STUDY OF THE EFFECTS OF HIGH INTENSITY SOUND ON TURBULENT INCOMPRESSIBLE FLOW

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ABSTRACT

The effects of propagating a sonic distrubance without reflection in a direction parallel but contrary to flow, over the entire flow, were experimentally studied in a 10-cm by 10-cm square duct with a fluid velocity of 6.8 meters per second, or pipe Reynolds number of 4.7×10^4. The effect was investigated over a range of sound frequencies of 300 to 1800 cps and sound pressure levels of 85 to 140 db re 0.0002 microbars. Sonic excitation reduced the low frequency components (below 300 cps) of the incoming turbulence. The turbulence reduction was greatest for a sound of frequency 700 cps and increased with increasing SPL. This reduction of incoming turbulence appears to retard transition to turbulence by reducing the amount of turbulence in air entering the duct thereby altering the turbulence profile without apparently changing the velocity profile.

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1. Introduction

The primary objective of this investigation is to study the effect on the transition from laminar to turbulent flow at low Mach number of high intensity plane sound waves propagating in a direction contrary to that of fluid flow.

The transition from laminar to turbulent flow of an incompressible fluid is a many-faceted problem of great interest to the hydrodynamicist and the aeronautical engineer. Attempts to obtain a detailed understanding of the mechanisms of transition have been carried out for a number of years. However, the phenomena are by no means well understood and investigation of these mechanisms and possible means of control continue unabated.

It is well known that the stability of flow can be influenced by sonic excitation. In a now classic experiment, Schubauer and Skramstad [5], while studying the transition from laminar to turbulent boundary layer flow in the Blasius velocity distribution near the surface of a flat plate, found that they could use a vibrating ribbon to introduce a controlled disturbance of known frequency and amplitude into the boundary layer and move the transition point to a position closer to the leading edge than is normally expected. Their results were then shown to agree with the Tollmein-Schlichting stability theory based upon the exponential growth of small disturbances [8].

Schubauer and Skramstad noted the effects of sound on transition in a qualitative manner:

> A 25-watt loudspeaker was installed in the top of the tunnel at the leading edge of the plate and fed by a variable frequency oscillator through an amplifier. Interesting effects were easily demonstrated. For example boundary layer oscillations could be introduced at will

by choosing the right frequency for a particular position and speed. Transition could be moved 1 or 2 feet ahead of its natural position by the right combination of intensity and frequency.[1]

These were "casual" observations; when quantitative measurement attempts were made, general agreement with Tollmein-Schlichting theory was observed.

In a recent experiment, Jackson and Heckl [1] used a localized sound source on the surface of a flat plate to produce similar results and noted that the effect of sound on their flow was to advance the transition point, thereby causing turbulence to become fully developed earlier with sonic excitation and thereby increasing the relative turbulence over the plate. Jackson and Heckl also noted as an incidental portion of their investigation that, when tunnel turbulence was increased by use of a tripping wire, sonic excitation caused a retardation of transition.[2]

Recent experiments conducted by Meyer, et al. at Physikalisches Institut der Universität Göttingen also examined the influence of a sound field on the boundary layer of a flat plate, using both local excitation on the flat plate and transverse sound radiated from a branch duct below the flat plate, and found that turbulence could either be excited or retarded by varying the frequency of their sonic input [6, 7].

Our study concerns itself with further investigation of the effects of sonic excitation on incompressible flow, specifically with flow in a square cross sectional pipe or channel with a mean fluid velocity of 6.8

[1] G. B. Schubauer and H. K. Skramstad, "Laminar boundary layer oscillations and transitions on a flat plate," National Advisory Committee on Aeronautics Report No. 909, 344 (April, 1943).

[2] Francis J. Jackson and Manfred A. Heckl, "Effect of localized acoustic excitation on the stability of a laminar boundary layer," Aeronautical Research Laboratories Technical Documentary Report, 24 (June, 1962).

meters per second or Reynolds number, based on hydraulic diameter[3] of 47,600. The sonic excitation is limited to frequencies between 300 and 1800 cycles per second and sound pressure levels of 80 to 140 decibels re 0.0002 microbars. The effect was studied in areas which are defined to be those of the entry region for pipe or channel flow where fully developed velocity profiles are not yet achieved.[4,5] This study is distinctive in that the disturbances imposed on the boundary layer are propagated without reflection in a direction parallel to flow and over the entire flow as opposed to previous investigations where local disturbances were introduced perpendicular to the direction of flow or in a branch duct.

Due to the lack of quantitative theoretical predictions other than the Tollmein-Schlichting theory previously mentioned, which does not apply to pipe flow but to transition over a plate, this study is necessarily of a phenomenological nature.

Results indicate that sonic excitation can retard transition to turbulence by reducing the amount of turbulence in the incoming air and thereby changing the turbulence profile in the pipe, without apparently changing the velocity profile.

This work is divided into four parts: (a) description of equipment, (b) preliminary studies, (c) development and description of procedures utilized to measure observed effects, and (d) the detailed descriptions of effects caused by variation of several parameters of the system.

[3] Hermann Schlichting, Boundary layer theory (McGraw-Hill, New York, 1960), Chap. 20, p. 517.

[4] C. C. Lin, The theory of hydrodynamic stability (University Press, Cambridge, 1955), Chap. 6, p. 98.

[5] Schlichting, pp. 502-505.

2. Description of equipment

The aero-acoustic facility used in this investigation was designed and constructed by Professors H. Medwin and J. V. Sanders of the Department of Physics at the United States Naval Postgraduate School in 1963 and 1964. This facility, with the exception of flow generating equipment and instrumentation, remained intact throughout this study.

<u>Construction of test duct</u>. The test duct, Fig. 1, consists of a 10-centimeter by 10-centimeter inside diameter square cross section pipe six meters long with ¼-inch steel walls. The inlet end of the pipe is connected to a square catenoidal or Salmon horn of sheet aluminum. The cross section of the horn is of the form:[6]

$$S = S_o \cosh^2 (x/h)$$

where S = cross sectional area

h = 60 cm.

cutoff frequency = 90.6 cps

This horn, fitting smoothly to the pipe, allows acoustic plane waves to be propagated from the pipe into the horn without significant reflection over the frequencies of the experiment and smooths the air entering the pipe. The test duct has nine openings or test positions, located as shown in Fig. 1.

Prior to being drawn into the test duct, air must pass through six screens of 20-wire-per-inch mesh placed three inches apart and an acoustically treated room as shown in Fig. 2. The flow is generated by a centrifugal blower powered by a 0.5 horsepower d.c. compound motor. Flow velocities of from 1 to 14 meters per second may be realized; higher velocities

[6] Philip M. Morse, Vibration and sound (McGraw-Hill, New York, 1948), p. 281.

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would require modification of motor wiring. The air intake flow path may be taken either from the main test room or outside the building by closing or opening windows and a door in the room housing the catenoidal horn.

Either flow path could be used but it was found that on windy days it was necessary to use the interior route to ensure that turbulence was not increased by the wind. This path was not used exclusively since the temperature variation in the main test room was excessive when all equipment was operating and all ventilation secured to ensure smooth flow. Although no temperature effect was noted, this flow path was deemed less than optimum since the possibility of temperature dependence was not entirely eliminated.

Anemometer. The DISA Constant Temperature Anemometer model 55 A 01, manufactured by DISA Elektronik A/S, of Herlev, Denmark, was used to measure instantaneous flow velocity of the air [2] . A miniature hot wire probe, Fig. 3, was used for all hot wire anemometer (HWA) data.

The wire used is five-micron diameter, platinum-plated tungsten wire of about one millimeter length fastened to thin nickel supports five millimeters long protruding from a cylindrical support of three millimeters diameter. (See appendix for detailed description of procedure for mounting wires to supports.) The resistance of the wire at 20° C is about four ohms. The anemometer reads d.c. bridge voltage and RMS bridge voltage. Bridge voltage fluctuations may be observed on a level recorder or oscilloscope by using the "turbulence out" connection.

The instrument is accurately calibrated by observing d.c. bridge voltage for a known velocity, determined from a pitot static tube mounted in a calibrating wind tunnel manufactured by DISA, and applying King's law which states:

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$$\frac{V^2}{R} = \propto + \beta\sqrt{U}$$

where V is bridge voltage, R is probe operating resistance, V_o is zero flow bridge voltage, U is mean flow velocity, and $\propto = \frac{V_o^2}{R}$. The constants may be graphically determined by plotting V^2 vs. $\sqrt{U}$. This procedure allows determination of velocities within a few centimeters per second. The root mean square percent turbulence may be determined from the formula:

$$\text{percent turbulence} = \frac{V_{RMS}(100)}{A \cdot U}$$

where

$$A = \frac{dV}{dU}$$

since $$\frac{V^2}{R} = \frac{V_o^2}{R} + \beta\sqrt{U}$$

$$\frac{2V}{R}\frac{dV}{dU} = \beta\frac{1}{2\sqrt{U}}$$

$$\frac{dV}{dU} = \frac{\beta R}{4V}\frac{1}{\sqrt{U}}$$

$$AU = \frac{\beta R}{4V}\sqrt{U}$$

but $$\sqrt{U} = (V^2 - V_o^2)\frac{1}{\beta R}$$

therefore $$AU = \frac{\beta R}{4V}\frac{(V^2 - V_o^2)}{\beta R} = \frac{V^2 - V_o^2}{4V}$$

and $$\text{percent turbulence} = 100\, V_{RMS}\frac{4V}{(V^2 - V_o^2)}$$ 7

Since Vrms and V may be read directly from both d.c. or mean velocity, U and percentage turbulence may be readily computed.

[7] Flowmeter DISA constant temperature anemometer 55A 01 instructional manual, DISA Elektronik A/S, Herlev, Denmark.

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Probe support mounting. The miniature probe is mounted in a probe support mounting, Fig. 4, which seals the duct and firmly holds the support while allowing movement of the probe support in the vertical direction to any desired depth. Each test position of the duct is tapped to allow the probe support to be mounted in any test position with minimal interference to flow.

Loudspeaker. A 100-watt Jensen Hypex Model DD-100 loudspeaker terminated with a catenoidal horn is mounted in the test duct expansion between the test duct and the blower intake. The horn is fabricated from brass following the catenoidal equations mentioned under test duct construction, with h = 10 cm and a circular cross section with throat radius of 2.5 cm. The theoretical cutoff frequency of this horn is 540 cycles per second. The experimental free field cutoff frequency is about 700 cps, but the test duct expansion loads the speaker so that only certain discrete frequencies propagate with low distortion in the pipe. These propagation characteristics limit the investigation of the effect of the frequency parameter to those frequencies which exhibit the least distortion.

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3. Preliminary studies

Prior to investigation of the actual effect of sound on the flow, preliminary studies were conducted to determine flow and acoustic characteristics of the test duct.

Flow characteristics. Flow characteristics were measured at a velocity of about 6.8 meters per second. The 6.8 meter per second flow was chosen as it is a velocity where low motor noise is transmitted into the test duct and from which either increases or decreases of speed can be made without rewiring the blower motor. It may be seenfrom Fig. 6 that the mean flow velocity profile at test position 1 is characteristic of the entry region for turbulent pipe flow:

> In sections close to that at the entrance the velocity distribution is nearly uniform. Further down stream the velocity distribution changes, owing to the influence of friction until a fully developed velocity profile is attained at a given cross section and remains constant downstream of it.[8]

It is seen from Figs. 6, 7, and 8 that the entire test section is in the entry region and that the velocity distribution is not yet that of fully developed turbulence after traveling 20 hydraulic pipe diameters to position 6. This is in agreement with J. Nikuradse, who predicts an entry region of from 25 to 40 pipe diameters[9] and a velocity profile as shown in Fig. 8.[10]

The RMS turbulence profile taken at test position 1, Fig. 6, shows a symmetric turbulence spike centered on the axis. This broad spike is about twice as turbulent as the background turbulence existing immediately

[8] Schlichting, p. 502.

[9] Ibid., p. 517.

[10] Ibid., p. 505.

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below the spike but above the boundary layer. The spike of turbulence is only slightly diminished as the velocity profile becomes more fully developed as seen at position 3, Fig. 7, where the fluid has traveled an additional 5.6 hydraulic pipe diameters. The background turbulence has increased from .5 percent to .6 percent and the outer edge of the boundary layer has moved up about 0.35 h/ho. This trend may be seen to continue by noting Fig. 8, where an additional 18 pipe diameters has been traveled resulting in a nearly fully developed velocity profile with background turbulence rising to about 1.0 percent and the boundary layer achieving a thickness of .74 h/ho.

In the transition region between laminar flow and fully developed turbulent flow, the d.c. velocity shows evidence of increasing frequency of occurance of turbulence spots as the boundary layer is reached; the spottiness manifests itself by fluctuating d.c. bridge voltage readings. These voltage fluctuations imply a band or spread of velocities, which are indicated by short horizontal lines representing the entire range of d.c. velocities seen at a given position. These fluctuations are also reflected in the increased spread of percent turbulence due to the dependence of the percent turbulence calculation on the d.c. bridge voltage as previously shown. It is seen that at position 3 the boundary layer velocity and turbulence fluctuations are very high. This intermittency was observed but no successful, reproducible data was obtained pertaining to the frequency of occurance of intermittency spikes.

The turbulence and velocity profiles may be considered to be symmetric although some deviations from symmetry were observed when the probe was raised to within one centimeter of the upper wall. This deviation is believed to be caused by some effect of the periodic shedding of

vortices from the plugs for unused test position holes.

In order to obtain the frequency characteristics of the turbulence, a one-third octave band level filter was used to analyse the turbulence at position 1 on the axis at various flow velocities. This information appears as Fig. 9 where turbulence output in decibels re 10 millivolts is plotted against third octave band center frequency for a number of fluid velocities. This test position was chosen when a rough qualitative survey of the reduction of turbulence was made in the early stages of the study, as it was the position which exhibited the maximum amount of reduction. This early and arbitrary choice of velocity and position for investigation was maintained in later work in order to minimize the number of parameters. Subsequent investigation showed that the type of turbulence reduction seen at the velocity and position initially investigated is characteristic of the effect throughout the entry region. It is noted that at velocity below one meter per second, Reynolds number R = 7,000, the pipe does not develop turbulence and flow remains laminar. This is in general agreement with the transition point for a square cross section pipe: R = 2300, which in our case would correspond to U = 0.33 meters per second.[11]

Noise characteristics of the test duct. The ambient noise characteristics of the test duct were examined to determine what noise levels and frequencies were being transmitted down the test duct from the centrifugal blower or its drive motor. It was found that the noise level in the room in which the blower and motor were housed was quite high compared to the

[11] Ibid., p. 517.

actual noise in the test duct. This room contained noise spikes of up to 81 decibels re 0.0002 microbars at frequencies below 50 cycles per second. At a flow velocity of 6.8 meters per second, predominant spikes of 71 db. were seen to occur in the duct at 120 and 180 cycles per second. The wide band sound pressure levels increased with increasing velocity but in no case did they rise above 88 db, nor did the wide band sound pressure level at a velocity of 6.8 meters per second ever rise above 80 decibels in the pipe.

Sound generating and propagating characteristics. It has been previously noted that only certain discrete frequencies could be obtained from the loudspeaker horn and propagated down the tube without extreme distortion. It is shown in Table I that at high sound pressure levels in the test section the second harmonic content of the sound being propagated increases. Part of the second harmonic strength is due to loudspeaker horn distortion; part can be attributed to the non-linearity of propagation in the medium which causes a buildup of other harmonics at the expense of the fundamental at these sound intensities. The frequencies listed propagate with less distortion than others and therefore were used to investigate the effect of sonic excitation. The frequencies all fall below the cutoff frequency for propagation of cross modes in the test duct, so that plane waves are propagated down the duct. The Salmon or catenoidal horn allows this wave to propagate out of the duct without reflection. The room housing the horn is thoroughly insulated with fiberglass, reducing reflection back up the test duct. Standing wave ratio (SWR) tests were conducted during the construction of the test duct by J. V. Sanders

and H. Medwin resulting in verification of the effectiveness of the termination and insulation by showing that the typical standing wave ratios for the frequencies of this experiment were approximately 2.0 db.

4. Measurement procedures

The "turbulence output" of the DISA hot wire anemometer (HWA) reflects fluctuations of bridge voltage which are normally read as RMS a.c. bridge voltage and converted to percent turbulence as described in the Equipment section. Since, in the presence of unidirectional flow, the acoustic particle velocity of the sound wave placed in the duct causes fluctuation of the bridge voltage at the frequency of the sound and its harmonics, meaningful values of the turbulence output cannot be read from the HWA RMS meter. A new procedure must therefore be developed which eliminates that portion of the turbulence signal caused by accoustic particle velocity but still retains the essential turbulence information. The information is contained in the turbulence frequency spectrum, but it would be valuable to develop a single number which would describe in a quantitative manner the effect of sound on the turbulence in the test duct. A logical solution to the above problems is to analyse the frequency characteristics of the turbulence output and retain that portion of the frequency spectrum which is significantly affected by the sonic disturbance.

Analysis of frequency characteristics of turbulence. A General Radio Corporation Wave Analyzer, Model 1900A, with 50 cps band width was connected to the turbulence output of the HWA and a spectrum level of the turbulence output at 6.8 meters per second was taken at test position 1 on the axis, Fig. 10. A sonic disturbance of 120 decibels re 0.0002 microbars and 900 cps in the test section was then propagated up the tube in a direction contrary to fluid flow. This frequency and SPL were chosen

as that combination easily propagated with minimal distortion as shown in Table I.

The frequency spectrum level of the turbulence output was then recorded in the same manner as above for the flow without sound, Fig. 11. By comparing Fig. 10 and Fig. 11 it can be seen that the magnitude of turbulence at lower frequencies is drastically changed by the sonic disturbance. It may also be noted that except for the sound harmonics above 1000 cycles per second the two figures are essentially the same. It was therefore determined that no critical turbulence data would be lost if frequencies above 1000 cps are ignored in further investigation.

To facilitate the taking of data, the very convenient Brüel and Kjaer Audio Frequency Spectrometer (one-third octave band), Type 2110, was used in conjunction with a B & K Level Recorder, Type 2304, Fig. 5, to obtain an automatic recorder trace of the magnitude of the rapidly varying turbulence output as a function of frequency band. These instruments produced traces as shown in Fig. 12. These recorder traces of the turbulence output for "sound" and "no sound" conditions at position 1 on the axis may be compared with the spectrum levels for the same conditions, Fig. 10 and Fig. 11. It may be seen that the spectrum level determined from the third octave trace is the same as the spectrum levels obtained from a narrow band instrument. It was therefore determined that the time and effort this instrumentation saved more than justified the loss of some frequency information due to use of wider band pass.

The B & K Level Recorder was calibrated to reflect the magnitude of turbulence output in decibels with respect to a standard turbulence output of 10 millivolts. This output was simulated by use of a signal generator for calibration of the system. The third octave recorder traces obtained in this manner can reflect changes of turbulence output of up to

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50 decibels re 10 millivolts turbulence. The turbulence output, however, is an inherently random, rapidly varying signal as seen by Fig. 12. In order to plot data produced in this manner, a method of averaging is required. A rather crude but effective method of averaging the magnitude of the signal in a given band was used: One of the authors would closely view the trace and without viewing plotted results would average the signal. Periodic checks were made by the other author to ensure that they agreed on the average given. It is felt that even with the above precautions that the third octave data obtained can be considered to contain errors of plus or minus one decibel. A certain amount of daily variation or data scatter was observed. This variation may have been caused by temperature or other unmeasured parameters, but they were most likely caused by the inherently unstable, random character of turbulence in a pipe.

Single number data. It can be seen by examining the third octave band and spectrum level curves for a "no sound" condition, Fig. 10 and Fig. 13, that most of the turbulence is contained in the band of frequencies below 300 cycles per second. It may be seen by examination of data taken at the same velocity and position but with sonic disturbance added, Fig. 11 and Fig. 13, that most of the effect of sound, other than that caused by the particle velocity at the frequency of the sound, also occurs below a frequency of 300 cycles per second. Since it was desired to obtain a single number to describe the reduction of turbulence, it was decided that a valid procedure would be to eliminate all turbulence frequencies above 300 cycles and limit the frequency of sonic disturbance to frequencies higher than 300 cycles.

From this point the phenomenon of turbulence reduction is described by specifying the turbulence output between 300 and 20 cycles per second. The lower limit is due to the characteristics of the B & K Level Recorder. Data obtained over this range shall be referred to as "300 low pass data". This 300 low pass data is obtained by inserting a Pacific Instrument Half-Octave Filter Set, which has a 300 cps low pass mode, and necessary impedance matching amplifiers into the electronic system before the level recorder as shown in Fig. 5.

The filter section of the B & K Audio Frequency Spectrometer may be taken out of the system to leave only the Spectrometer's amplifier in the circuit by throwing one switch. This allows the selection of either third octave or 300 low pass data by throwing two switches, one on the Pacific Filter Set and one on the B & K Spectrometer. This procedure allows both types of data to be taken on the same level recorder trace and therefore allows utilization of the same averaging procedure for either type data.

5. The effect of high intensity sound upon incoming turbulence.

The results of the investigation of the effect of high intensity sound on turbulence will be discussed as follows:

1) The effect of sound on the spectrum of turbulence using narrow band and one-third octave band techniques.

2) The effect of sound on turbulence as characterized by 300 cps low pass filter techniques.

3) Turbulence reduction as a function of distance from the entry.

4) Velocity and percent turbulence profiles with and without sound.

5) Miscellaneous observations.

Much of the data to be discussed was obtained at test position one on the duct axis with a mean flow velocity of 6.8 meters per second; exceptions will be noted. It is felt that these conditions typify the flow characteristics of the duct and the results are therefore of general applicability, as discussed in the Measurements section.

Turbulence spectra. The general effects of sonic excitation upon the turbulence spectra are: (1) to reduce that portion of the turbulence which is below about 300 cps, (2) to slightly increase or not affect the turbulence above 300 cps, (3) to produce large spikes attributable to the accoustic particle velocity at the frequency of sonic excitation, and (4) to have no measurable effect upon the turbulence above 1000 cps. The first two effects result in a general flattening of the turbulence spectrum below 1000 cps except at the sonic frequency. The last characteristic allows all the significant aspects of the problem to be determined by measurements taken below 1000 cps.

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The one-third octave turbulence spectra for test position one on axis, Fig. 13, exhibits the same characteristic as the narrow band spectra of Fig. 10 and Fig. 11. When a sonic disturbance is introduced, for example at 900 cps and 120 db, the effect is to reduce the level of the turbulence below the 320 cps band. There is little effect upon the spectrum above the 320 cps band except for the spike at the sound frequency of 900 cps which has a maximum amplitude of -7 db re 10 millivolts.

The amount of turbulence reduction is a function of both the frequency and the sound pressure level of the sonic disturbance. Fig. 14 shows the effect of varying SPL at a constant frequency, 900 cps. One can see that, in general, as the SPL increases the low frequency components of turbulence decrease while above the 300 cycle band the turbulence is either the same or slightly higher than the "no sound" spectra. The effect of sonic excitation was not detectable at SPL's below about 87 db which is approximately the background noise level in the duct. No investigations were made using this technique above 130 db. Fig. 15 and Fig. 16 depict the effect of varying the SPL parameter while holding frequency constant at 500 cps and 1400 cps respectively; these curves display the same characteristics as the 900 cps family of curves.

The effect of holding SPL constant and varying frequency is shown in Fig. 17. The turbulence spectra without sound and with sound of frequencies between 350 and 1800 cps are shown in this figure. Close examination of this figure reveals that there appear to be "cutoff" frequencies, both high and low, above or below which sound has no effect at a given SPL. In between these cutoff frequencies there is a frequency which has the maximum effect. This apparent optimization of sound frequency effectiveness is investigated further in the next section.

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The effect of sonic disturbance using 300 cps low pass filter. The effect of sonic excitation upon turbulence was investigated using the 300 cps low pass filter method described in the Measurements section. The results of this investigation are shown in Fig. 18 and Fig. 19. the ordinate of Fig. 18 is decibels reduction of turbulence from the "no sound" conditions; the 300 low pass in -5 db re 10 millivolts, which corresponds to an RMS turbulence velocity of approximately 5 cm per second (0 db reduction = -5 db re 10 millivolts).

Two regimes of effect appear in Fig. 18. The region below SPL's of approximately 120 db shows that turbulence reduction is related in a very complicated manner with sound frequency and sound pressure level. As SPL approaches 120 db the reduction is approximately proportional to sound pressure squared. At 120 db the acoustic particle velocity is approximately 5 cm per second; it appears therefore that as the acoustic partical velocity exceeds the turbulence RMS velocity the reduction of turbulence is proportional to the sonic intensity.

Constant reduction contours from Fig. 18 are shown in Fig. 19. The most effective (reduction) frequency is approximately 700 cps, as all other frequencies are less effective reducing incoming turbulence at the same SPL. As SPL is increased the contours become less curved, indicating less frequency dependence for a given reduction.

Turbulence reduction as a function of test position. In order to investigate the phenomenon of the interaction of sound and turbulence more completely, parameters other than frequency and SPL were varied. Holding mean flow velocity and vertical position constant at 6.8 meters per second and on axis respectively, the distance from the entry was

varied and effect of sonic excitation observed.

Fig. 20 and Fig. 21 depict the results obtained when test position is varied. The on-axis turbulence with no sound is essentially constant at -5 db *re* 10 millivolts. A general trend toward less reduction is noted as X, the distance from the entry, increases.

One striking characteristic of these curves is the presence of numerous sharp break points. For example, in Fig. 20c there is a sharp break between test positions 3 and 4 for both the 140 and 120 db curve. It will be noticed that as SPL decreases the break point moves toward the entry. This same characteristic is also noticeable in Fig. 20b. Fig. 21b and Fig. 21c exhibit similar characteristics as frequency varies at constant SPL. These breaks indicate that the distance to which the sound affects the flow is a function of both SPL and sound frequency.

Velocity and percent turbulence profiles with sound. Velocity profiles were taken with a sound disturbance of 700 cps at 140 db as well as without sound (discussed in Preliminary studies, see Figs. 6, 7, and 8). No significant deviation was observed.

Fig. 29 shows the 300 low pass turbulence profiles obtained at test positions 1 and 3. The percent turbulence figures were obtained by converting the 300 low pass turbulence in decibels to volts to obtain a 300 low pass voltage which was then used in the equation

$$\text{percent turbulence} = \text{Vrms}\ \frac{100\ 4V}{V_o^{\ 2} - V^2}$$

as previously discussed.

The percent turbulence profiles have the same general characteristics as the overall percent turbulence of Figs. 6, 7, and 8 except of course they are scaled down since they include only that portion of the turbulence spectra between 20 and 300 cps.

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When sound is introduced into the duct main flow, the axial and background turbulence are both reduced to the same low amount (less than 0.06 percent turbulence), see Fig. 22, while no clear effect is observed in the boundary layer.

Miscellaneous observations.

Siren as a sound source. Attempts were made to extend the data of Fig. 18 and Fig. 19 to SPL's above 140 db using a siren as a sound source. This siren had been used in previous investigations and SPL's of about 169 db were obtained. Due to finite amplitude progressive wave distortion, mild shock waves were observed in the test duct. Two factors rendered the siren investigation inconclusive: A great deal of noise was radiated by the siren, and mounting the siren required changing the hydrodynamic and acoustic characteristics of the duct.

Sound propagating downstream. The speaker was placed at the inlet to the test duct with essentially the same results as with the sound directed contrary to the wind flow direction. However, due to the poor acoustic termination of the downstream end of the tube, no exact measurements were possible. At all frequencies tried from 300 to 1300 cps and at all SPL's from 100 db to 130 db, the on-axis turbulence at test position one was reduced by approximately the same amounts as when the sound source was in its designed location. However, it must be emphasized that the poor acoustic termination undoubtedly resulted in a strong standing wave being present during these measurements.

Pressure as a function of X. Attempts to measure pressure differentials between test positions using pitot static tubes were inconclusive due to the very high inertia of the pitot static equipment used. Although some

[illegible]

variations were noted, they were very random in nature with a mean of zero change in pressure over all lengths of the duct investigated.

Turbulent spots in transition zone. The transition from laminar to turbulent flow is characterized by the appearance of spots of turbulence. It was qualitatively observed that the area in which a given number of spots of turbulence per unit of time occurs is moved downstream when a sonic disturbance was initiated. This effect was noted between test positions 3 and 4 when the same intermittency characteristics observed in position 3 without sonic excitation appeared in test position four. No quantitative data pertaining to the effect was successfully taken, but it is felt that the movement of the transition area is real and significant.

6. Conclusions and summary.

The results described in the preceding sections indicate that high intensity sound does reduce that portion of the turbulence spectrum below 300 cps in the entry region of the duct. The effect may be essentially divided into three regions: the boundary layer, the axial turbulence, and the off-axis turbulence.

Effect in the boundary layer. It may be seen from Fig. 18 that the turbulence contained in the boundary layer is not affected a measurable amount and therefore appears to have no dependence on frequency or sound pressure level over the range of the experiment. It is not unreasonable to predict that further investigation with an anemometer which is sensative to very small fluctuations of velocity might very well show that a measurable effect does occur in the boundary layer; in fact, it is difficult to visualize a phenomenon which would drastically reduce the turbulence in the air entering the duct without affecting the turbulence in the boundary layer itself.

Effect on the axial turbulence. The on-axis turbulence is reduced about 20 db to 0.06 percent at position one and less as the background increases, as seen when the test position is changed, Fig. 22. This reduction is dependent on frequency and sound pressure level: the reduction is optimized at 700 cps and increases with increasing SPL; if the SPL is decreased or the frequency changed, the magnitude of the reduction decreases. The general effect of sound on turbulence is that reduction varies with pressure to the second power over the range of the experiment, Fig. 18.

Effect on the off-axis turbulence. At a frequency of 700 cps and SPL of 140 db, the turbulence in the region located between the axis and the boundary layer is reduced about 14 db by the sonic disturbance. No

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generalizations pertaining to the effect or relationships between the axial turbulence and the off-axis area can be made on the basis of these observations.

General observations. The region in which a maximum amount of turbulence reduction occurs is seen to be moved downstream as sound frequencies nearer to the optimum (700 cps) are chosen and as SPL is increased, Fig. 20 and Fig. 21. It also has been qualitatively observed that the region in which spots of turbulence occur, i.e., the transition area, was moved downstream under the effect of sonic excitation.

It appears that the sonic disturbance in the range studied reduces the magnitude of the turbulence in the incoming flow but does not affect the mass flow in the duct and does not influence the velocity profile. It is therefore concluded that the mechanisms of transition and their means of control in pipes remain essentially unknown but that turbulence in the free stream is reduced by the employment of sonic excitation of the appropriate frequency and sound pressure level.

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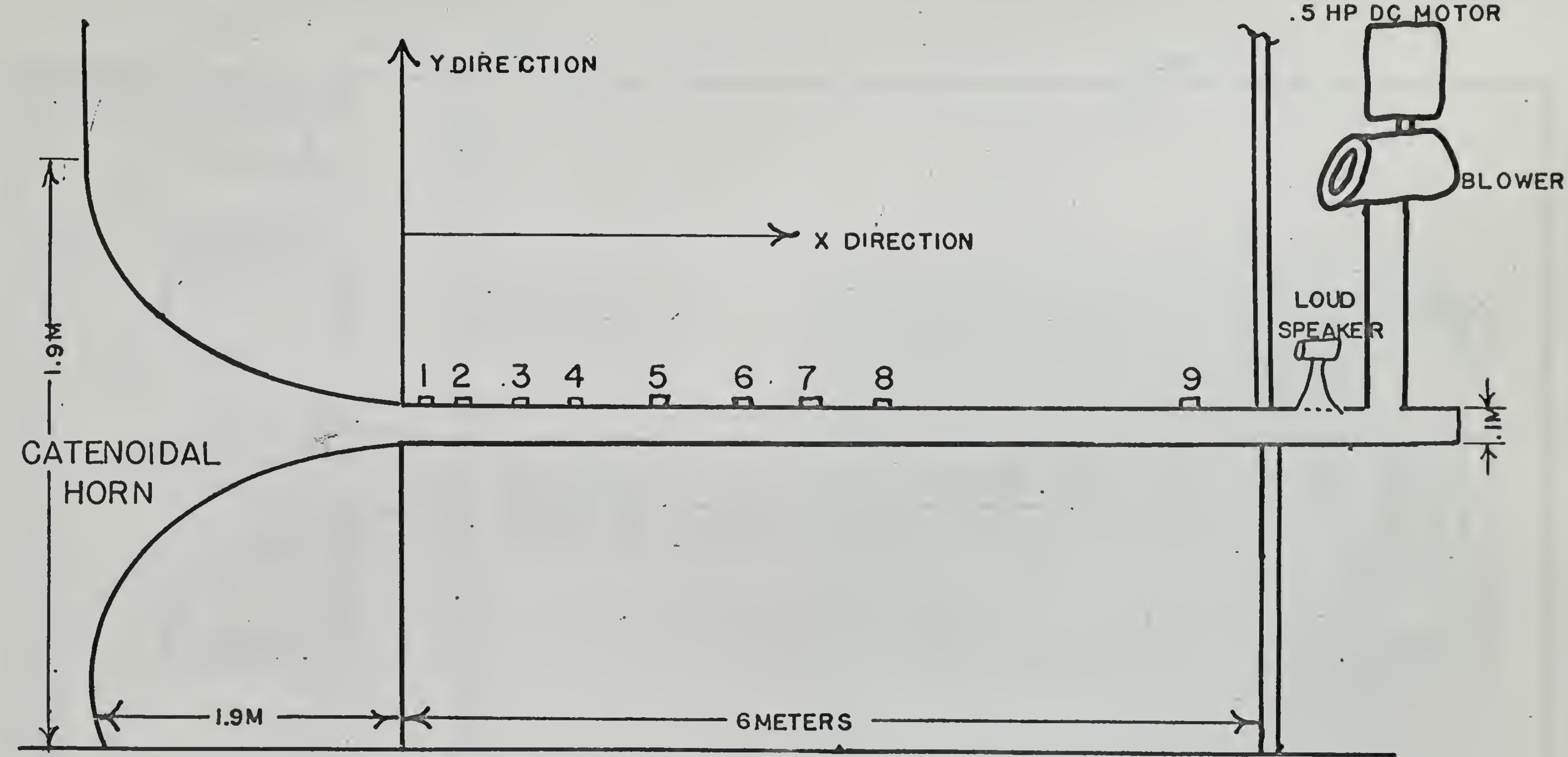
Frequency in cycles per second	Sound Pressure Level of Fundamental in db *re* 0.0002 microbar	Sound Pressure Level of Second Harmonic in db
500	100	53
500	110	72
500	120	92
500	135	120
700	100	53
700	110	68
700	120	87
700	140	126
900	100	35
900	110	64
900	120	88
900	135	116
900	140	125
1400	100	42
1400	110	58
1400	120	82
1400	140	122

TABLE I

Second Harmonic Content of Plane Sound Waves Propagated in Tube with Fluid Velocity = 0



SCALE
HORIZ. : 1" ≈ 1 METER
VERT. : 2" = 1 METER

FIG. 1 SKETCH OF TEST DUCT, AND BLOWER ARRANGEMENT

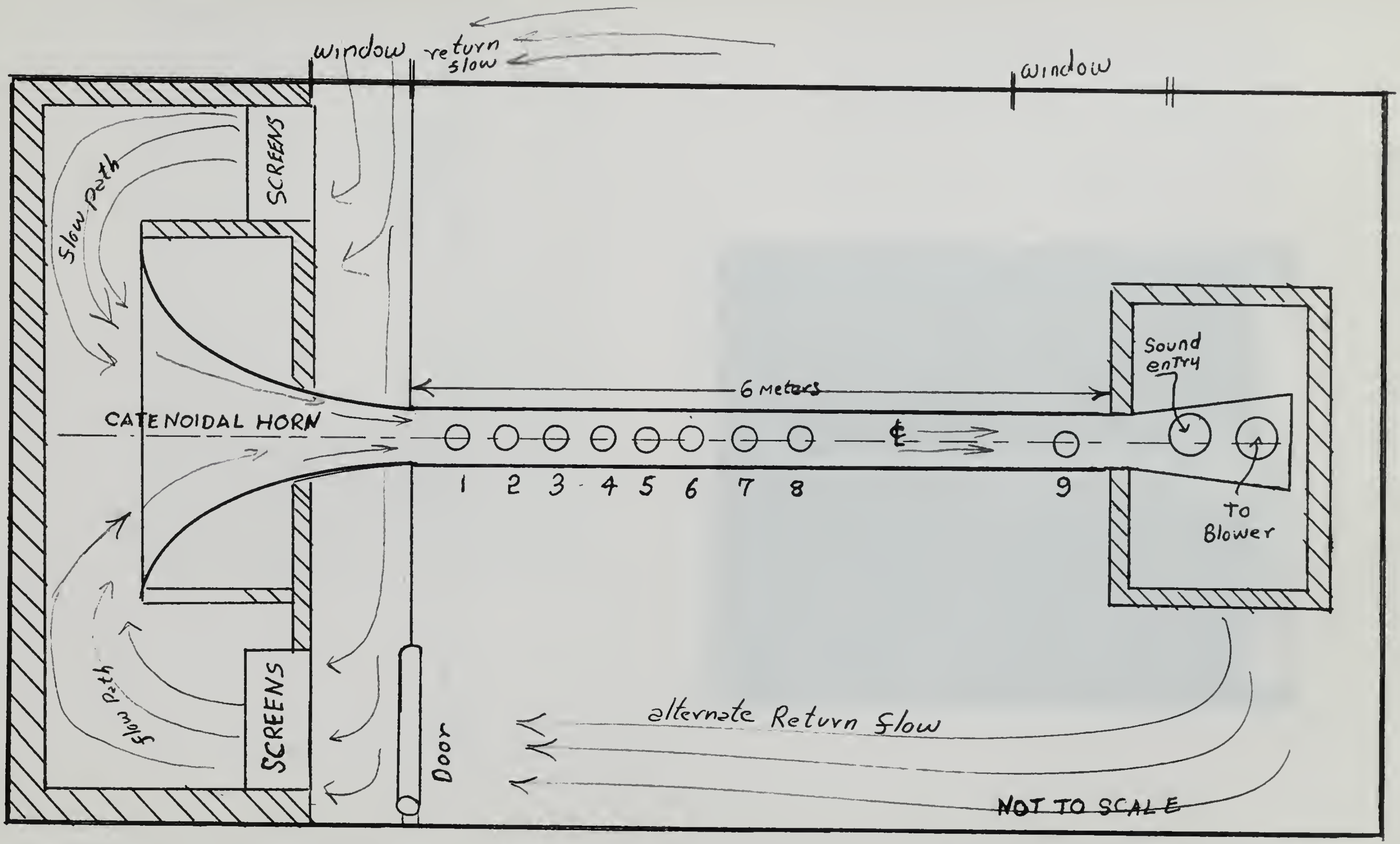


FIG.2 GENERAL ARRANGEMENT OF TEST DUCT

FIG. 3 MINIATURE HOT WIRE PROBE WITH 5 MICRON DIAMETER WIRE MOUNTED

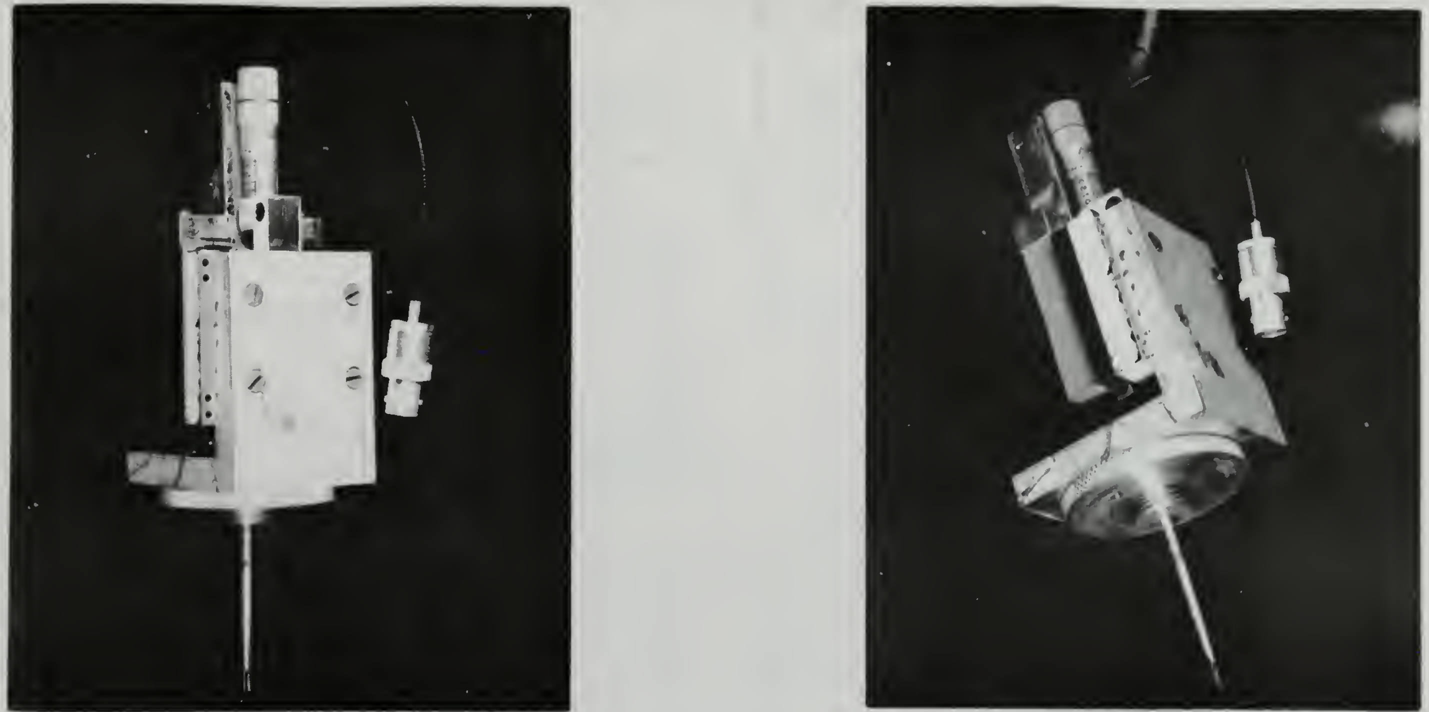


FIG. 4 HOT WIRE ANEMOMETER PROBE SUPPORT MOUNTING

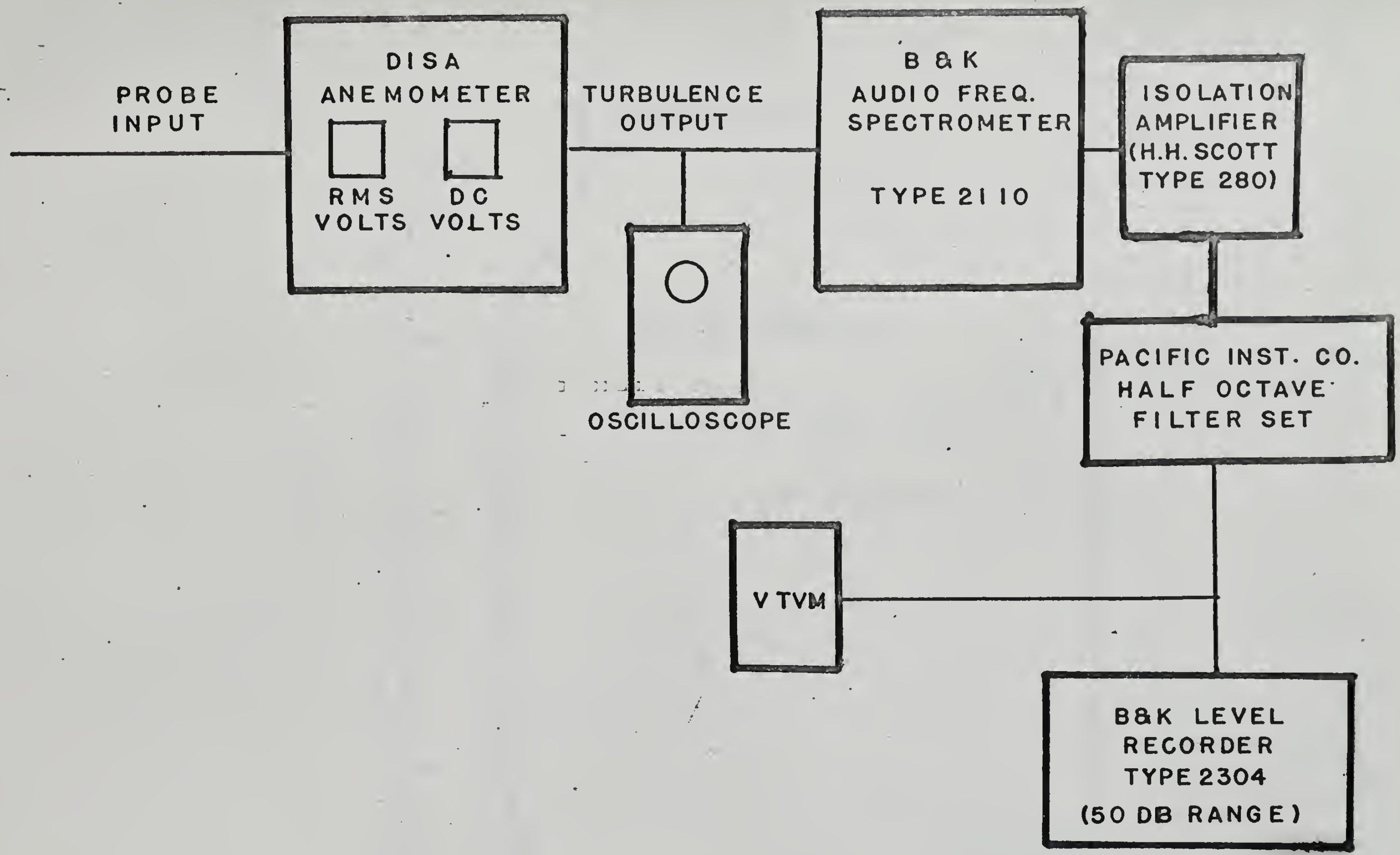


FIG.5 SCHEMATIC OF ELECTRICAL CIRCUITRY

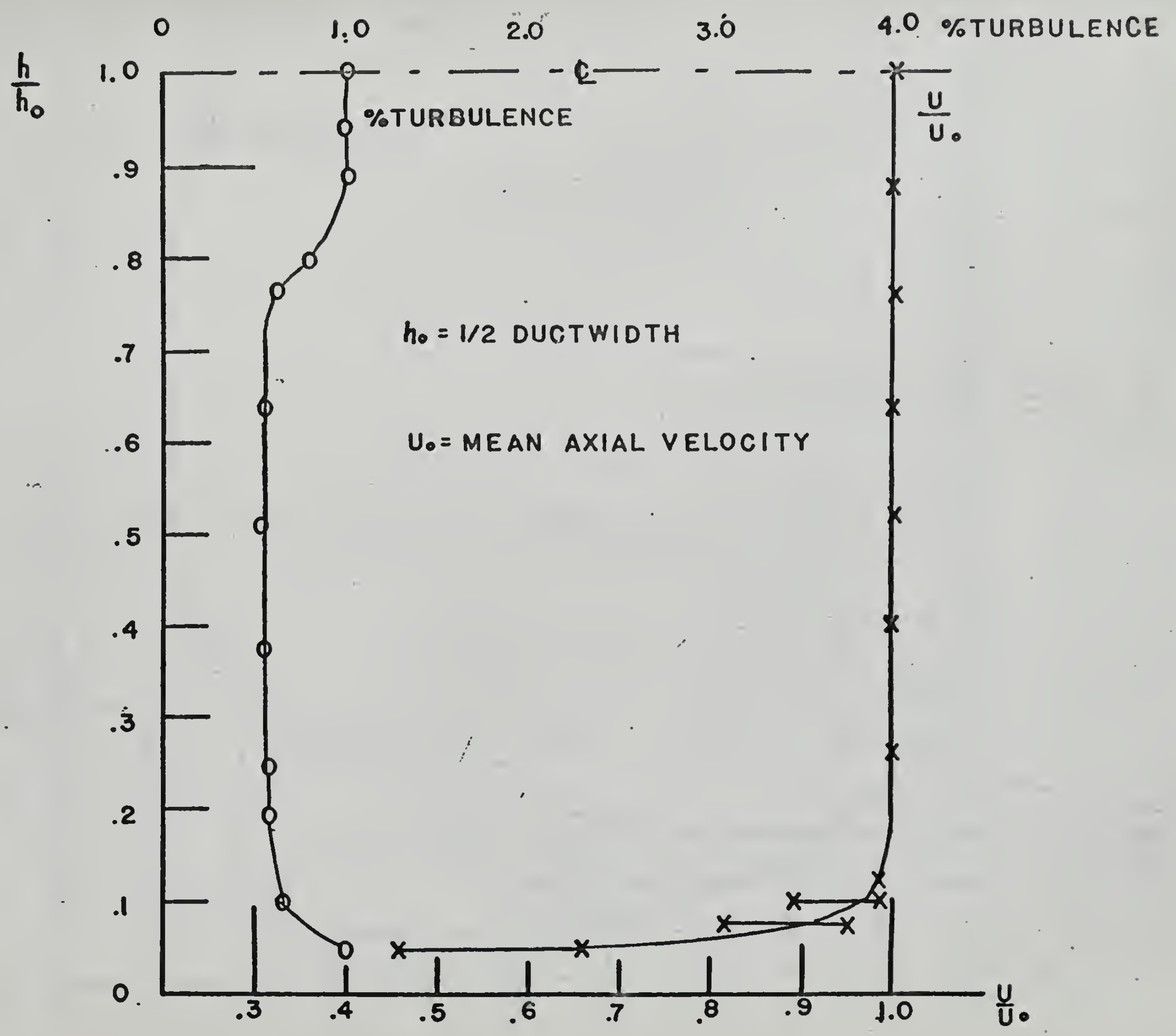


FIG. 6 TURBULENCE AND VELOCITY PROFILES AT TEST POSITION ONE

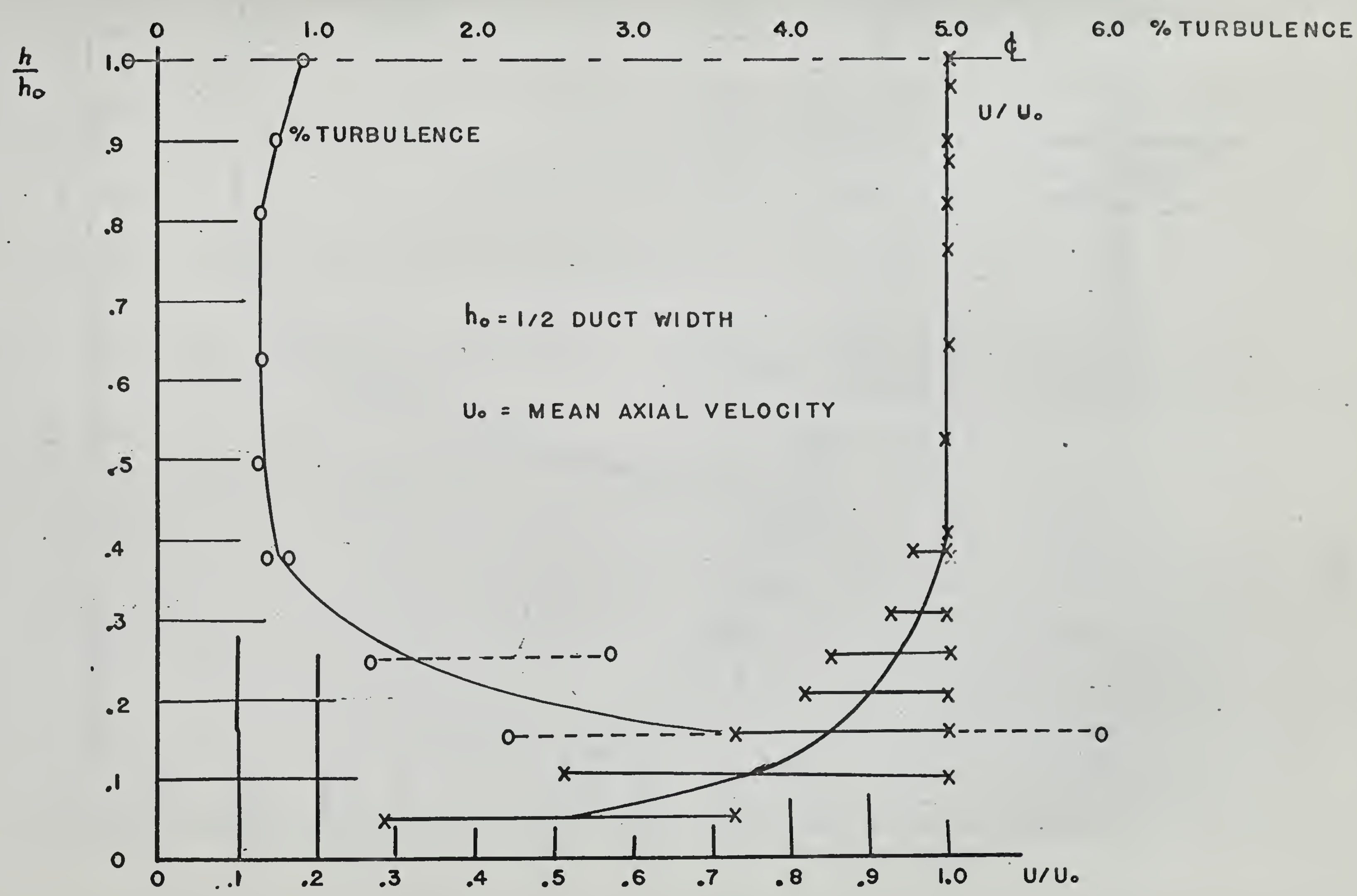


FIG. 7 TURBULENCE AND VELOCITY PROFILES AT TEST POSITION THREE

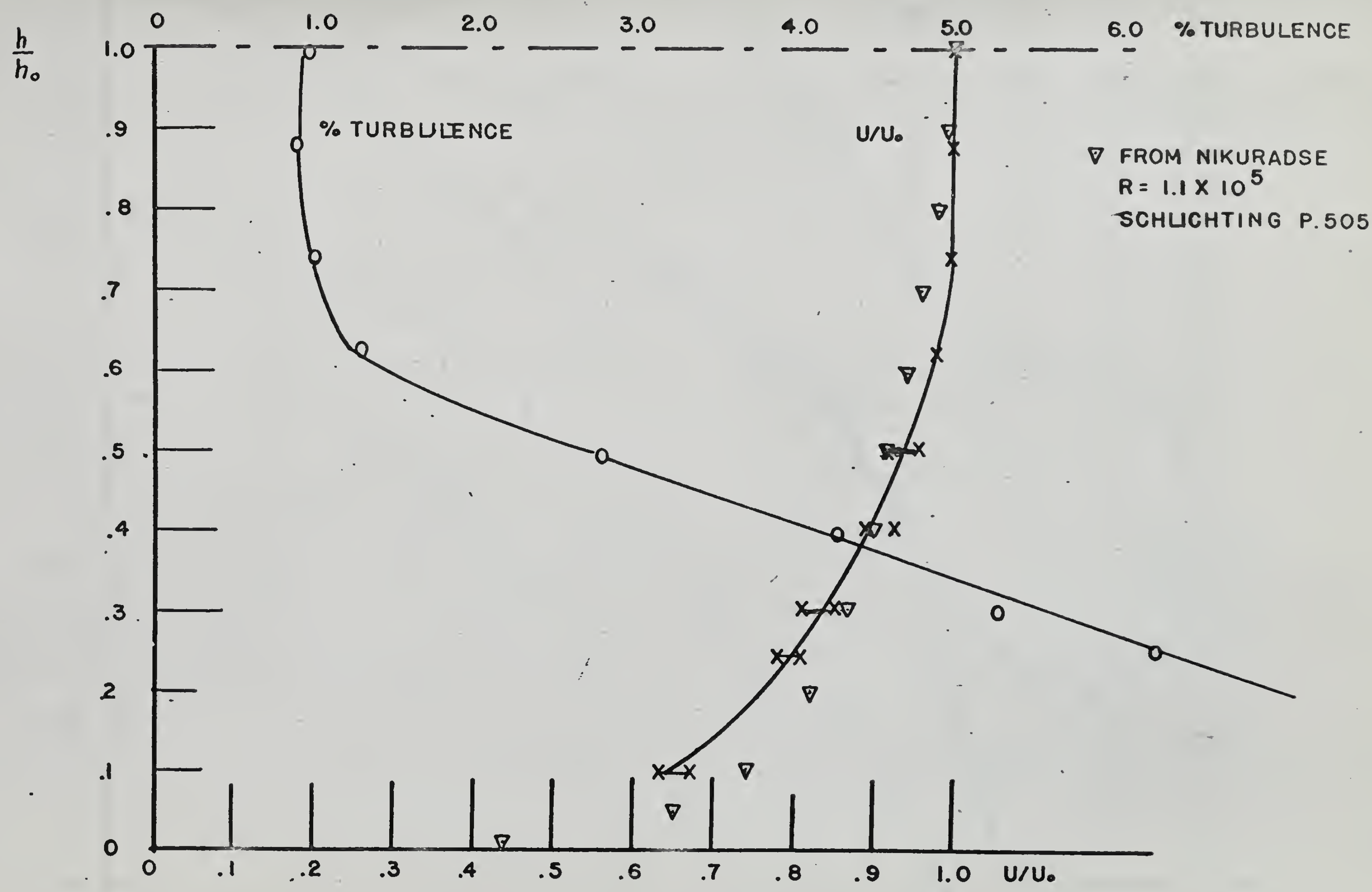


FIG. 8 TURBULENCE AND VELOCITY PROFILES AT TEST POSITION SIX

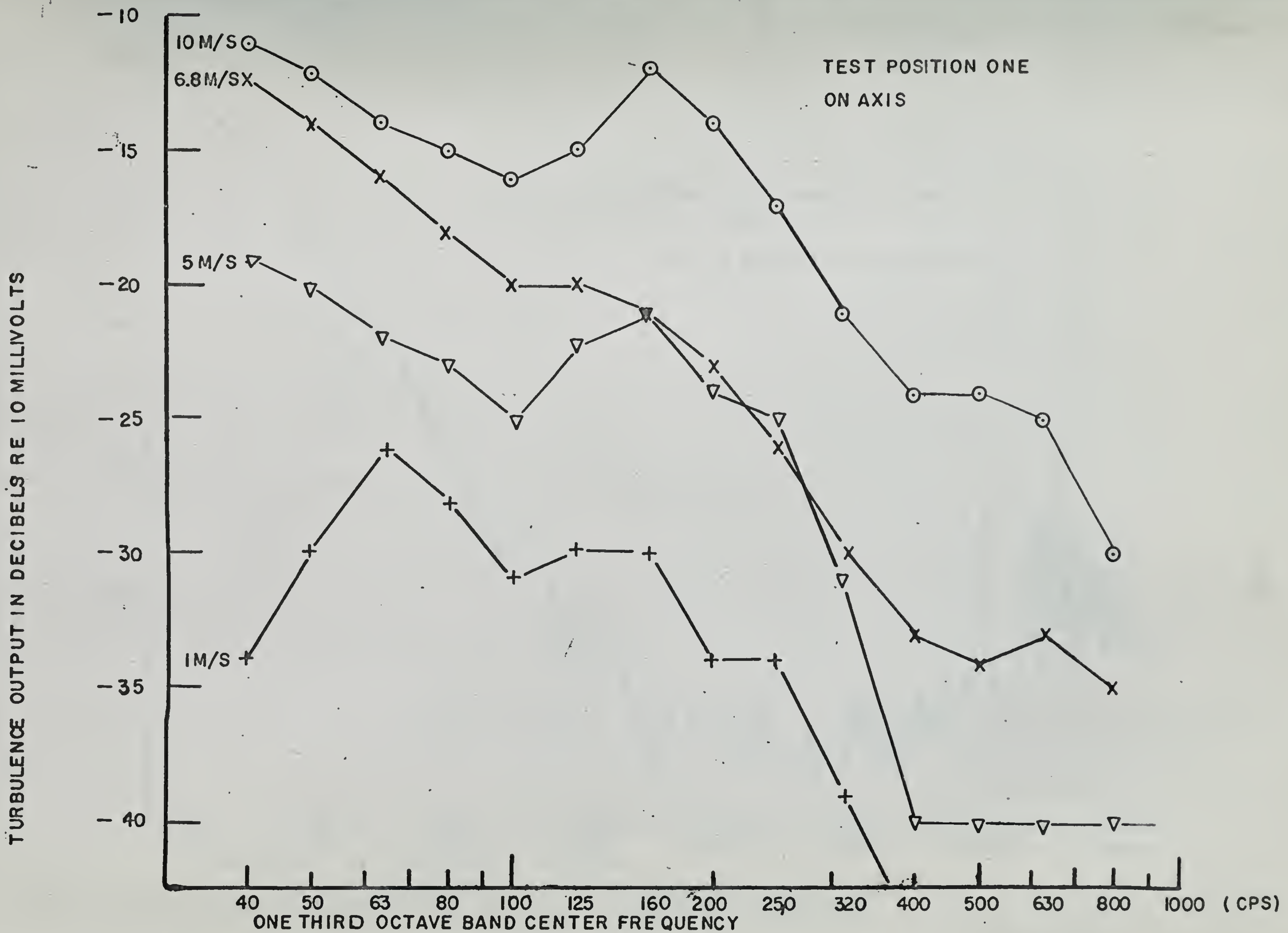


FIG.9 TURBULENCE SPECTRA AT TEST POSITION ONE, VELOCITY VARIED

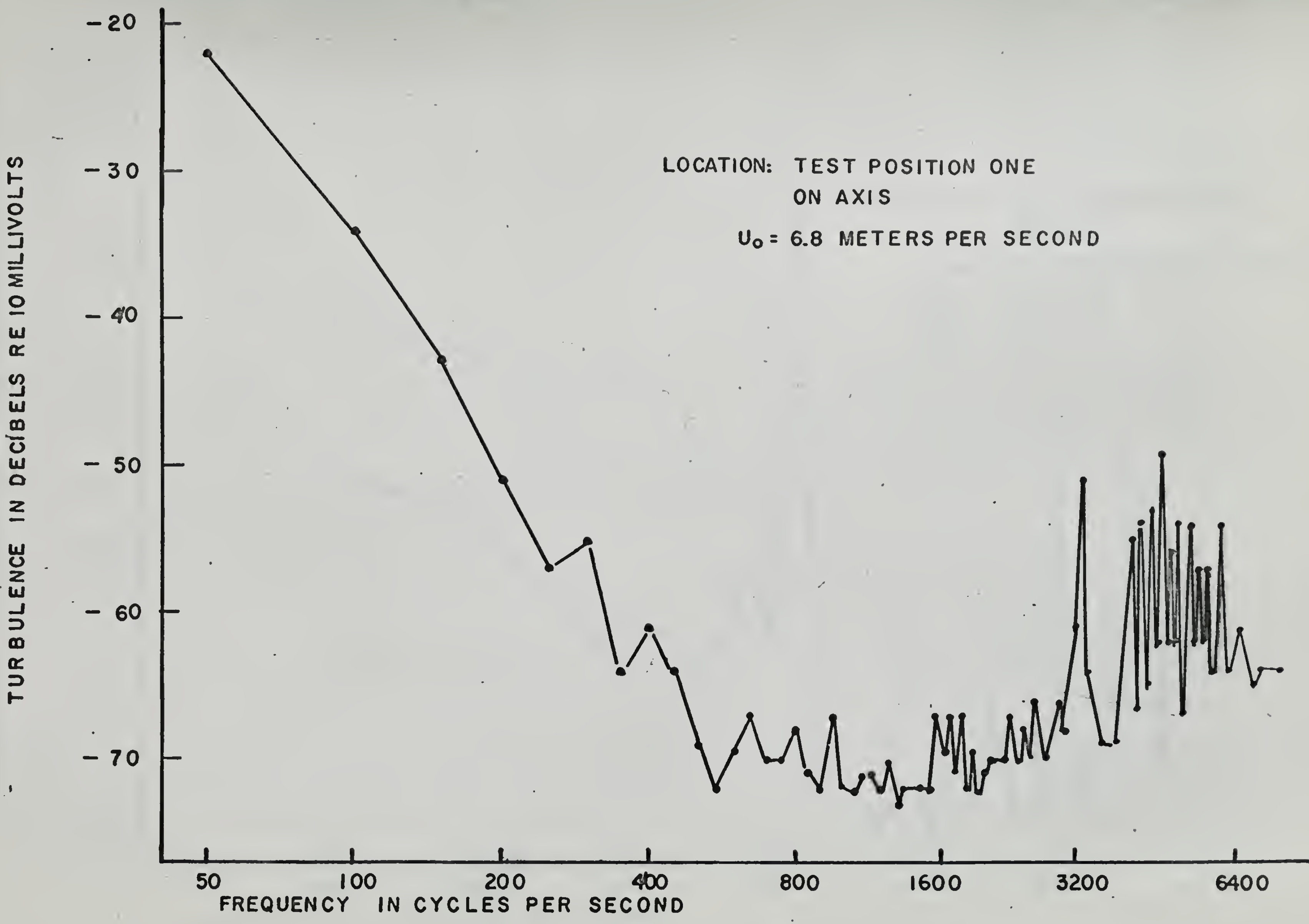


FIG. 10 SPECTRUM OF TUBULENCE WITHOUT SONIC EXCITATION

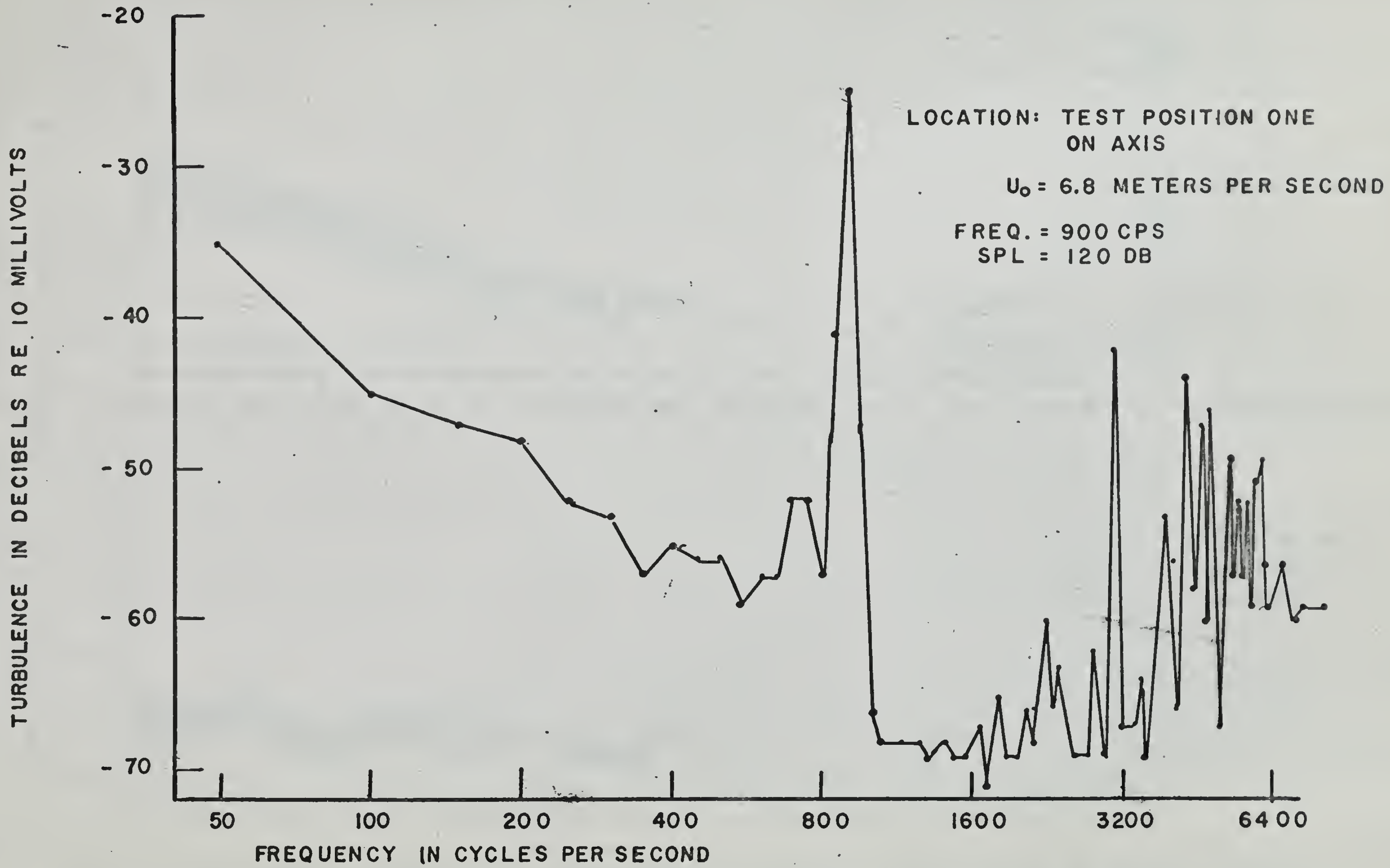


FIG.11 SPECTRUM OF TURBULENCE WITH SONIC EXCITATION

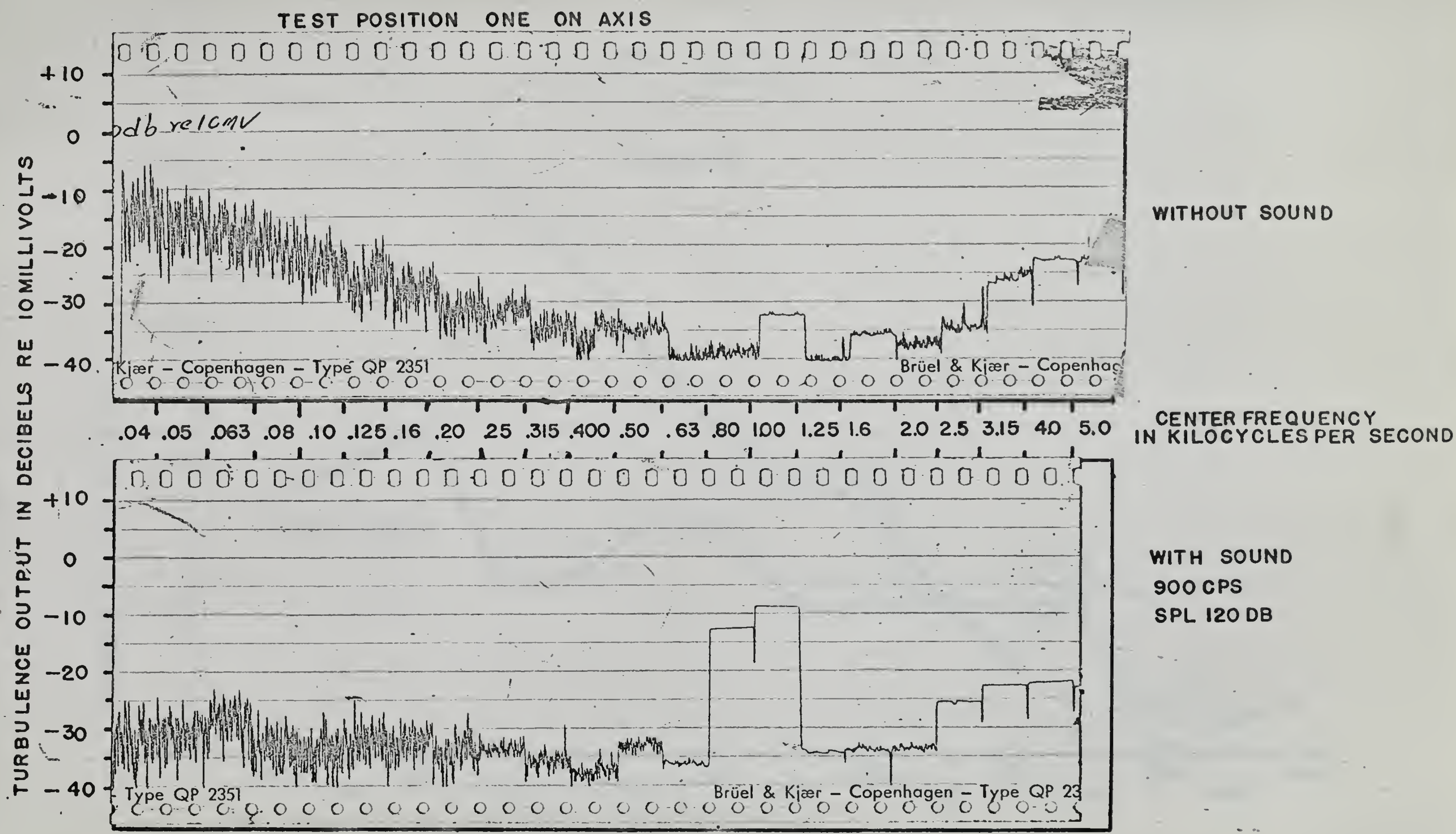


FIG. 12 RECORDER TRACES OF TURBULENCE OUTPUT WITH AND WITHOUT SOUND

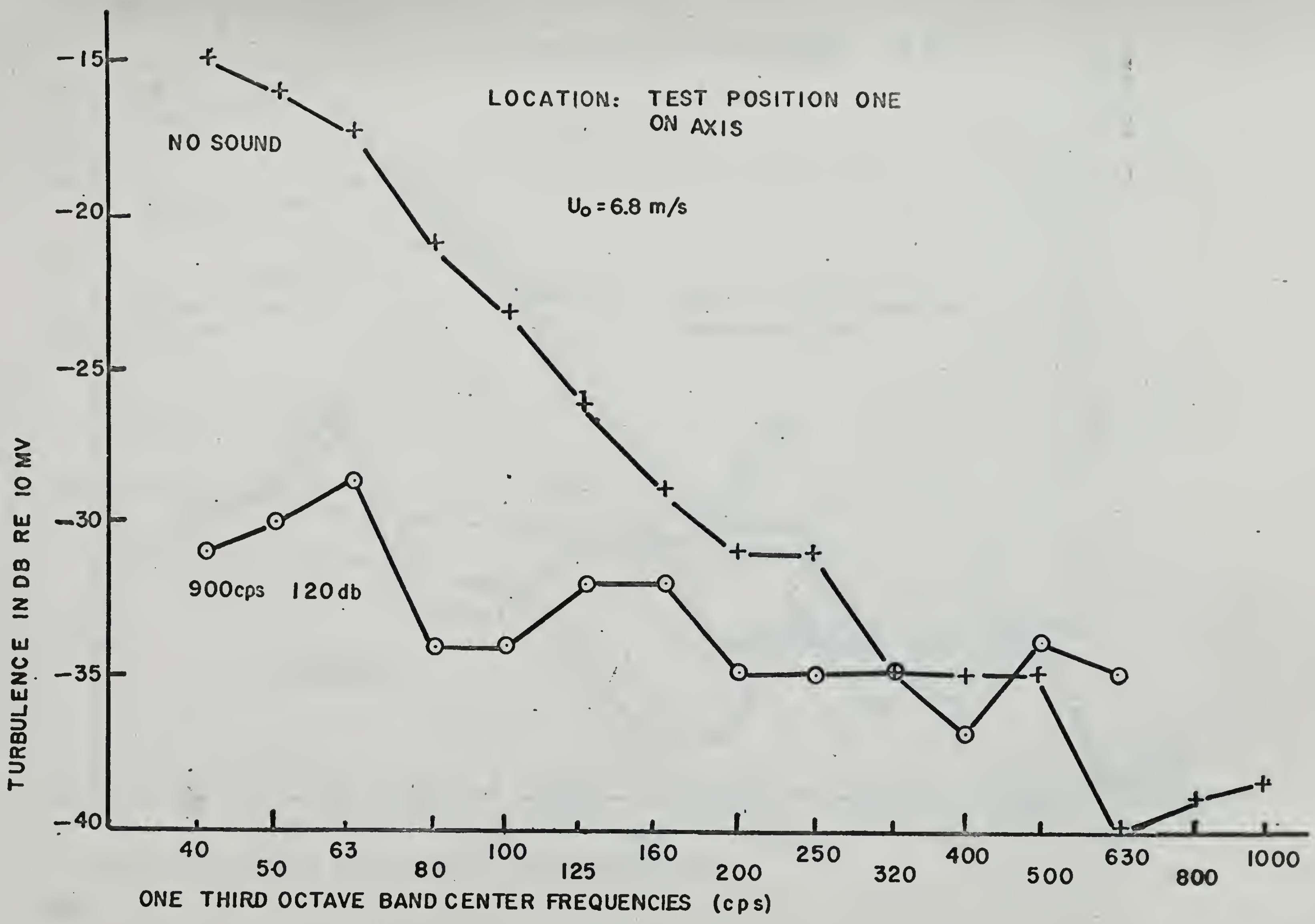


FIG.13 TYPICAL TURBULENCE SPECTRA WITH AND WITHOUT SONIC EXCITATION

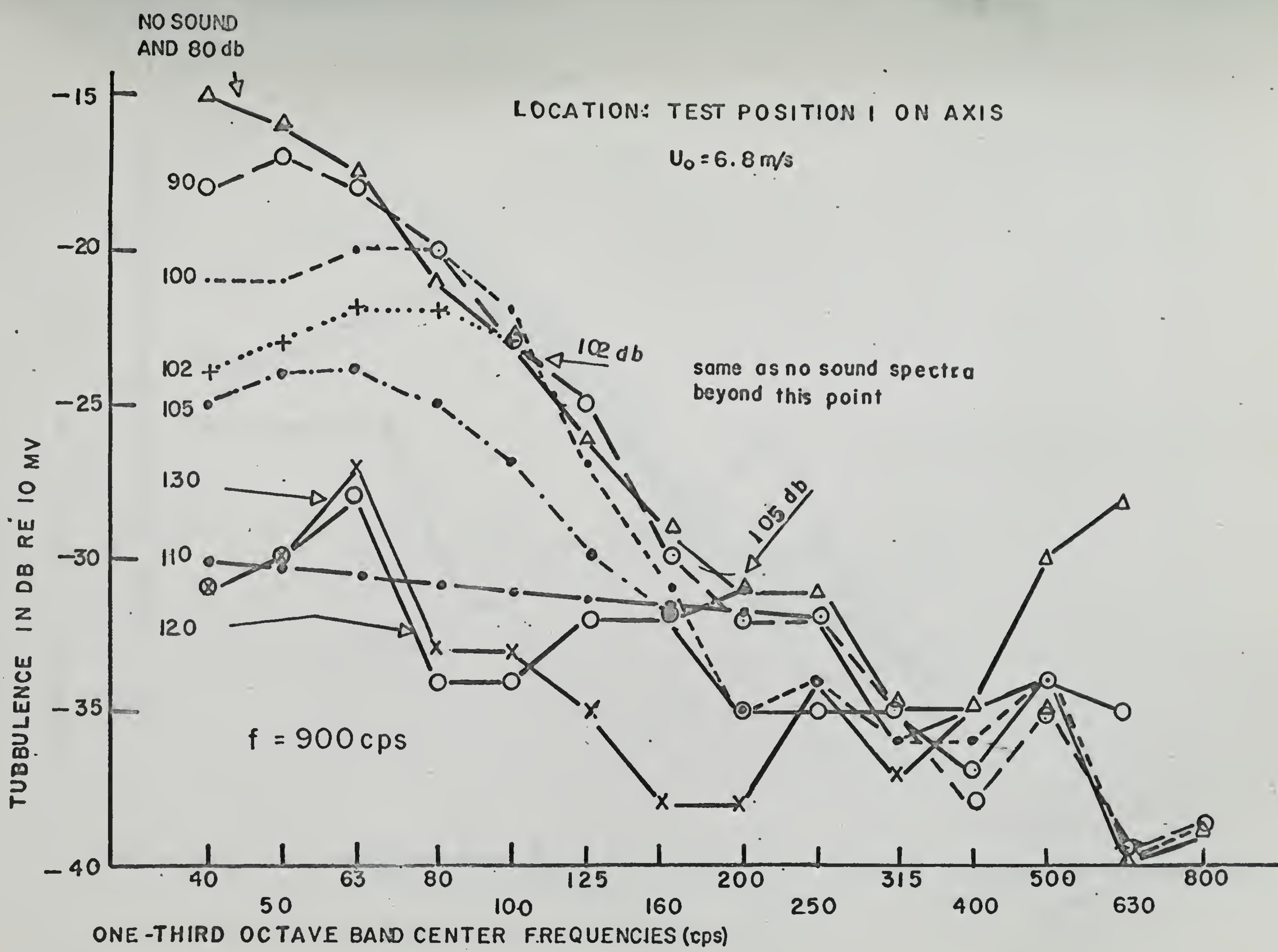


FIG. 14. TURBULENCE SPECTRA; SPL VARIABLE; FREQUENCY CONSTANT AT 900 CPS

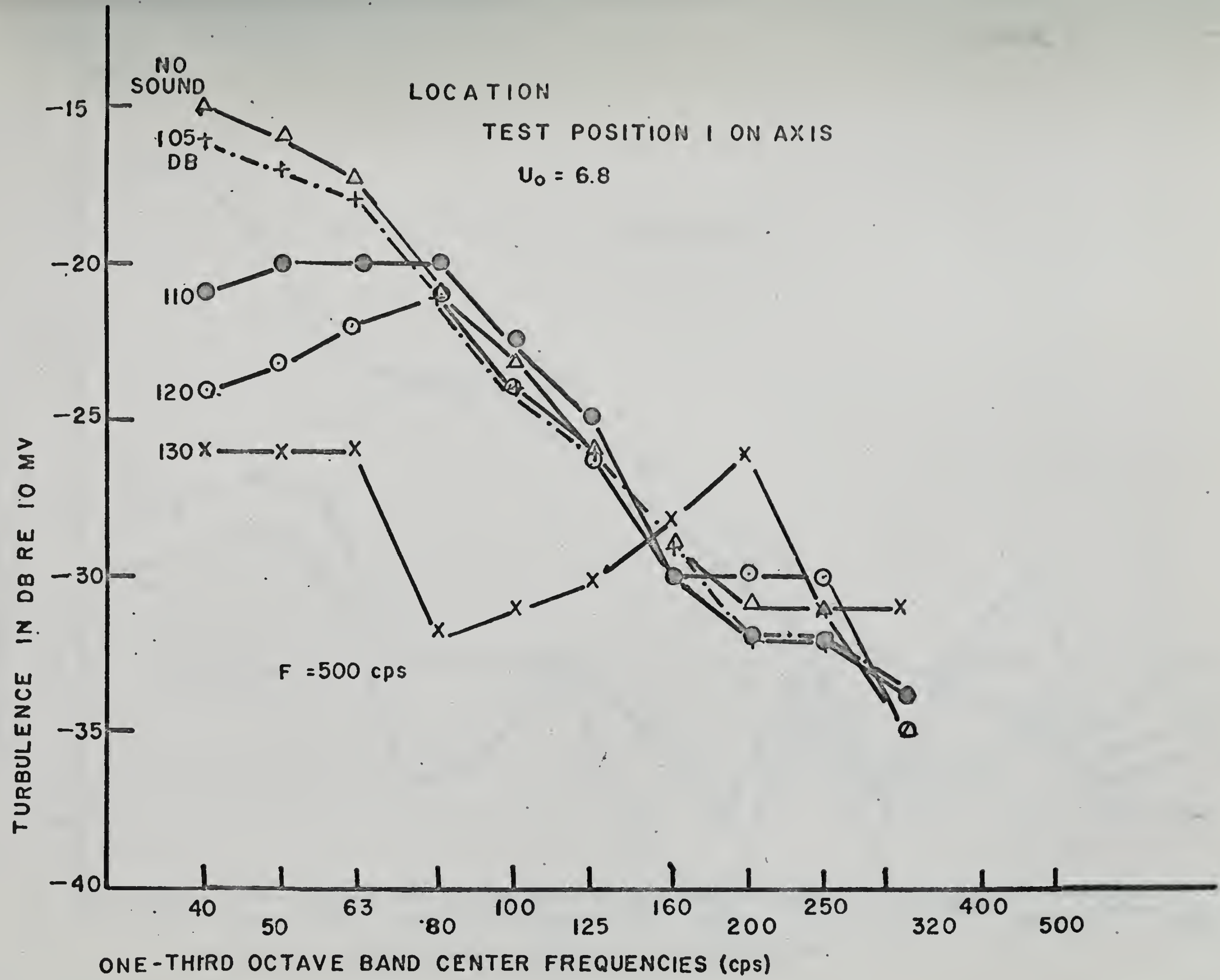


FIG 15 TURBULENCE SPECTRA; SPL VARIABLE; FREQUENCY CONSTANT AT 500 CPS

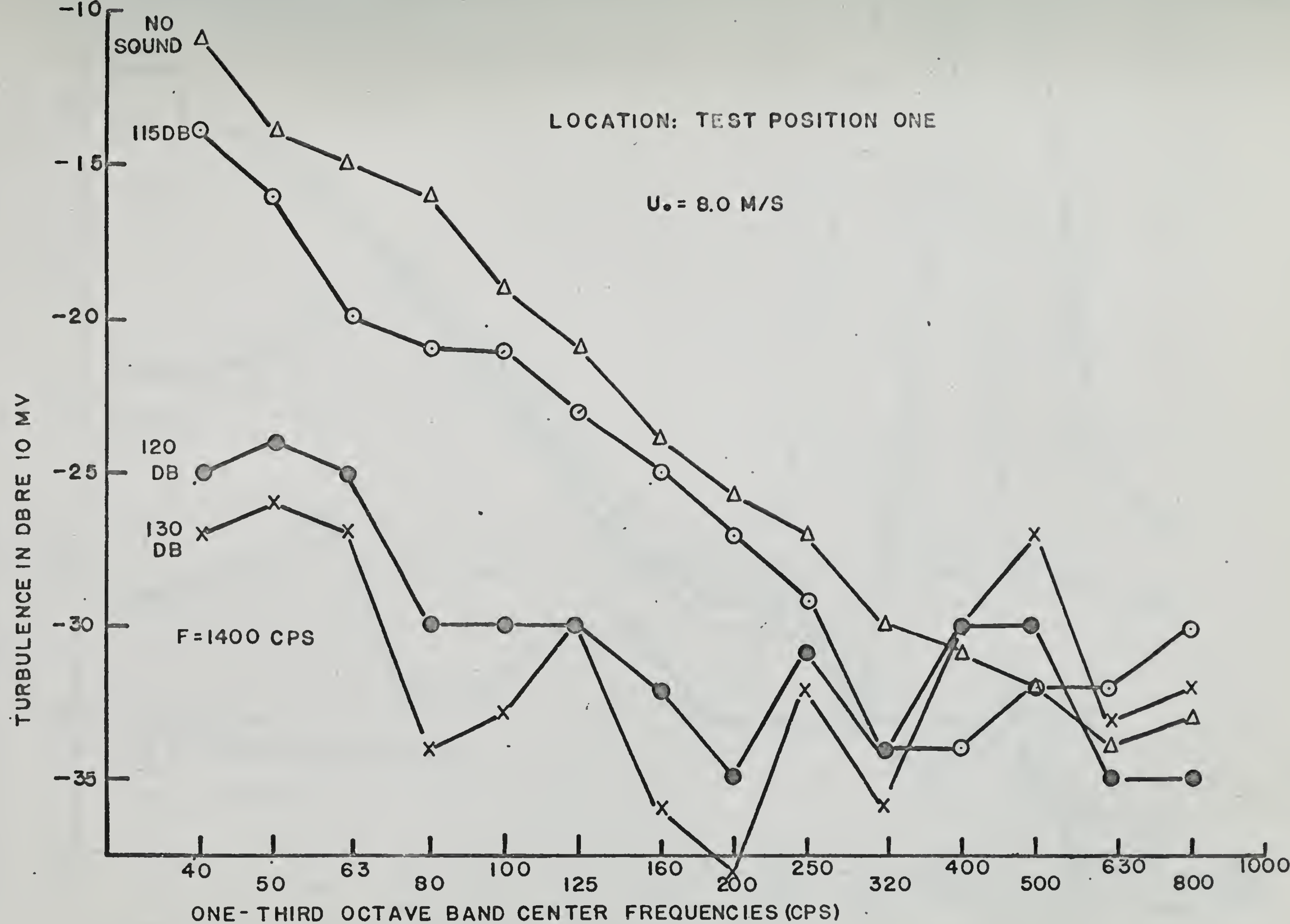


FIG.16 TURBULENCE SPECTRA; SPL VARIABLE; FREQUENCY CONSTANT AT 1400 CPS

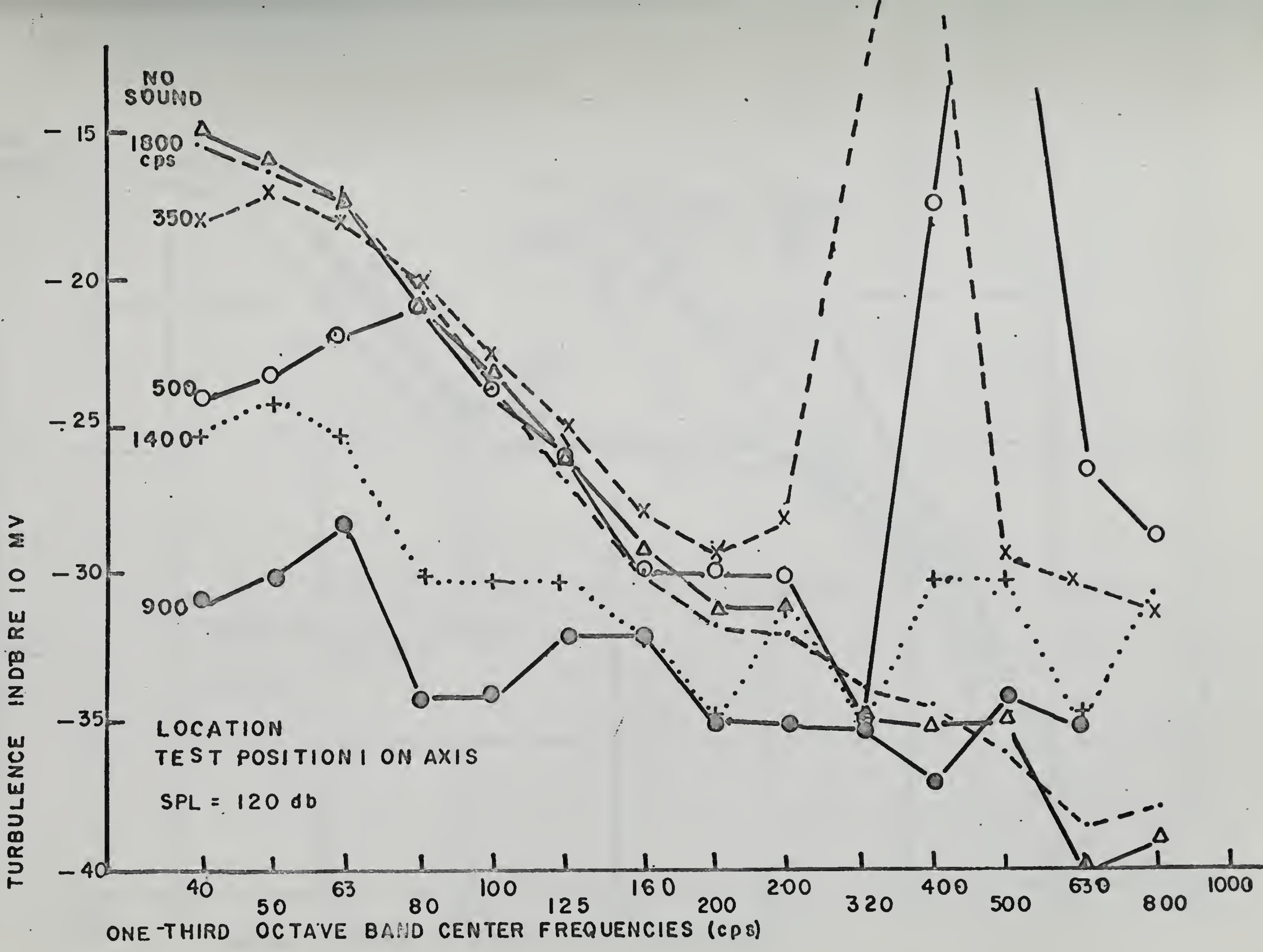


FIG.17 TURBULENCE SPECTRA; SPL CONSTANT; FREQUENCY VARIED

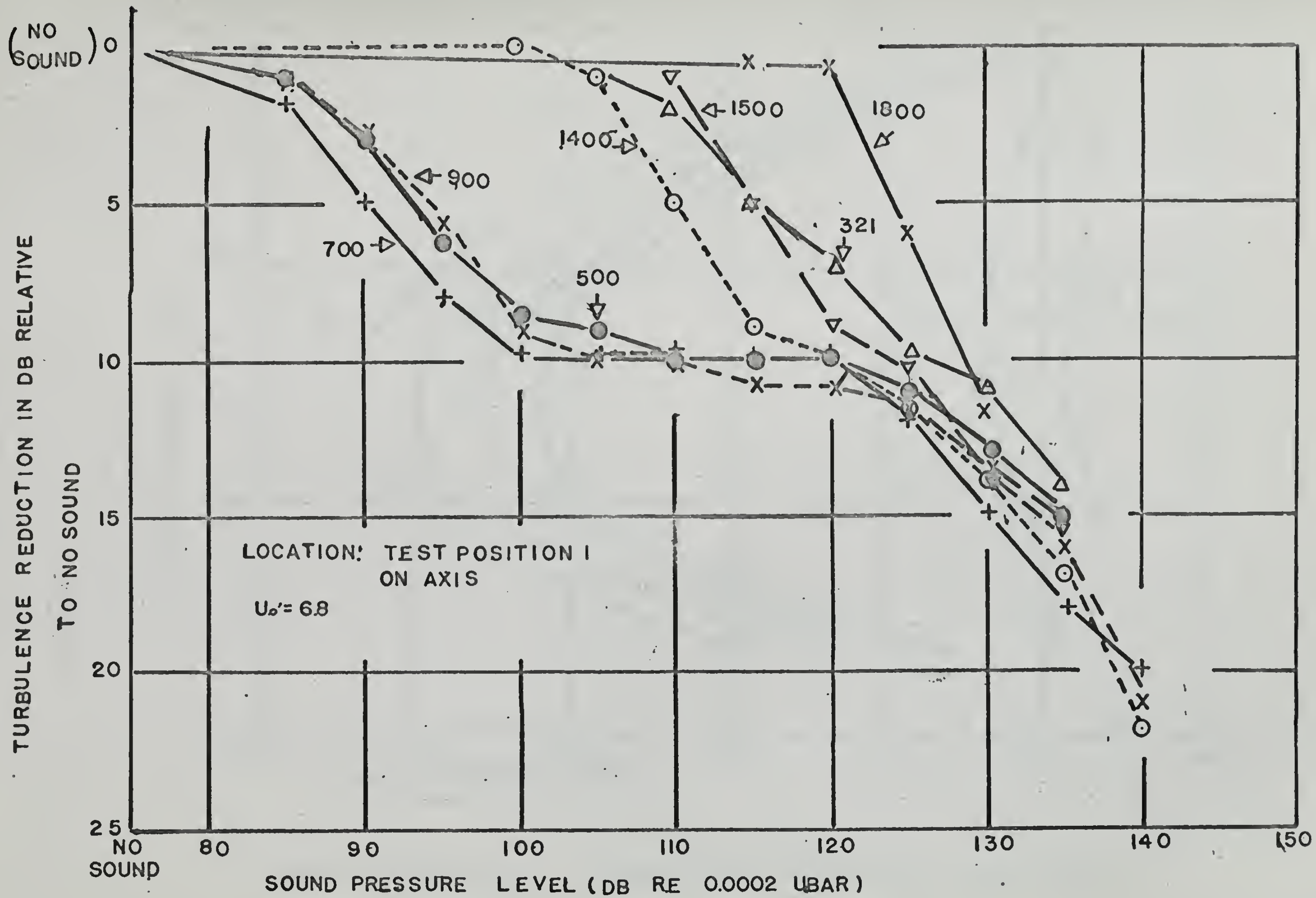


FIG.18 EFFECT OF SONIC EXCITATION UPON TURBULENCE

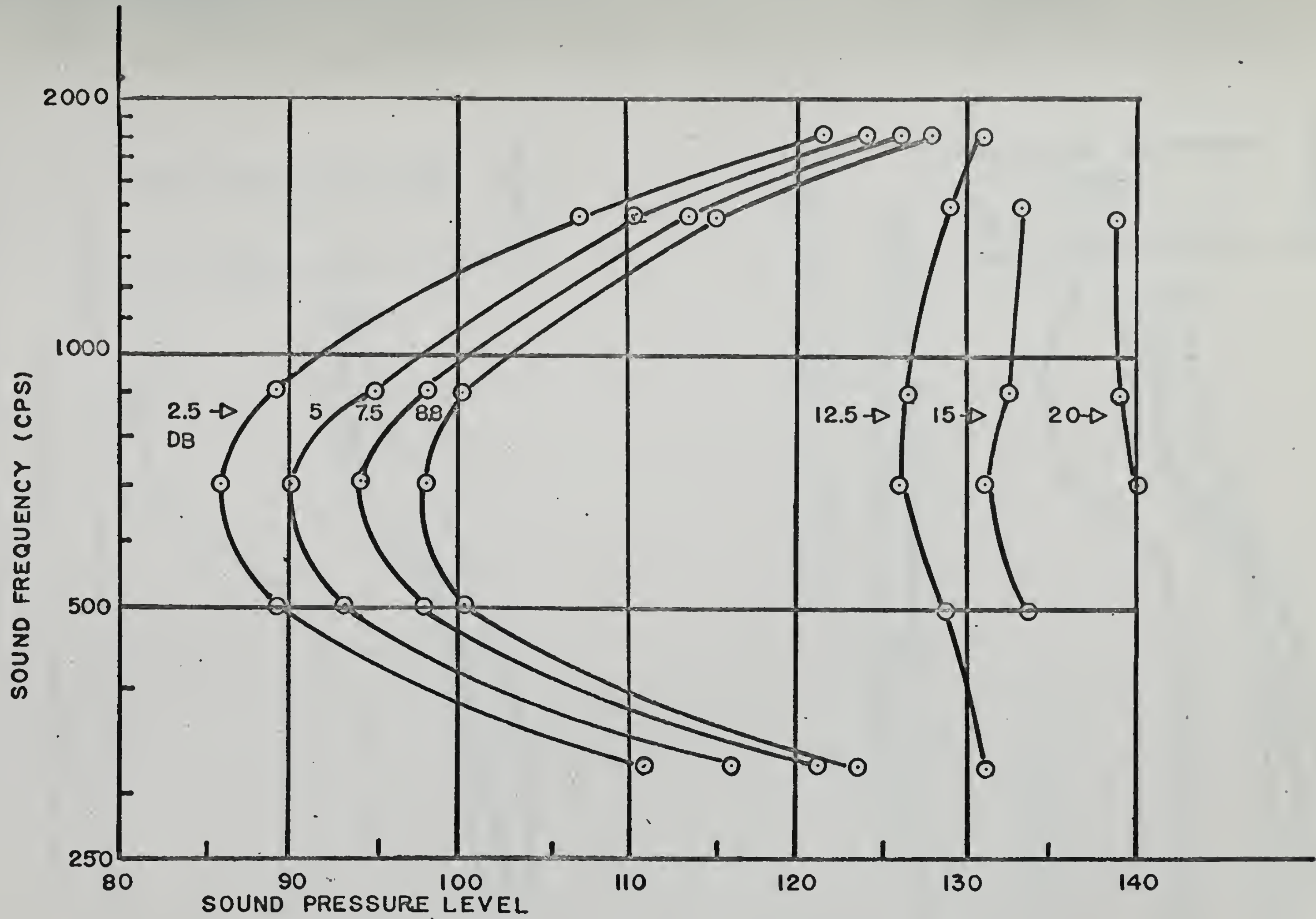


FIG. 19 CONSTANT TURBULENCE REDUCTION CONTOURS

FROM FIG. 18

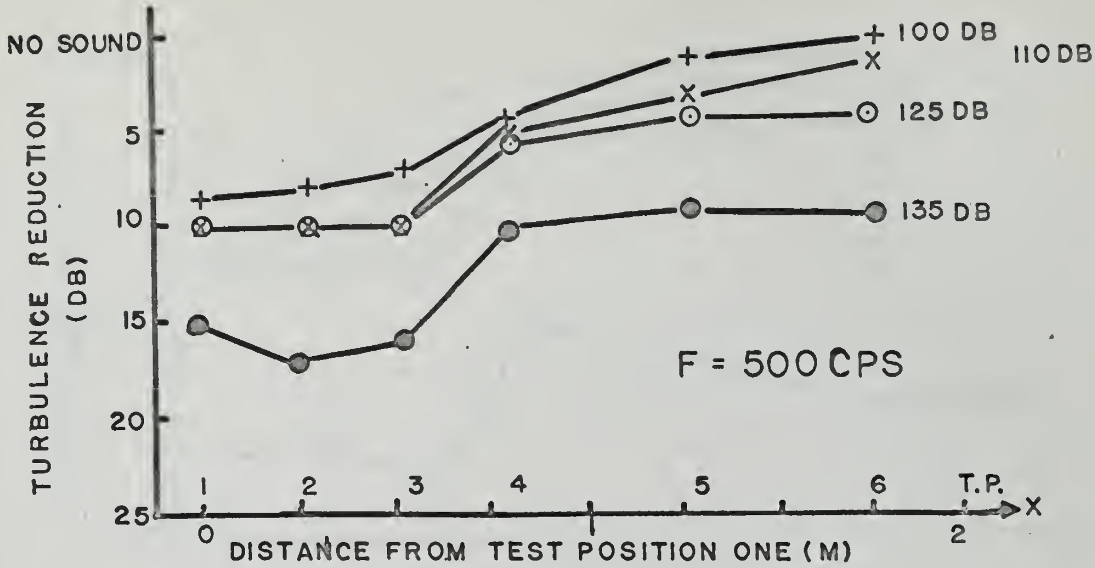


FIG.20(A) FREQ. = 500 CPS

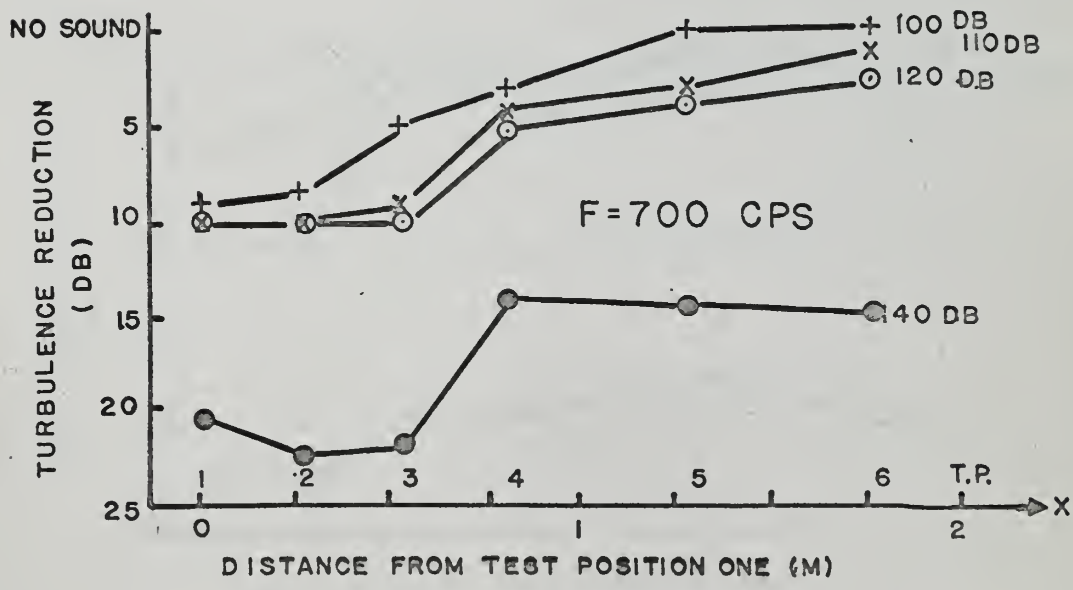


FIG.20(B) FREQ. = 700 CPS

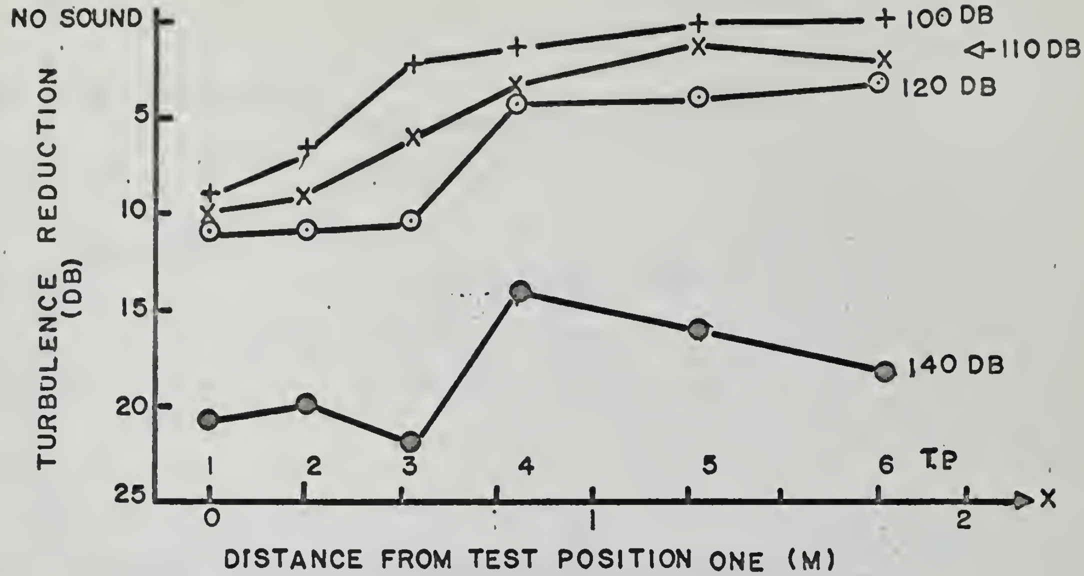


FIG.20(C) FREQ.= 900 CPS

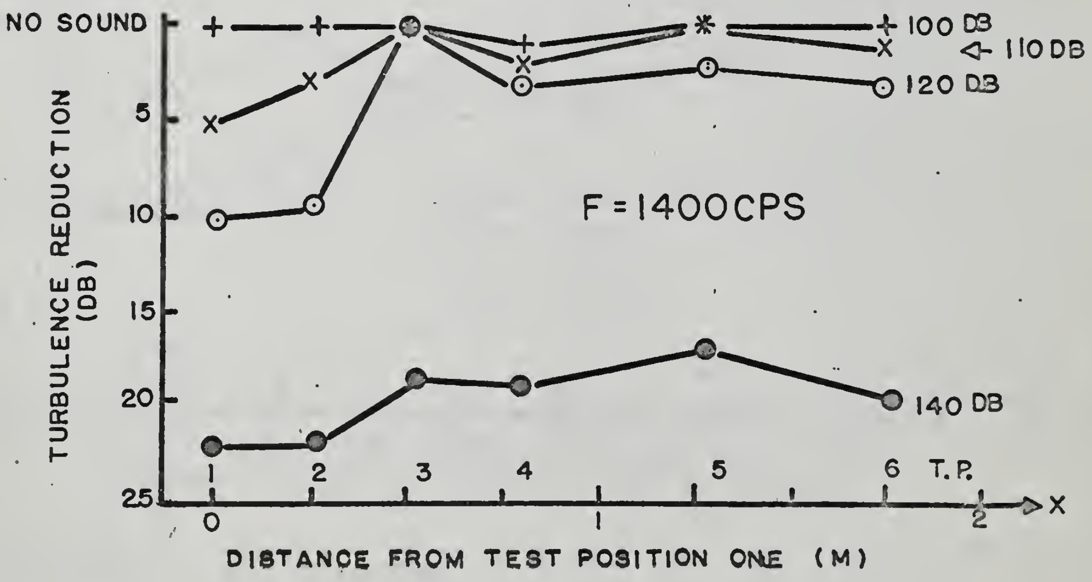


FIG.20(D) FREQ. = 1400 CPS

FIG.20 EFFECT OF SONIC EXCITATION UPON TURBULENCE AS DISTANCE FROM ENTRY IS VARIED

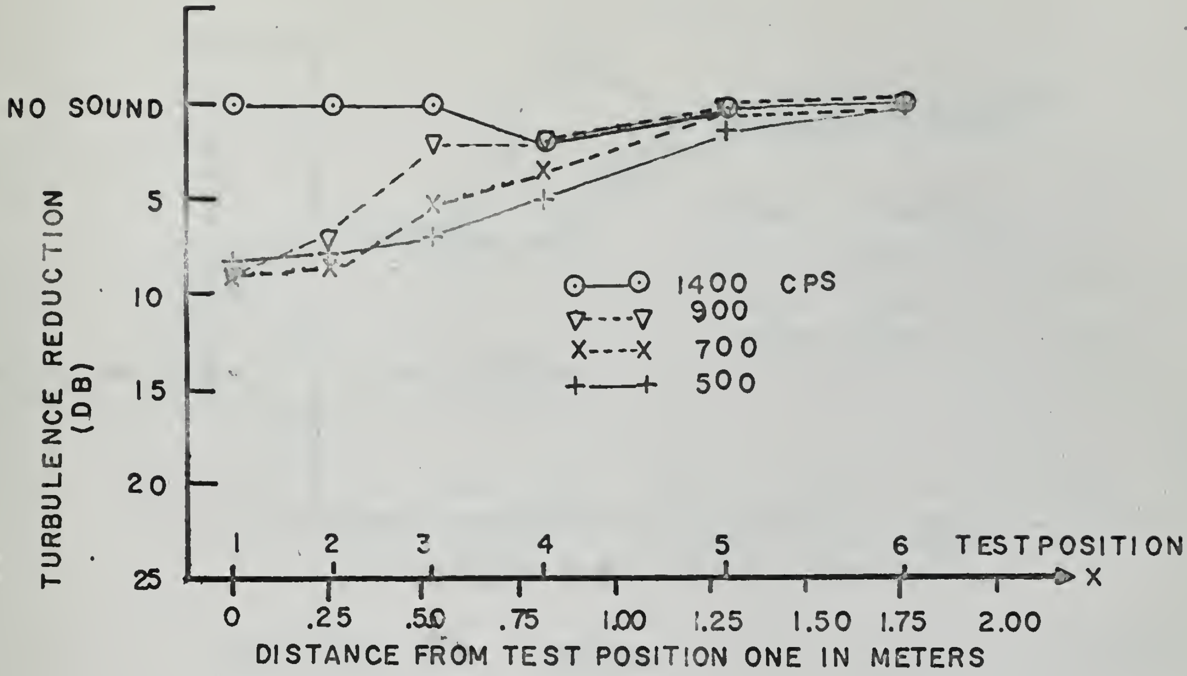


FIG. 21 (A) SPL = 100 DB

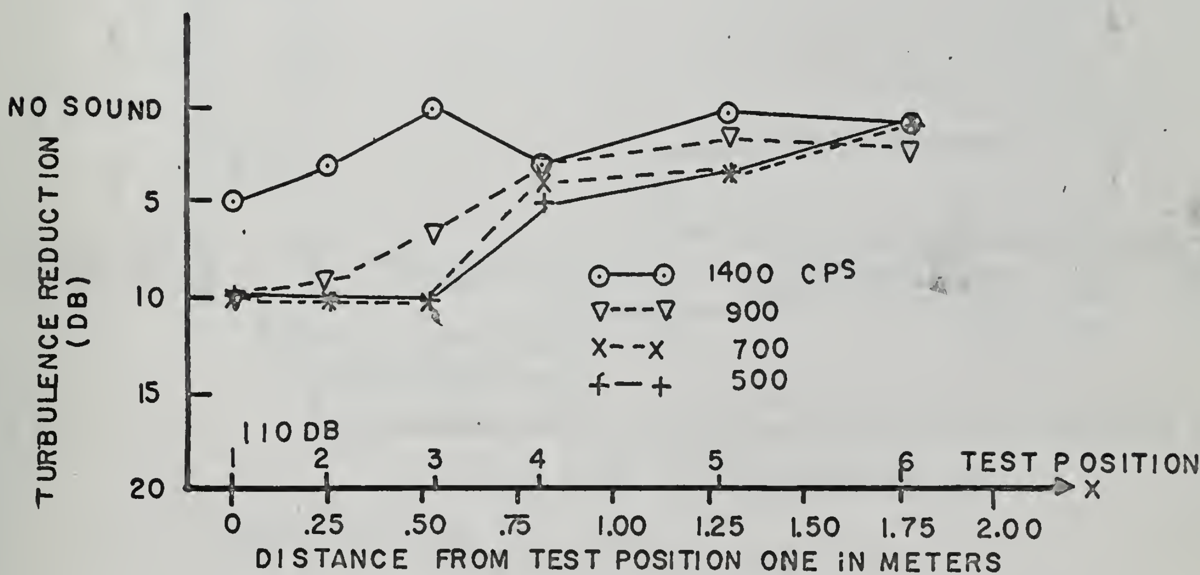


FIG. 21 (B) SPL = 110 DB

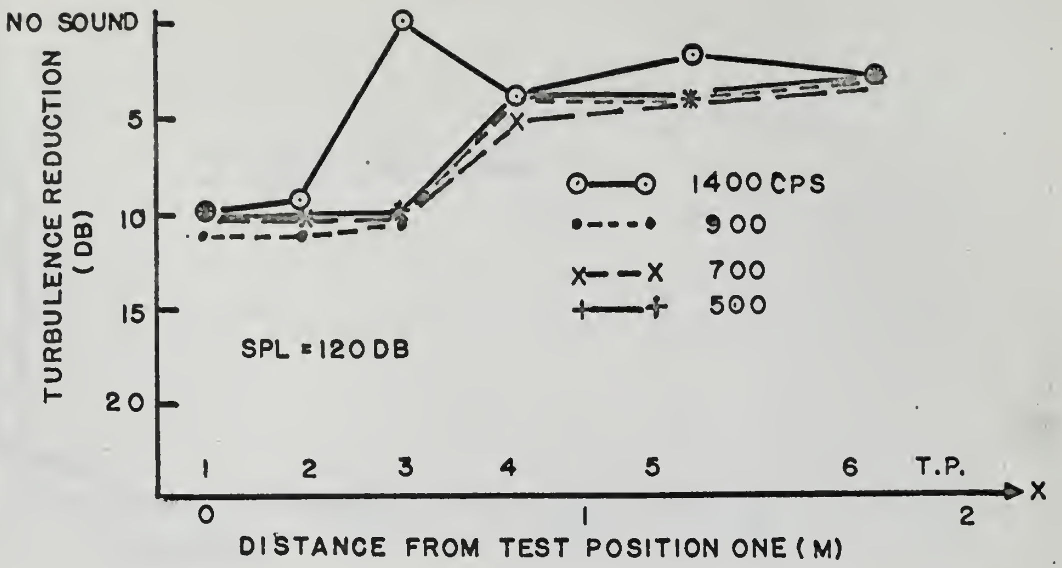


FIG. 21 (C) SPL = 120 DB

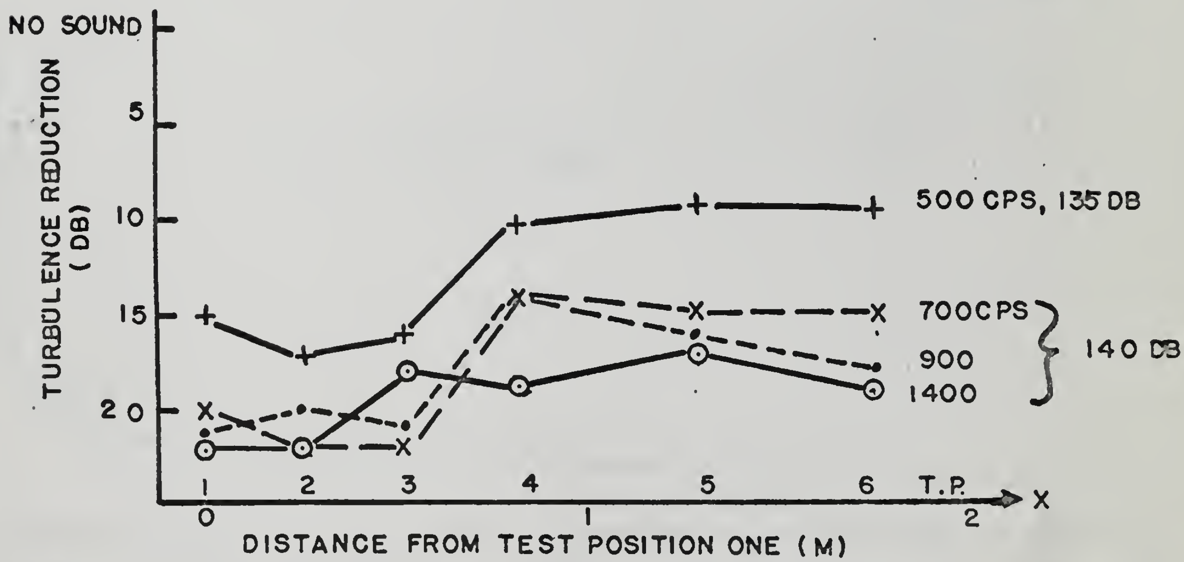


FIG. 21 (D) SPL AS LISTED

FIG. 21 EFFECT OF SONIC EXCITATION UPON TURBULENCE AS DISTANCE FROM ENTRY IS VARIED.

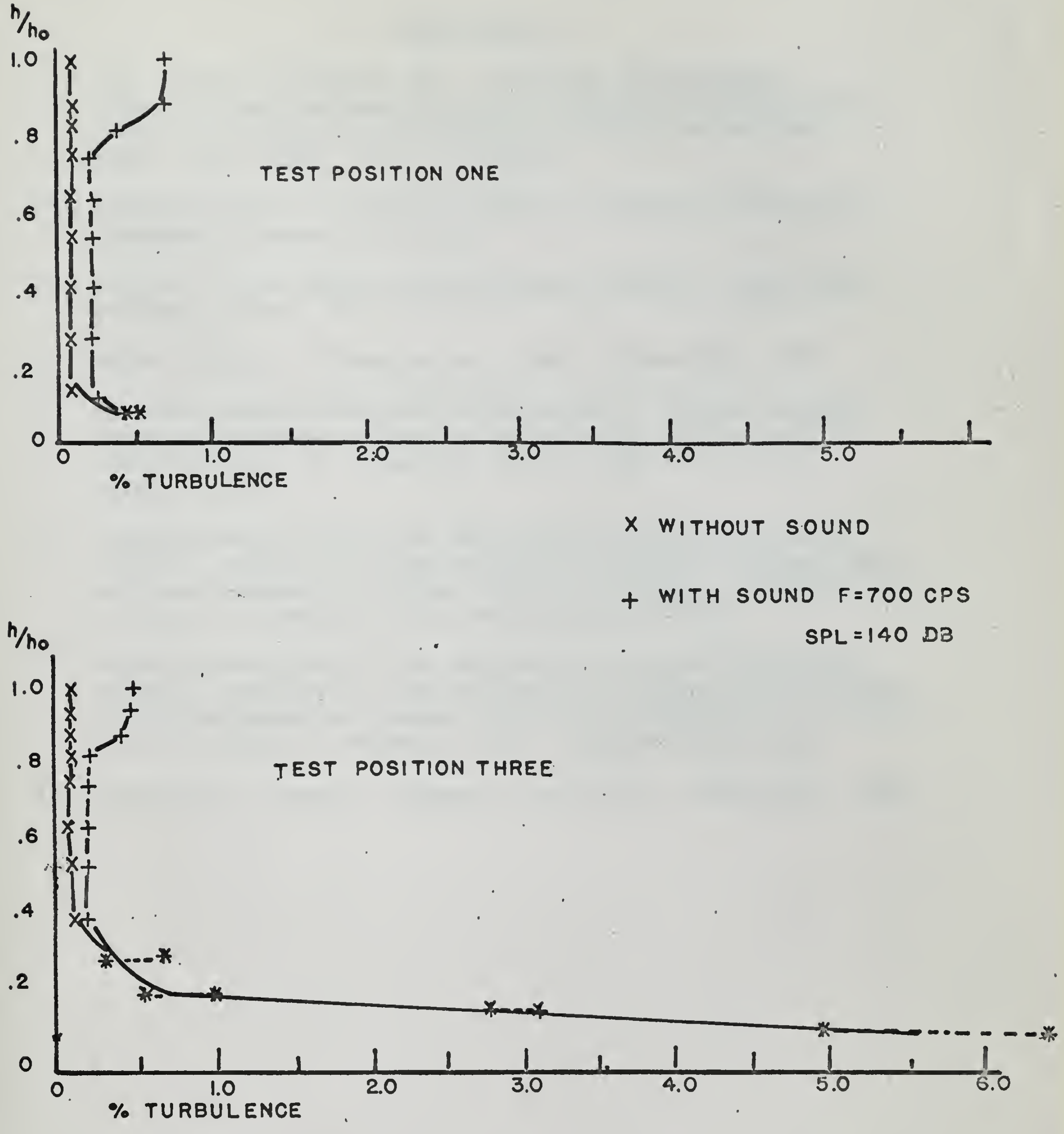


FIG. 22 EFFECT OF SONIC EXCITATION UPON TURBULENCE PROFILES

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APPENDIX

SODERING OF HOT WIRES

The mounting of the five micron diameter platinum-plated tungsten wire to the nickel probe supports can be a tedious and time-consuming process. A procedure for accomplishing this in an efficient and expeditious manner was developed during the course of the experiment. The time and effort this method saves warrants its inclusion as an appendix to this thesis.

Wires are fragile and, either due to carelessness or equipment malfunction, may easily be broken. It has been found that they may be locally repaired rather than returned to the manufacturer for service without changing the resistance of the probe or the response of the anemometer. This procedure is economical and eliminates excessive dead time after a wire casualty as replacements may be repaired in odd moments.

The equipment required to affect the repair is:

1) Spool of replacement wire
2) Jeweler's loupe
3) Tweezers
4) Masking tape
5) 60% silver - 40% tin solid soder
6) Sodering iron with about a 1 mm fine point
7) A Variac or powerstat to control voltage to the iron
8) A vise
9) Sodering flux, recommended Lloyd's flux
10) A medicine dropper
11) Scissors

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The small size of the wire requires that something be done to increase its visibility and enable one to handle it. This is accomplished by removing it from the spool by folding a small piece of masking tape over the end of the wire. With the tape suspended below the spool, fold another 1 cm square piece of tape over the wire about 1 cm up from the first. Being careful not to stress the wire, cut the upper tape in half using the scissors. This leaves the 1 cm long piece of wire with a small piece of masking tape folded over each end and also allows one to locate the bitter end remaining on the spool.

Place the probe in a vise with the nickel supports horizontal. Adjust the power supply which controls iron temperature until it is just hot enough to melt soder. Using the hot iron, remove all soder and wire remnants from the supports.

When the supports are clean, pick up the end of the piece of wire, easily located because of the tape, and place the wire over the two supports, about 0.5 mm from the tips and perpendicular to the supports. The weight of the tape on each end of the wire serves to keep the wire tight with no slack. Apply flux to the iron and nickel supports using the medicine dropper. Silver the iron, then reduce the heat slightly. Using the loupe to see the wire, place a small amount of soder on the two wire-support junctions. When a small amount of soder smoothly covers the junction, remove the iron. A word of caution: very little soder is required.

The joint may be tested by holding the masking tape with the tweezers and applying a small amount of force upward. If the joint is solid the wire will break, leaving the 1 mm long piece firmly mounted between the

supports. If the wire pulls out, the tape may be replaced in the desired position and another attempt made.

Upon completion of the repair, the probe should be washed in a stream of water and then blown dry to remove all vestiges of the flux. This washing serves the dual purpose of cleaning and performing another strength test to ensure that the wire is firmly mounted. It is suggested that the wire be closely inspected at this time to reaffirm the strength of the joint.