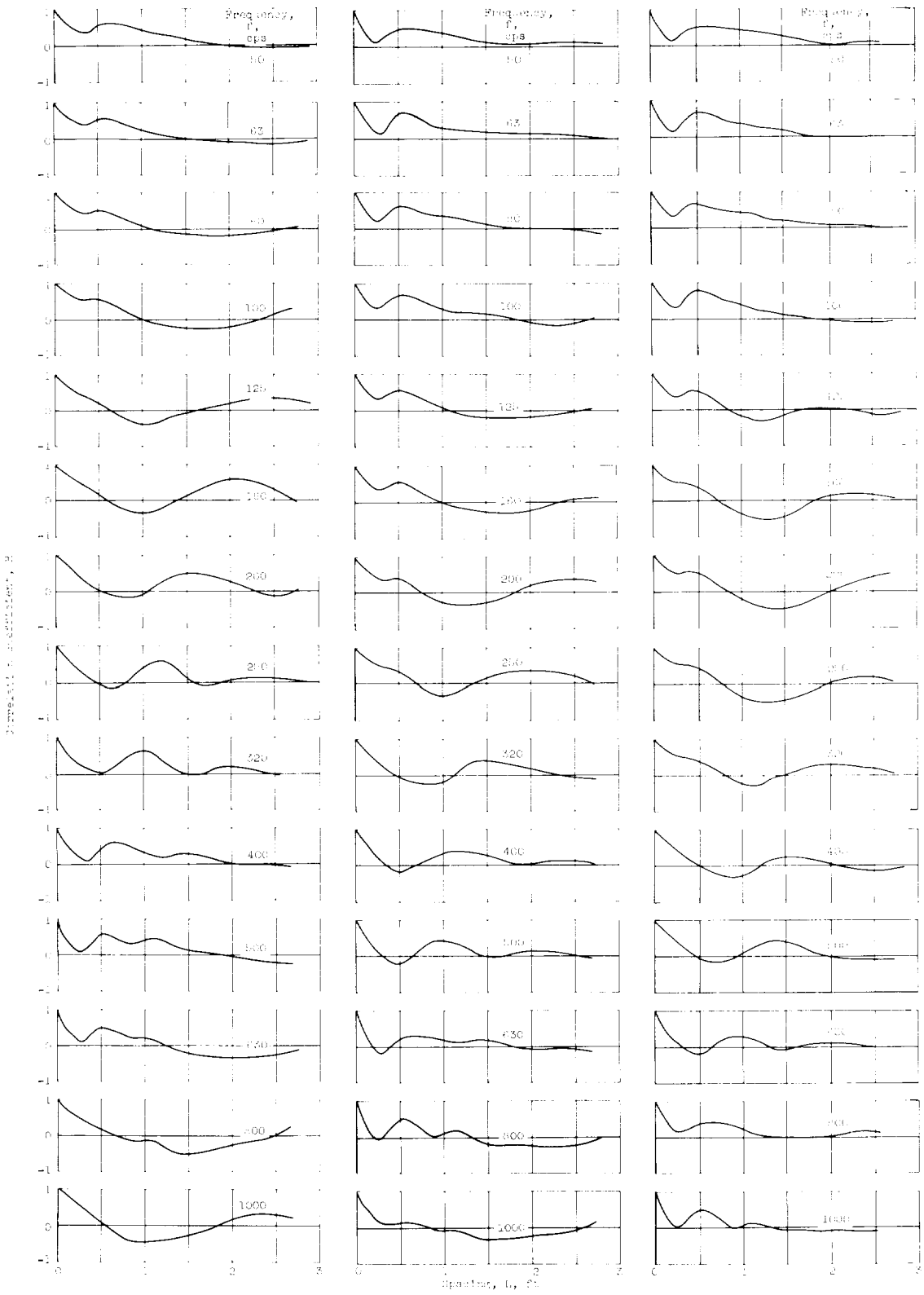
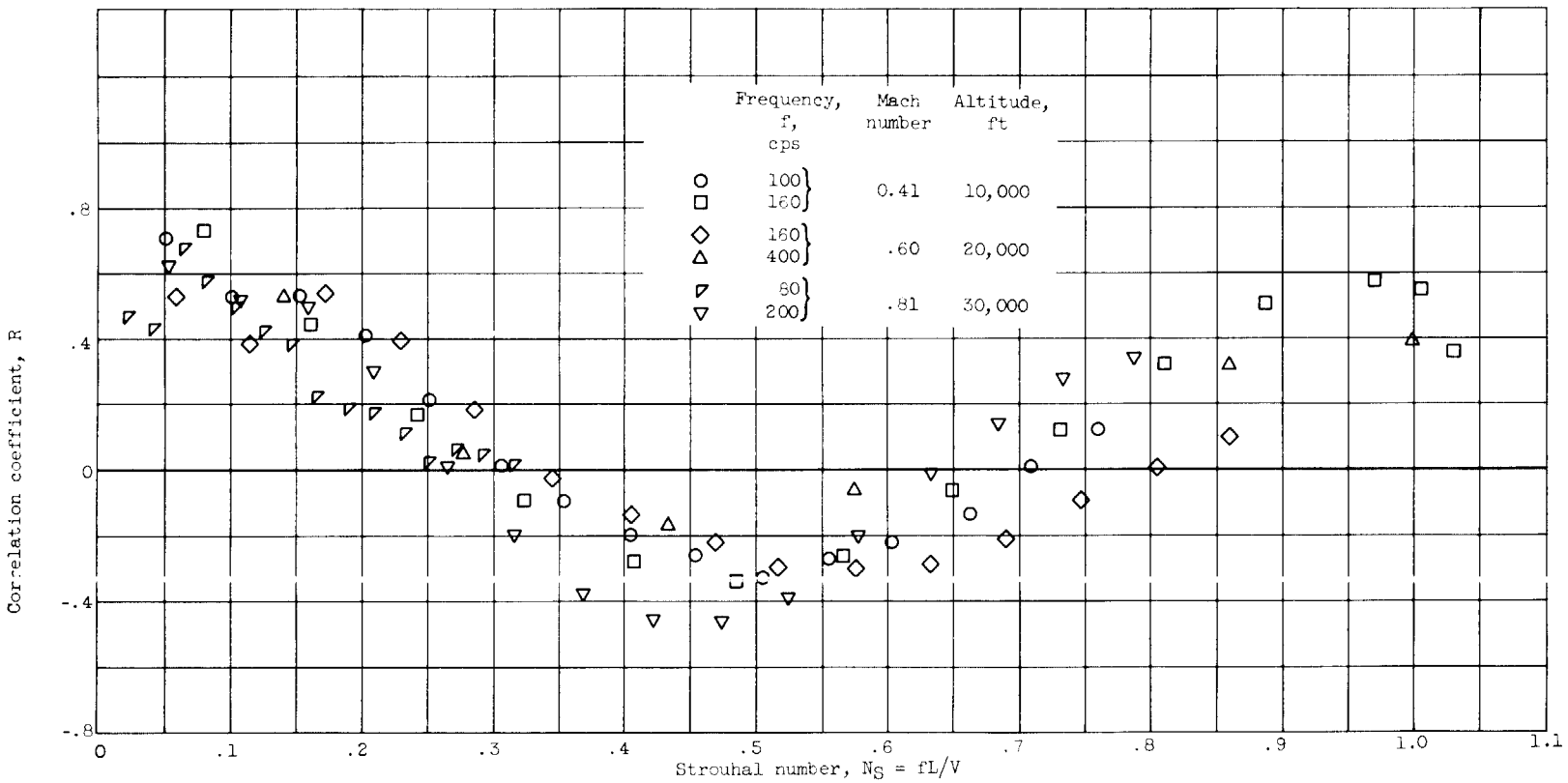


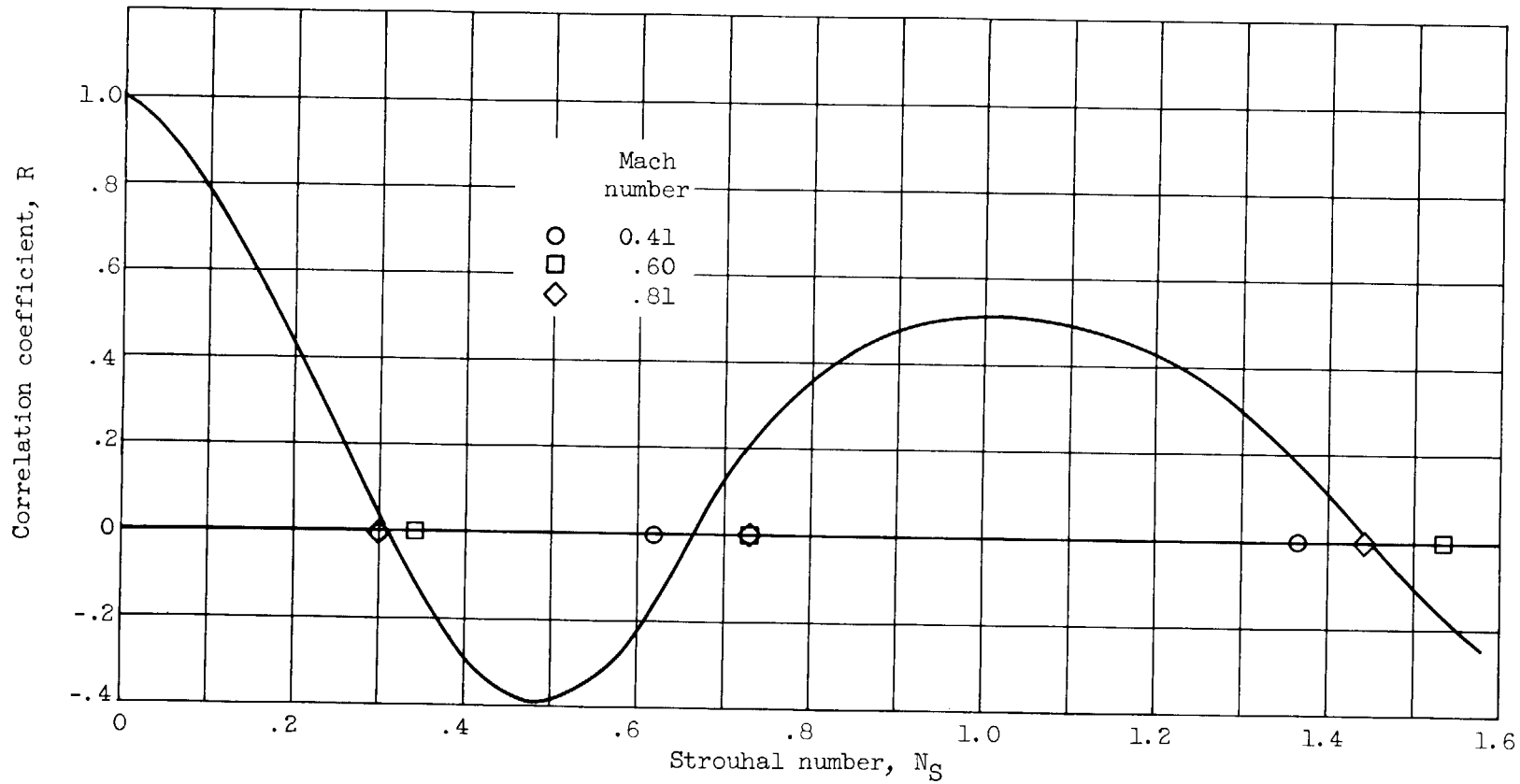
(a) Mach number, 0.41. (b) Mach number, 0.60. (c) Mach number, 0.81.

Figure 12. - Variation of correlation coefficient with spacing. Altitude, 20,000 feet.



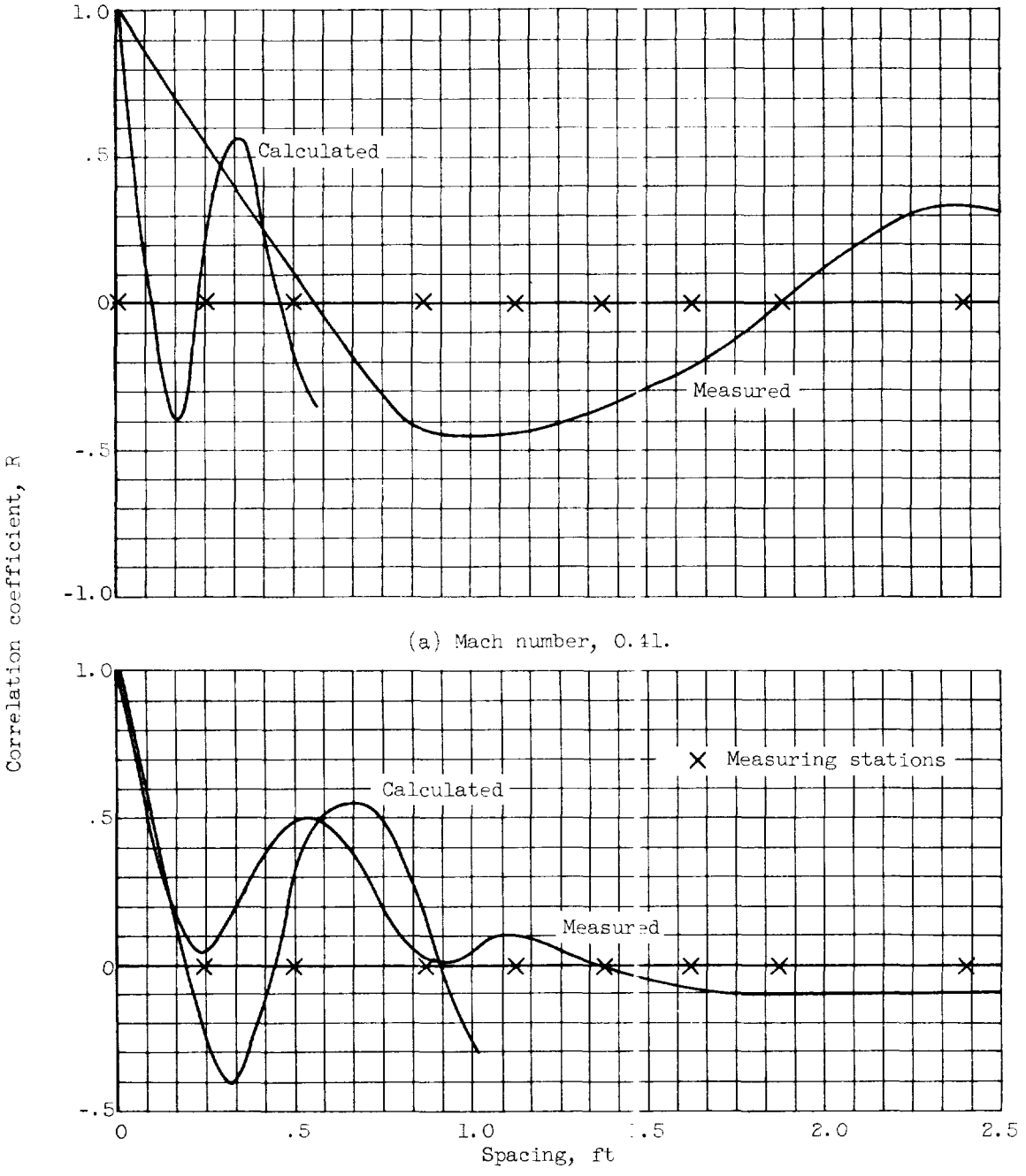
(a) Various Mach numbers and altitudes.

Figure 13. - Variation of correlation coefficient with Strouhal number.



(b) Altitude, 20,000 feet.

Figure 13. - Concluded. Variation of correlation coefficient with Strouhal number.



(a) Mach number, 0.41.

(b) Mach number, 0.81.

Figure 14. - Measured and calculated correlation coefficients at 1000 cycles per second. Altitude, 20,000 feet.