LOUDSPEAKER COMPENSATION USING INTEGRATED CIRCUITS

A Thesis

Presented to

the Faculty of Graduate Studies and Research

Department of Electrical Engineering

University of Manitoba

In Partial Fulfillment

of the Requirements for the Degree

Master of Science in Electrical Engineering

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by

Lubomyr Borys Shulakewych

May 1969

To my wife

Oksana

ACKNOWLEDGEMENT

The author wishes to thank his thesis advisor Prof. M. A. K. Hamid for supervising the topic and Prof. A. Simeon for suggesting and supervising the work initially.

Thanks are also extended to the National Research Council of Canada whose financial support, in the form of a Research Grant, made this research possible.

ABSTRACT

The principal axis frequency response of a loudspeaker is compensated using standard synthesis techniques and the desired flat response is obtained. The technique is based on a pole-zero cancellation of the loudspeaker response using integrated circuit operational amplifiers and resistance - capacitance components. Subjective tests with both male and female listeners confirm that the response is greatly improved. It is anticipated that in order to approximate an ideal frequency response for good listening, this type of compensator should be incorporated into the preamplifier.

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CHAPTER I

DESIGN OF COMPENSATING NETWORKS

1.1 INTRODUCTION

The aim in reproducing speech and music is to obtain the original sound. The loudspeaker is the weakest link in any sound system for a desired reproduction of sound. It may be compared to a sounding board of a musical instrument which is excited into a multiplicity of resonances by an electro-mechanical vibrator. In order to provide natural sound, it would have to be an ideal transducer - a piston of zero mass, stiffness and friction.

The frequency response of a loudspeaker is used to assess the loudness of transmitted speech or music, quality of reproduction, and the ability of the loudspeaker to produce intelligible speech in a given acoustic environment. It is a measure of the sound pressure amplitude on a designated axis, and at specified distance, as a function of frequency for a constant electrical input. Having obtained the frequency response, the logarithm of the magnitude is taken to obtain a Bode plot. From the Bode plot the transfer function of the loudspeaker can be approximated. Thus the frequency response is the most significant single criterion upon which to base a judgment on the merits of a loudspeaker.

It is the purpose of this thesis to provide a circuit approach to the compensation problem when given any loudspeaker frequency response, obtained under any acoustical environment, with any type of excitation. From this frequency response a Bode plot may be derived, and a compensating circuit synthesized to provide the desired response.

Three steps are needed in any frequency response compensation: the approximation by a Bode plot; the determination of the actual response desired; and the synthesis of the compensator network.

Having obtained the frequency response in Bode plot form, one must try to compensate in some meaningful way. For this, approximation techniques are available to locate the most significant poles and zeros. The resulting piecewise linear response is then represented by a certain polynomial having the expected order, degree and break frequencies.

Loudspeaker and psychoacoustic theory provide the conditions for a desired frequency response. Beranek[1] states that for proper sound reproduction, a flat response over the frequency range 70 - 7000 Hz is desirable for most listeners. Loudspeaker theory states[1] that the frequency response begins with a + 2 slope. In mathematical form this is described by the relation:

$$G_D(S) = K_D \frac{S^2}{(S + a_1)^2} \qquad \text{--- (1.1)}$$

where G_D (S) is the desired response, K_D is a constant and $a_1 = 2\pi\, 70$ radians / second.

In order that the desired response, described by equation 1.1, be obtained, a network called the compensator can be synthesized from the loudspeaker transfer function and the equation of the desired response. Thus, by use of synthesis techniques a compensating network may be built which, when cascaded with a loudspeaker will provide a pleasing sound to the ear.*

1.2 COMPENSATION BY OPERATIONAL AMPLIFIERS AND CONVENTIONAL RC COMPONENTS

Integrated circuit operational amplifiers and RC components are used for synthesizing the loudspeaker simulator and compensator. Passive RLC networks have been used for compensating loudspeakers,[4] however the inductors were large, heavy and lossy at these frequencies. Active RC networks provide almost every desirable feature of passive RLC networks and provide more flexibility in circuit design.

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* See Ref. 2 and 3 for previous work on active circuit loudspeaker compensation.

A model of an ideal operational amplifier is shown in Fig. 1.1.

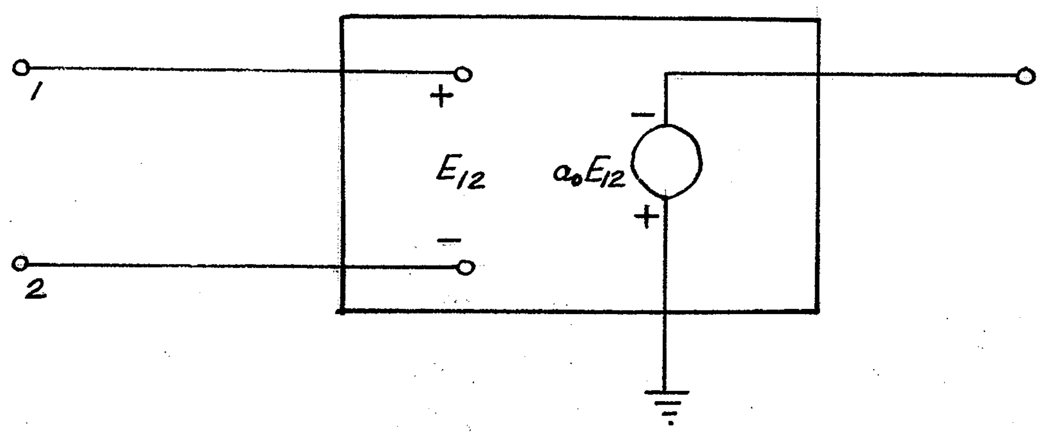

FIG. 1.1 IDEAL MODEL FOR AN OPERATIONAL AMPLIFIER

This differential input operational amplifier may be described as an ideal voltage amplifier of very low output impedance (assume zero), very high input impedance (assume infinite) and very high gain. The output voltage as seen from Fig. 1.1 is proportional to the difference in the voltages applied to the two input terminals. The operational amplifier may also be used to approximate ideal voltage amplifiers of low gain, negative impedance converters, or gyrators.

The basic active RC feedback configuration of an ideal voltage amplifier with high gain is shown in Fig. 1.2 with input, output and feedback networks.

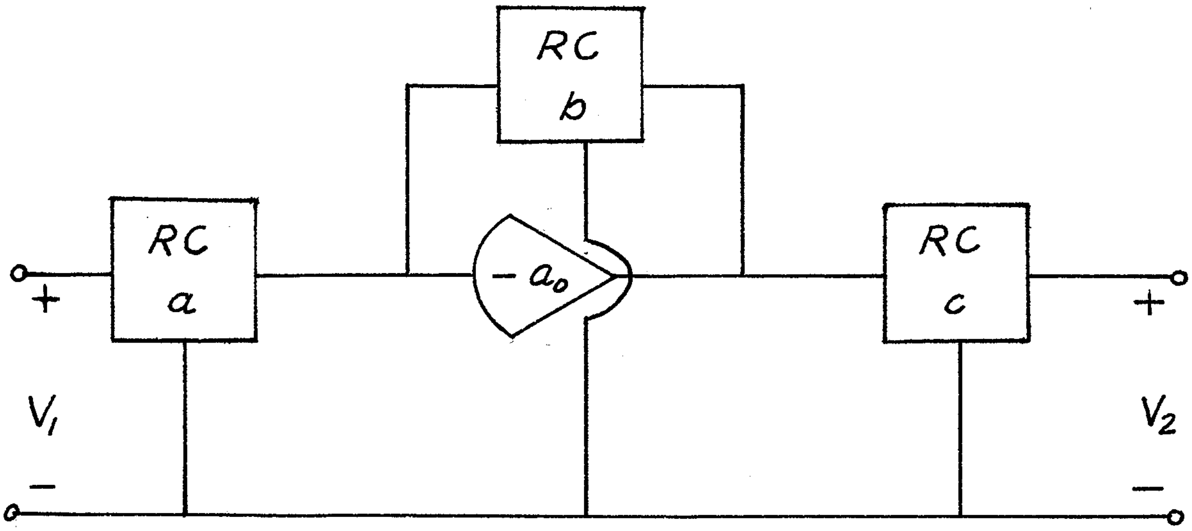

FIG. 1.2 AN ACTIVE RC NETWORK CONFIGURATION WITH FEEDBACK

In order to utilize the low output impedance of the operational amplifier, the circuit shown in Fig. 1.3 is used.

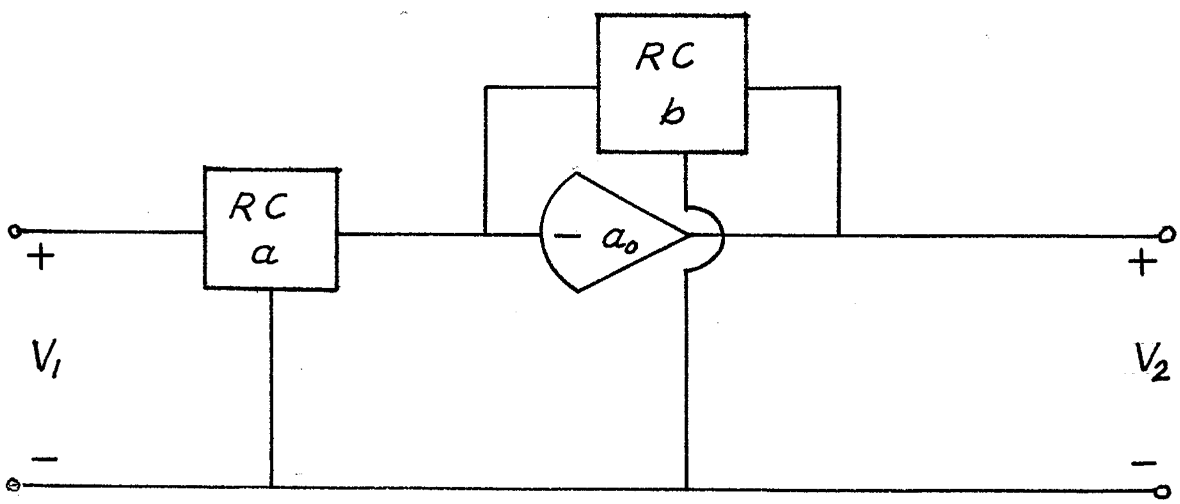

FIG. 1.3 CIRCUIT USED FOR SYNTHESIS

The voltage relationship of this circuit can be shown to be [5]

$$\frac{V_2}{V_1} = -\frac{Y_{12a}}{Y_{12b}} \qquad \text{--- (1.2)}$$

where Y_{12a}, and Y_{12b} are the short circuit admittance parameters for the two ports a and b, respectively.

The advantages of using the circuit shown in Fig. 1.3 are: the impedance level (and thus the D.C. gain) may be varied without varying the position of the poles and zeros; positive and negative feedback may be used; loading effects are negligible when this type of circuit is cascaded, as the input impedance can be made very high and output impedance is almost zero. All of these advantages are integral to our compensation problem.

Since high order polynomials may be factored into first and second order terms, any transfer function may be written as a product of first and second order poles and zeros of any degree. Thus in general for a loudspeaker, the following transfer function can apply.

$$G_L(S) = K_L \quad \frac{S^2 \quad (S + a_2) \; (S^2 + 2\rho_2 S + w_2^2 \;) \ldots\ldots}{(S + a_1) \quad (S^2 + 2\rho_1 S + w_1^2 \;) \ldots\ldots} \quad \text{---(1.3)}$$

where a_1 and a_2 are a pole and zero respectively, w_1 and w_2 are the natural frequencies of the poles and zeros, ρ_1 and ρ_2 are the damping factors, and K_L is a constant.

This typical loudspeaker transfer function may be compensated by pole - zero cancellation to provide the desired response. The desired response describec by equation 1.1 is obtained by cascading the compensator and the loudspeaker.

1.3 CIRCUIT DESIGN

Upon obtaining the transfer function of the desired compensator, means of synthesizing this function are investigated. Synthesis of first and second order poles and zeros are considerered using standard synthesis techniques.

Several considerations must be accounted for when designing the required circuits. Stability must be insured; the inherent poles of the amplifier must be accounted for when designing the network; and the D.C. gain of the compensator should be approximately one, so that the attenuation is not too great. The networks should be designed to provide flexibility of adjustment of poles and zeros to accomodate a shift in loudspeaker poles and zeros or use with other loudspeakers.

Standard formulas from Fifer[6] and the Burr Brown Handbook of Operational Amplifier Active RC Networks[7] are used for synthesizing the derived transfer functions. The transfer functions used in this design, with their short circuit parameters, circuit configurations and design formulas are shown in Appendix A.

1.4 LIMITATIONS OF THE TECHNIQUE

The techniques described in the previous sections have certain disadvantages. Besides the limitations of operational amplifier circuits, as described in the Handbook of Operational Amplifier Applications[8], there are further disadvantages of compensation:

a) Pole and zero locations of the Bode plots are estimated from physical measurements, and they are not precisely known. These poles and zeros may shift with time due to environmental changes. It is not possible to realize exact cancellation in these cases. In the case of a pole or zero near the jw axis, if cancellation is not exact, very great errors may be caused on the derived Bode plot.

b) The frequency response is taken at one level. If the loudspeaker is grossly nonlinear, cancellation may not occur but an undesired singularity may be introduced.

c) An error is introduced in approximating the loudspeaker frequency response by straight lines of integer slope. RC components used for synthesis also introduce an error as they cannot provide a network to fit the loudspeaker approximation exactly. Care must be taken that the compensator agree with the initial desired curve.

d) A Bode plot analysis is adequate for a one dimensional case, but does not provide any information for the three dimensional case. Therefore, in the case of the loudspeaker the directivity is not considered.

None of the limitations mentioned above are restrictive, as will be seen later. However, they should be kept in mind when this problem is approached.

CHAPTER II

EXPERIMENTAL CONSIDERATIONS

2.1 PSYCHOACOUSTIC CONSIDERATIONS

In order to appreciate the approach to the design and performance of the compensator, it is necessary to discuss subjective effects of hearing.

The subjective effects that need be considered are: differential thresholds, masking, critical bands and phase effects. As most of the research carried out in the psychoacoustic field has been under monaural conditions, these results shall be presented, and where known, binaural effects will be given.

It is known that the variation in the intensity and frequency enables us to detect changes in the stimulus. Knudsen[9] and Riecz[10] determined the differential threshold or difference limen intensity.

The differential sensitivity of the ear ranges from 0.25 to 1.0 db depending on the frequency and sound intensity level. Beranek and Peterson[11] state that binaurally a change of 1 db is hardly noticeable, and 3 db is usually significant. It is a change in this intensity which provides us with the design limits of the possible variation of the compensation circuit. That is the frequency response may be regarded as flat as long as the intensity fluctuations about a desired response do not exceed 3 db.

A phenomenon similar to the difference threshold of intensity is masking. It is defined as the number of decibels by which a listener's threshold of audibility is raised by the pressure of another masking sound. Fletcher[12] found that only the noise in a narrow frequency band on either side of the pure tone serves to mask the tone. Over this critical band the ear acts like a filter. Critical bands for listening are shown in Fig. 2.1 for monaural and binaural listening. When the critical band is zero, the masking in db will be zero. As the bandwidth is increased the masking in db will increase in direct proportion to the logarithm of the bandwidth up to the critical value Δfc. Above this width no further masking of pure tones occurs.

Bruel and Kjaer[13] state that, "According to existing theories of hearing the ear responds to the sound much in the same way as a constant percentage bandwidth analyzer having a bandwidth of about 1/3 octave". This allow us to approximate the critical bandwidth of the ear with 1/3 octave readings. Ideally, the detector's bandwidth should equal the critical bandwidth of the ear.

Mathes and Miller[14] performed experiments to test the

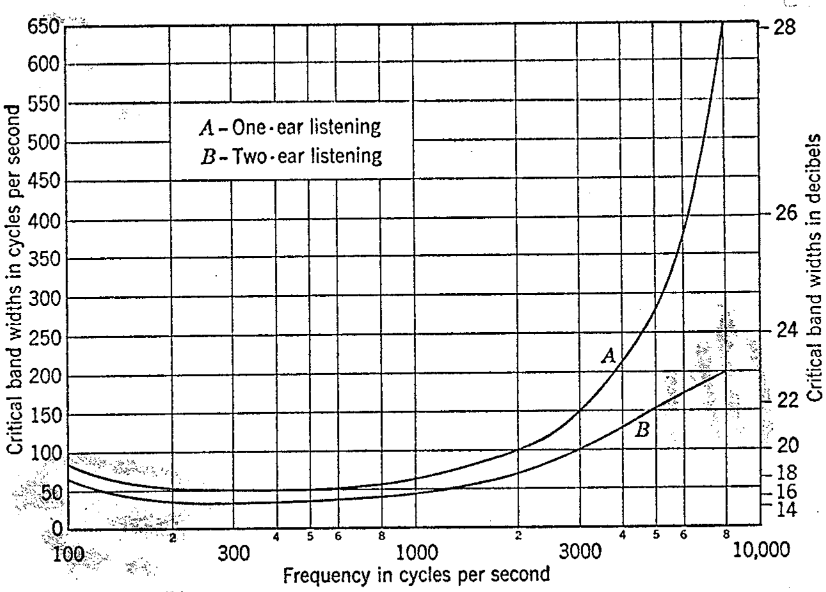

FIG. 2.1 CRITICAL BANDWIDTHS OF HEARING (Ref.1, p.365)

effects of phase on monaural perception. They found that the stimulus pattern which differed only in phase was readily distinguishable by the ear. However, Licklider in his Basic Correlates of Auditory Stimulus[15] states three necessary conditions for monaural phase effects. These are:

a) Important components in the stimulus must be close together in frequency,

b) There may not be too many frequency components, and

c) The phase changes must make clear cut differences in the envelope of the wave form.

When using a loudspeaker for sound or music, the above conditions would not be noticed by the ear. It is for this reason that a minimum phase network can be assumed. Thus if the system is stable, all the poles are in the left hand plane, and the gain response or Bode diagram specifies the phase response.

2.2 RADIATION CHARACTERISTICS OF LOUDSPEAKER IN FREE SPACE

The radiation intensity along the principal axis of the loudspeaker is known as the frequency response. For the sake of convenience, the response is discussed using a loudspeaker in an infinite baffle with readings taken in free space.

Standard piecewise linear approximations are used to approximate the loudspeaker frequency response. Below the fundamental resonance of the loudspeaker, which occurs in the typical range (30 - 250 Hz), the slope of the response increases by 12 db per octave as shown in Fig. 2.2 region A.

If the loudspeaker is assumed to be acting as a rigid piston in an infinite baffle, the pressure produced at the midfrequencies at distance r depends only on the power radiated and the directivity factor. Over the midfrequency range C, the frequency response is almost constant. Corrington[16] showed that in practice the diaphragm starts to break up into variations along the diameter. Due to this, smaller resonances usually appear along this portion of the curve.

At higher frequencies a second resonance may occur as shown in region D. Above this region the diaphragm breaks up and vibrates with modal circles. These vibrations introduce very sharp and distinct resonances. These resonances decrease for a loudspeaker in an infinite baffle with a 12 db per octave overall slope, as shown in region E.

The baffle has a very notable effect on the response of a loudspeaker system. An unbaffled speaker has a pressure increase of 18 db per octave below the first resonance[1]. Above the first resonance the pressure increases 6 db per octave. The baffle introduces a resonance of its own which is usually

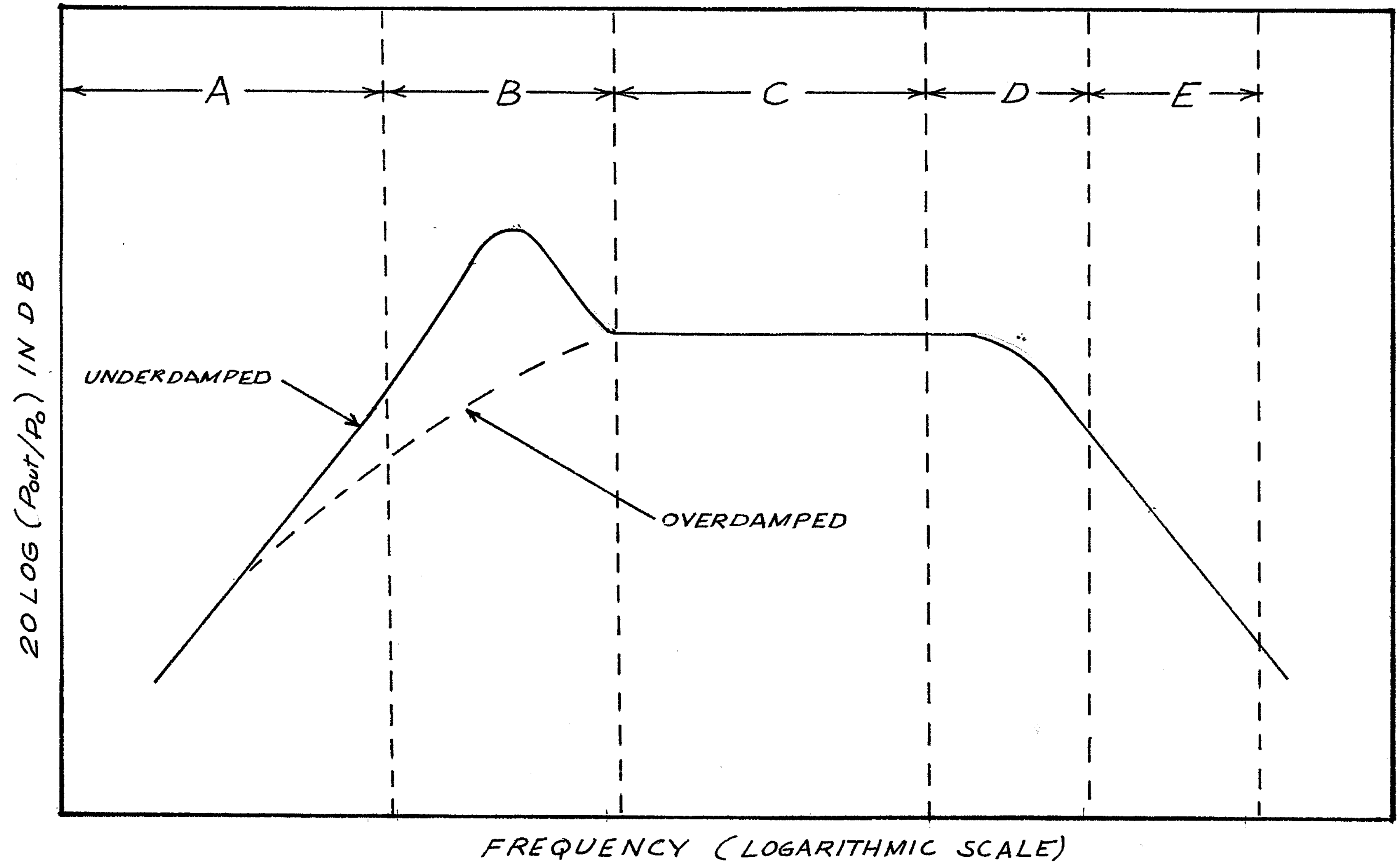

FIG. 2.2 THEORETICAL FREQUENCY RESPONSE OF A DIRECT RADIATION LOUDSPEAKER IN INFINITE BAFFLE

quite large and lies in the mid-frequency range. Further information on the baffle effect may be found in Beranek[1] and Nichols[17] article.

2.3 EFFECT OF ENCLOSURES ON SOUND

It is necessary to minimize the reverberation in any enclosure for the sound to be pleasing. In order that free space be simulated, a large enclosure is necessary. The following requirements must be met for an enclosure to be "large":

a) The ratio of the mean free path* to the wavelength must be large.

b) The enclosure must be an irregular shape or contain reflecting objects which set up many reflections per second.

c) The enclosure should have a variable angle of incidence and variable absorption coefficients.

In a large enclosure, standing waves are set up at all angles of incidence and the sound field in the room may be described as a diffuse sound field. In this diffuse sound field the peaks of the standing waves lie very near to each other and an average reading may be obtained.

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* Mean free path is defined as the average distance a sound wave travels in a room between reflections from the bounding surfaces.

A convenient quantity to describe an enclosure is known as the reverberation time. This is the time required for the sound to decay to 10^{-6} of its original value. It is known that the reverberation time of an average living room is 0.5 seconds. Psychological studies indicate that if a room has a reverberation time of 0.3 seconds then most listeners are not disturbed by the echoes (or overhang) of sound. Studies[16] show that echoes occur if the isolated reflected wave returns after more than 67 msec. These echoes or reverberations may be eliminated by acoustically treating any enclosure. With the enclosure properly treated only the loudspeaker characteristics have to be considered.

CHAPTER III

ACOUSTIC MEASUREMENTS FOR LOUDSPEAKERS

3.1 INTRODUCTION

The frequency response measurements for loudspeakers are discussed in the subsequent sections. In this way the characteristics of two loudspeakers were investigated.

The enclosure used for measuring the frequency response of the loudspeakers was the University of Manitoba microwave anechoic chamber. This was the "largest" enclosure available. Care was taken to locate the microphone in the free far field. Beranek [18] states "assuming a source radiating wideband noise and assuming an analyzing filter one octave wide, it is good engineering practice to place the microphone at least 1/4 feet away from all room surfaces. The wavelength is evaluated at the centre of the lowest frequency band of interest." It was assumed that the listeners will use the loudspeaker in the free far field. Tests were carried out with two types of frequency inputs: pure sine wave and white noise inputs. For all cases the microphone was placed perpendicular to the axis of the loudspeaker. Since directivity is natural to a person listening, it was sufficient to measure only the principal axis response.

3.2 MEASUREMENTS FOR FIRST LOUDSPEAKER

Various tests were performed on the first loudspeaker to obtain a meaningful basis for compensation. The object of these tests is to obtain the loudspeaker frequency response and transfer function. From the transfer function a network may be synthesized approximating the loudspeaker, and the loudspeaker may be studied electrically.

The following are the physical characteristics of the first loudspeaker:

9" (height) x 9" (width) x 4½"(depth)

closed box baffle,

5" diameter speaker,

5 watt output,

Fiberglass behind speaker in baffle to damp out vibrations,

4 ohm impedance.

To obtain the frequency response with sine wave excitation, the following apparatus was used:

Heathkit sine generator,

502 A Oscilloscope,

Low output impedance ($\approx \frac{1}{10} \Omega$) power amplifier

50 volt 1.5 amp power supply.

1560 P3 GR microphone

1551C GR sound level meter

50' cable (attenuation 6.7 db over audio frequencies)

The white noise excitation tests employed apparatus as follows:

1390 B GR random noise generator

1560 P3 GR microphone

1554 A GR vibration analyzer

1521 A GR graphic level recorder

50' cable (attenuation 6.7 db over audio frequencies)

Low output impedance ($\approx \frac{1}{10}\ \Omega$) power amplifier.

50 volt 1.5 amp power supply.

For the sine wave excitation the frequency was varied manually in the range 40 to 10,000 Hz. The equipment setup is shown in Fig. 3.1. The input to the loudspeaker was kept constant by means of a monitoring oscilloscope and the principal axis frequency response was obtained. The equipment layout in the microwave anechoic chamber is shown in Fig. 3.2.

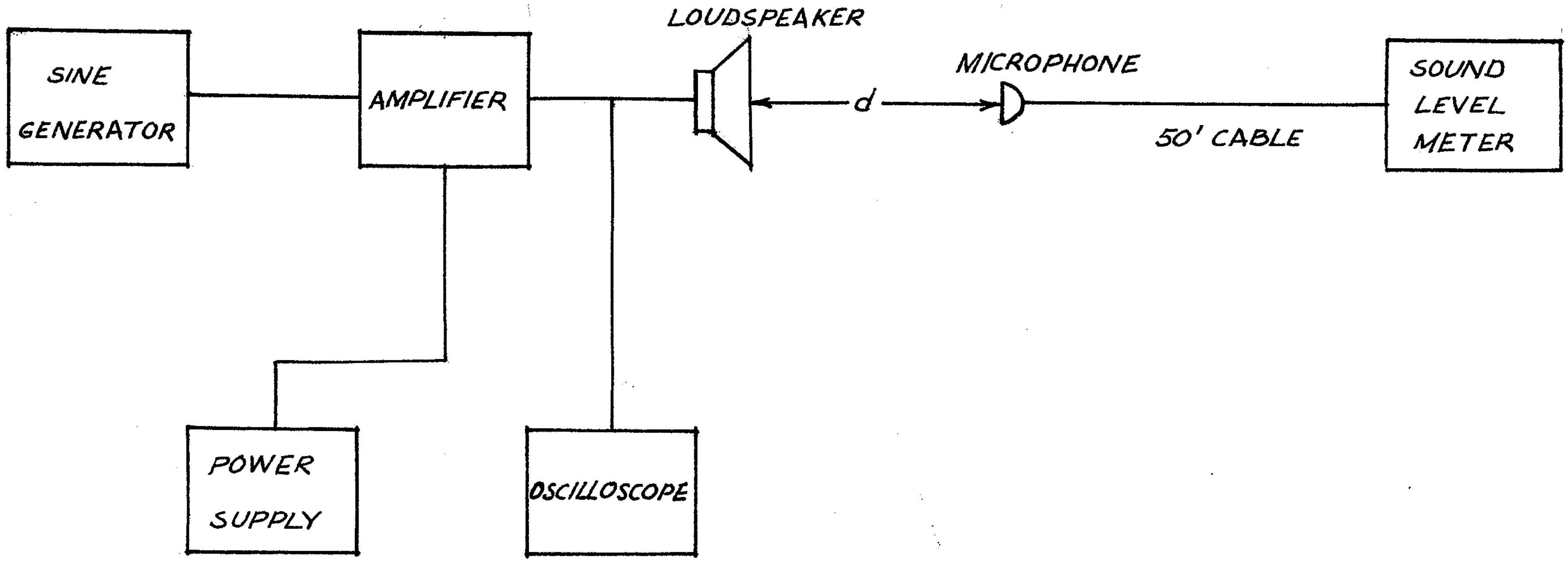


FIG. 3.1 EXPERIMENTAL SETUP FOR PURE TONE FREQUENCY RESPONSE

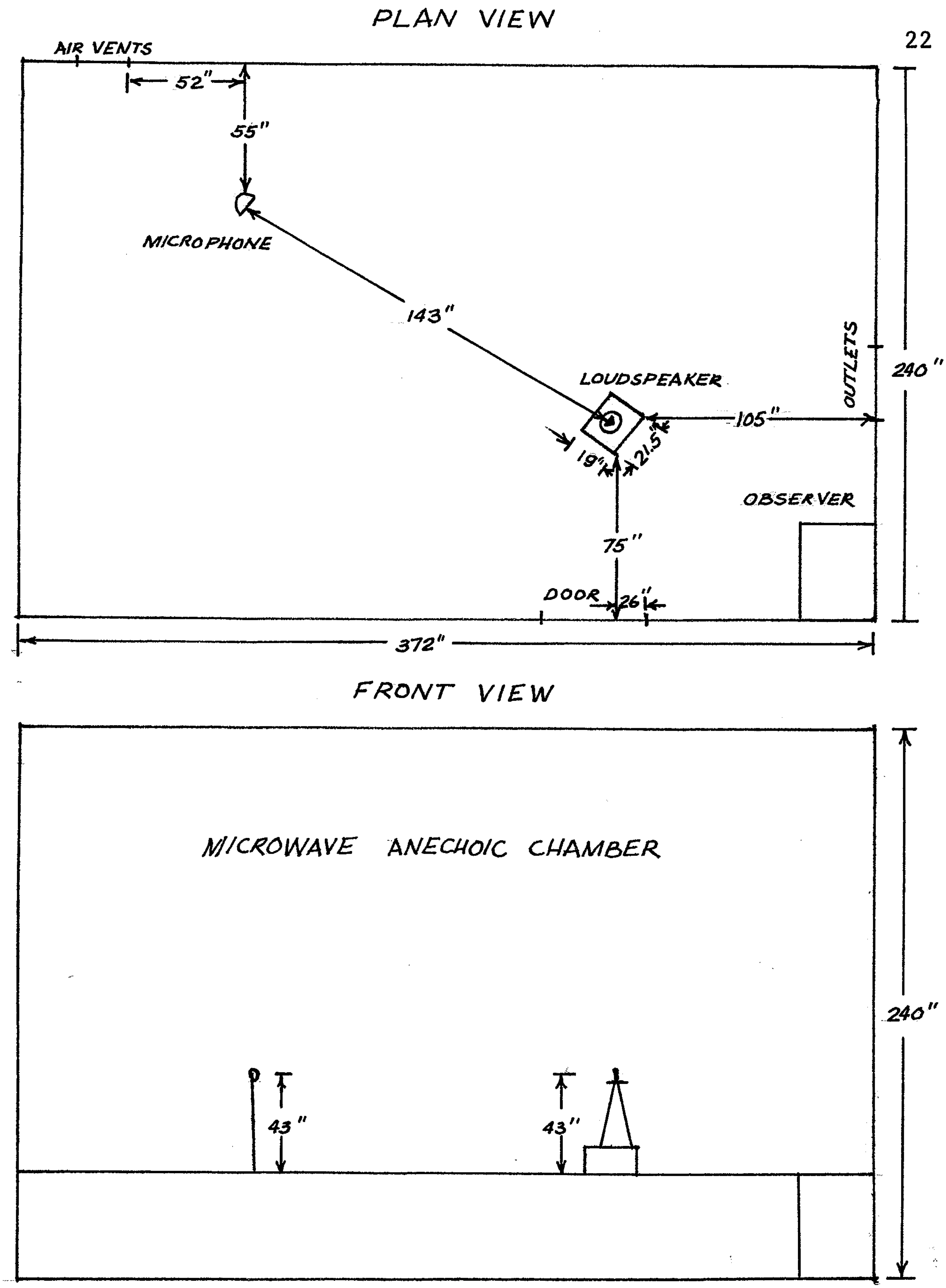


FIG. 3.2 PHYSICAL LAYOUT FOR MEASUREMENTS

For the random white noise tests, a white noise source in the 20 - 20,000 Hz frequency range was applied to the loudspeaker. The block diagram of the set up is shown in Fig. 3.3. The response was detected by a sound level meter. For all white noise measurements 6.7 db must be subtracted from sound pressure values on the curves to account for the cable attenuation. The vibration analyzer was set to provide either an octave, a 1/3 octave or an 8 percent narrowband readout. The graphic level recorder was mechanically linked to the vibration analyzer and plotted the frequency response. Both the 1/3 octave and the narrowband detection were used to approximate the hearing of the ear. The following tests were made:

TEST 3.1 SINUSOIDAL FREQUENCY RESPONSE OF LOUDSPEAKER

The frequency response of the first loudspeaker was obtained using a sinusoidal excitation, three different input levels were used.

TEST 3.2 SINUSOIDAL FREQUENCY RESPONSE OF LOUDSPEAKER WITH VARIED MICROPHONE POSITION

The frequency response of the first loudspeaker

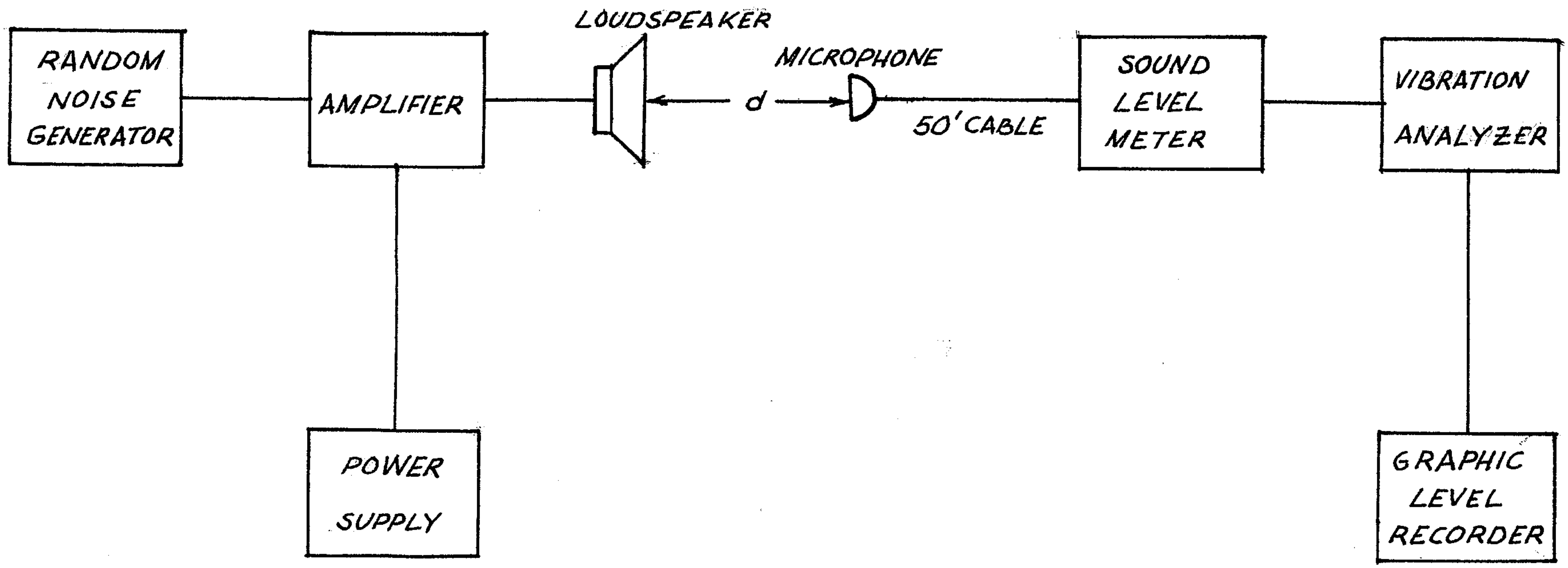


FIG. 3.3 EXPERIMENTAL SETUP FOR WHITE NOISE FREQUENCY RESPONSE

was obtained as in Test 3.1, but a different microphone location was used.

TEST 3.3 WHITE NOISE FREQUENCY RESPONSE OF LOUDSPEAKER

The frequency response of a loudspeaker was obtained using a white noise input. Eight different locations of the microphone were used. The matched impedance amplifier was used.

TEST 3.4 WHITE NOISE FREQUENCY RESPONSE OF LOUDSPEAKER WITH VARIED ENVIRONMENT

The frequency response of a loudspeaker was obtained using a white noise excitation. The environment was changed from the previous three tests, but separation between loudspeaker and microphone was the same as in Test 3.2. A low output impedance amplifier was used.

3.3 RESULTS OF MEASUREMENTS FOR FIRST LOUDSPEAKER

The data for Tests 3.1 and 3.2 is listed in Tables I and II, and shown in Figure 3.4 and 3.5, respectively. The results for Test 3.3 are provided in Appendix B. The results of Test 3.4 are shown on Fig. 3.6.

Several observations were made from these results. The

TABLE I

SINUSOIDAL FREQUENCY RESPONSE OF FIRST LOUDSPEAKER

d = 126"
Vpwr supply = 40V
a) Vin = 2V peak to peak

requency Hz	Sound Pressure Level Re 0.0002 ubars db	Frequency Hz	Sound Pressure Level Re 0.0002 ubars db
40	43.5	1100	75.8
62	44.4	1140	75.9
70	46.0	1260	71.2
87	47.0	1430	52.0
93	43.0	1610	66.8
100	50.4	1760	59.9
105	55.7	1800	64.2
115	52.0	1870	51.6
134	58.0	1980	55.2
160	62.2	2020	52.6
187	70.2	2110	61.5
200	67.5	2220	65.0
216	62.9	2260	60.0
225	63.0	2320	63.4
240	51.0	2400	52.1
254	61.5	2550	60.6
268	47.1	2620	57.1
298	63.0	2680	65.2
310	52.0	2900	70.4
331	62.4	3160	57.5
365	67.0	3250	67.0
411	59.1	3420	72.4
428	65.8	3720	67.6
480	69.5	3990	69.8
501	65.9	4710	60.8
545	71.1	4800	65.6
600	62.5	5200	67.6
640	72.2	5800	73.0
700	65.6	6890	64.2
740	72.5	7000	69.6
810	63.1	7600	63.6
840	69.5	7800	69.1
880	62.7	8200	54.9
920	72.8	8650	62.5
950	66.6	9300	51.2
1000	74.0	10000	44.8
1040	71.2		

b) Vin = 1V peak to peak

Frequency Hz	Sound Pressure Level Re 0.0002 ubars db	Frequency Hz	Sound Pressure Level Re 0.0002 ubars db
40		820	49.0
70	45.0	840	63.5
97	46.0	865	55.0
110	51.1	890	62.1
120	48.0	920	66.3
130	51.6	950	59.0
140	52.0	990	67.1
150	52.0	1150	70.2
165	55.0	1380	57.0
175	55.0	1480	48.0
187	60.0	1560	56.0
200	62.1	1650	57.8
212	46.0	1860	49.5
225	58.0	1880	47.0
240	44.5	1900	50.0
250	56.0	2020	52.0
265	47.0	2200	57.0
289	55.0	2650	50.5
300	58.1	2800	60.8
310	45.0	2970	61.0
320	54.3	3040	58.2
342	55.4	3400	61.5
360	55.7	3600	45.0
400	59.7	3700	52.8
410	48.7	4000	64.0
445	61.1	4150	67.8
450	59.1	4500	58.6
460	53.0	4800	62.1
490	63.1	5800	65.9
502	59.0	7000	62.6
540	64.6	8000	56.1
600	59.8	8400	53.2
640	66.0	9500	44.0
700	59.0	10000	42.0
740	65.5		
760	49.1		
785	63.1		

c) Vin = 1.5V peak to peak

Frequency Hz	Sound Pressure Level Re 0.0002 ubars db	Frequency Hz	Sound Pressure Level Re 0.0002 ubars db
40	45.0	1050	71.3
64	44.0	1150	75.6
88	46.0	1250	67.8
105	51.9	1350	66.9
110	53.2	1450	47.8
120	47.0	1500	59.8
135	55.0	1600	59.7
160	58.7	1710	63.1
190	69.0	1890	54.5
210	59.2	2100	57.8
220	61.0	2200	60.5
240	51.6	2400	52.0
250	59.2	2500	57.1
264	45.0	2660	64.6
280	56.0	2820	66.6
300	61.2	3020	58.1
316	54.2	3100	64.1
340	57.3	3450	69.5
370	58.7	3600	66.1
397	63.0	3800	65.0
410	60.0	4290	71.2
430	63.4	4500	66.1
440	58.8	4980	57.9
490	65.0	5200	65.2
520	63.7	5620	69.1
580	61.0	6250	71.0
620	66.8	6800	63.8
700	61.0	7000	68.3
740	67.2	7600	65.1
790	61.6	8400	59.0
840	65.9	9500	47.0
920	68.2	10000	45.0

TABLE II

SINUSOIDAL FREQUENCY RESPONSE OF FIRST LOUDSPEAKER

WITH VARIED MICROPHONE POSITION

d = 143"
Vpwr supply = 40V
Vin = 2V peak to peak

Frequency Hz	Sound Pressure Level Re 0.0002 ubars db	Frequency Hz	Sound Pressure Level Re 0.0002 ubars db
20	39.0	1060	62.0
40	39.0	1180	66.5
60	40.0	1200	62.3
70	40.0	1280	74.5
75	41.0	1400	47.0
80	43.0	1500	68.0
90	43.5	1600	59.7
100	48.0	1680	54.8
110	43.7	1750	64.0
132	56.0	1840	60.0
140	44.2	1920	63.8
185	59.8	2000	62.8
200	62.8	2080	62.7
208	61.0	2100	49.2
213	50.0	2140	60.5
235	69.0	2200	53.8
250	60.5	2340	67.2
265	26.5	2550	62.5
270	53.2	2740	57.9
295	62.8	2850	67.2
310	57.1	3000	63.2
345	62.7	3120	68.0
350	64.5	3400	67.5
370	55.2	3800	62.5
390	62.8	4000	69.6
410	67.6	4100	65.1
450	67.2	4300	68.9
500	64.0	4900	68.1
580	67.4	5000	65.7
630	66.4	5400	68.6
660	62.0	5800	69.6
720	72.6	6600	69.2
780	65.9	7100	64.2
830	66.1	7300	63.2
860	69.2	8150	67.1
920	67.8	8850	58.0
1000	68.6	10000	49.6

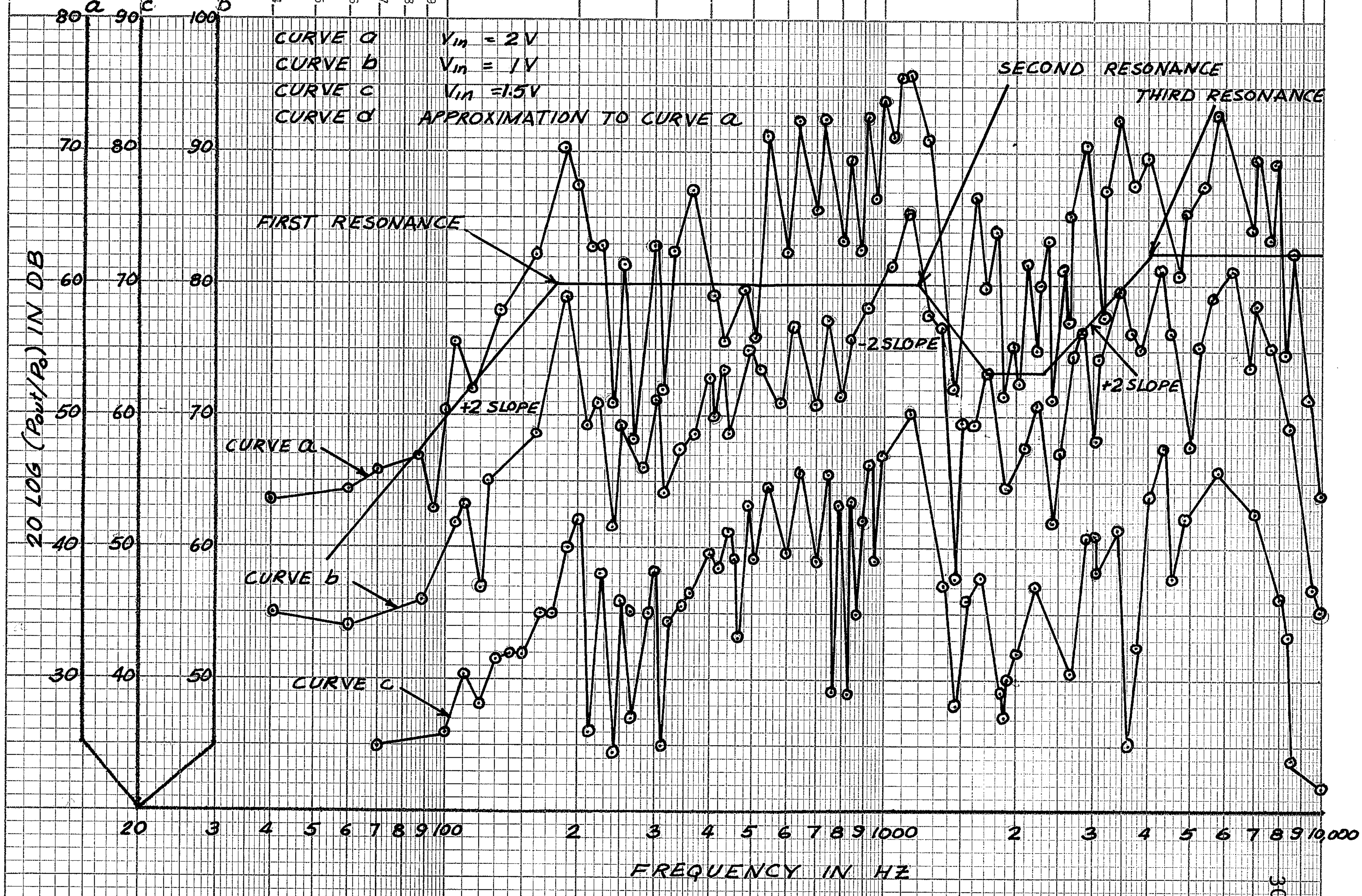


FIG. 3.4 SINUSOIDAL FREQUENCY RESPONSE FOR FIRST LOUDSPEAKER

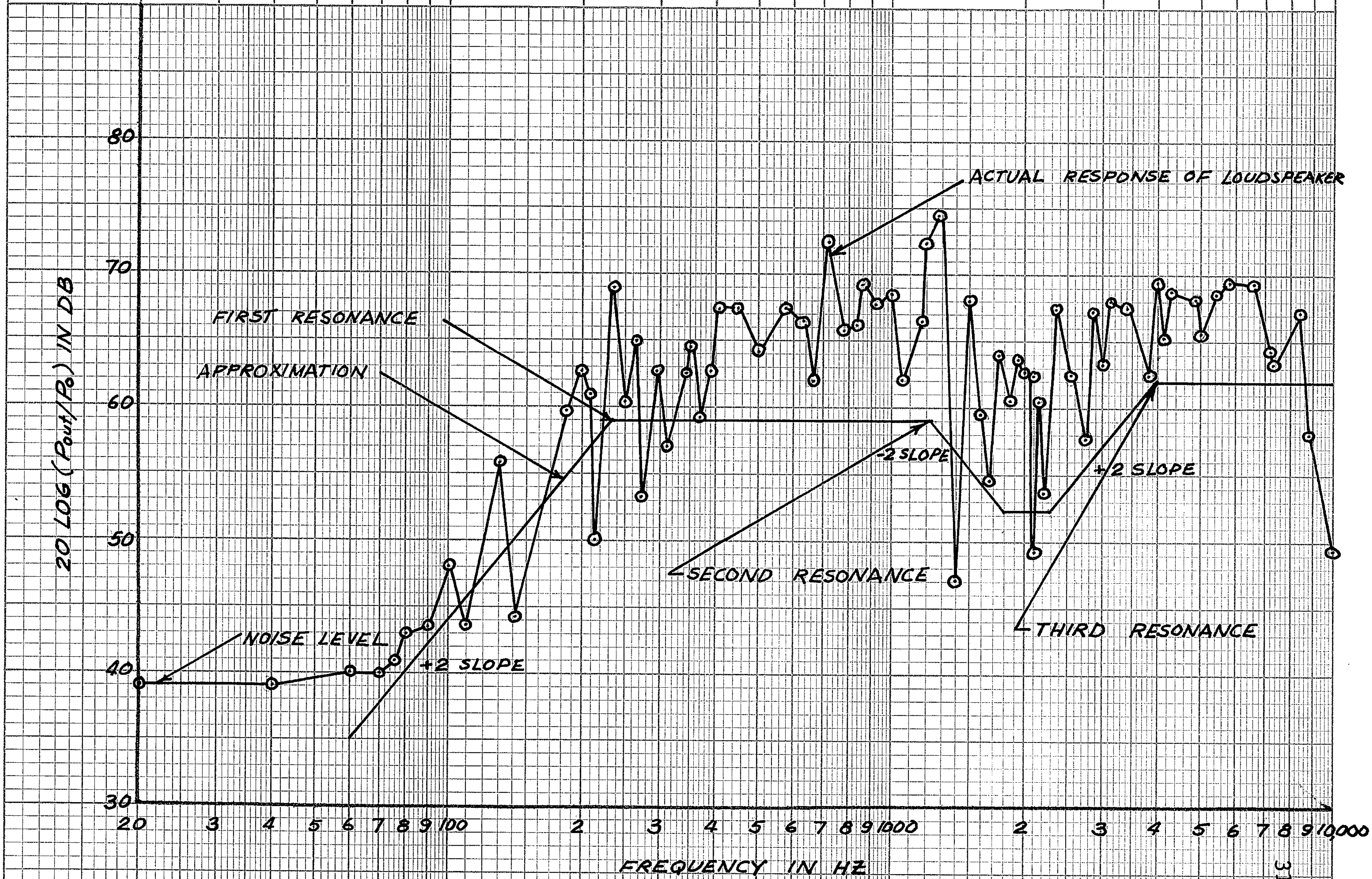


FIG. 3.5 SINUSOIDAL FREQUENCY RESPONSE FOR FIRST LOUDSPEAKER

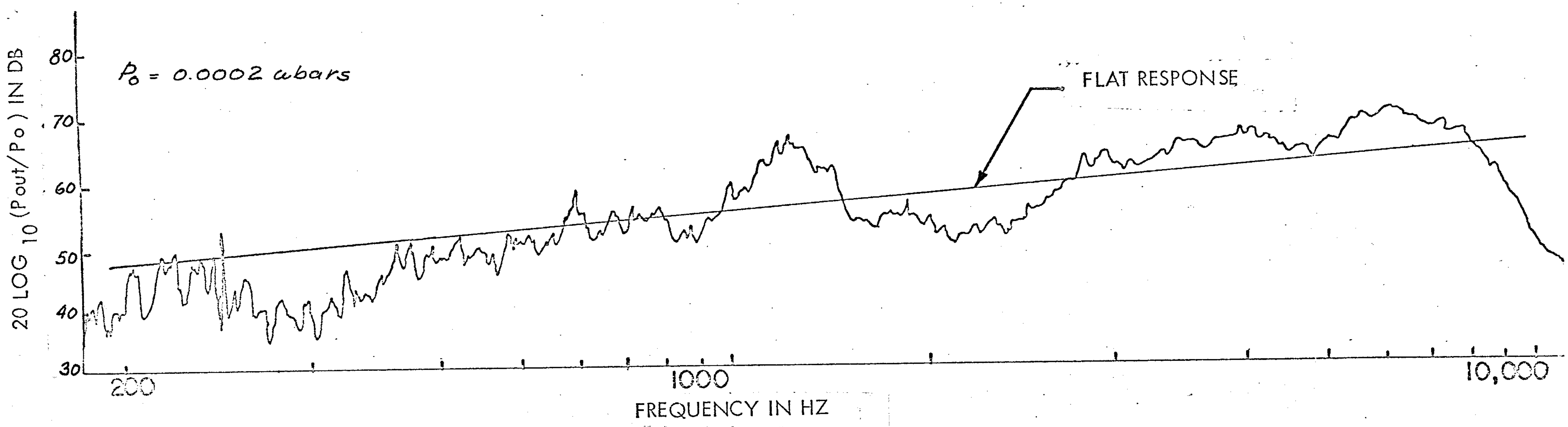


FIG. 3.6 WHITE NOISE FREQUENCY RESPONSE OF FIRST LOUDSPEAKER

data plotted on Fig. 3.4, for 2 volts peak to peak input, and was approximated by piecewise linear approximations. Three resonance points were chosen for the approximation.

$f_{resonance}$	Gain at resonance
190 Hz	10.5 db
1150 Hz	16 db
4000 Hz	8 db

These second order poles are not shown on the figure. With the piecewise linear approximations and second order singularities, a good approximation was obtained to the loudspeaker response.

Since the ear does not detect every resonance shown in the curve, an average response was used for simulation of a loudspeaker.

A + 2 slope initiates the frequency response. The readings at the very low frequencies (< 80 Hz) were largely due to the ambient noise level. At the high frequencies (> 8000 Hz) the frequency response dropped because of the microphone frequency response characteristic[19].

The linearity of the speaker was determined from curves a and b when the input was doubled. At low frequencies (up to 1200 Hz) the loudspeaker was approximately linear as the two curves varied by approximately 6 db. At higher frequencies the response became very erratic and the loudspeaker seemed to be non-linear. Further tests using white noise excitation were required to show when the loudspeaker is linear to the ear.

The results from Test 3.2 are shown on Fig. 3.5. Upon comparing Fig. 3.4 and Fig. 3.5 it was evident that the overall frequency response was similar. This indicated that the transfer function of the loudspeaker remains fairly constant for different locations of the loudspeaker, and different distances between loudspeaker and microphone.

The frequency response in Fig. 3.5 was also approximated with piecewise linear approximations having integer slopes and the following second order poles:

F resonance	Gain at resonance
225 Hz	11 db
1200 Hz	17 db
4000 Hz	8 db

From this approximated curve the transfer function of the loudspeaker was obtained and a simulating network synthesized.

From the results of Test 3.3 a study was made of the variation of resonances in the loudspeaker when subjected to a white noise excitation. Narrowband and one-third octave reading were obtained to approximate the ear's response with critical bands of hearing. A flat response on any of the eight graphs shown in Appendix B for this test was provided by a line having a 3 db per octave slope since the readings were made with narroband and one third - octave detection. This line was chosen to pass through 2700 Hz in order to provide a reference for the resonances. Table III shows the variation and maximum magnitude of peaks and depressions of the eight curves. The peaks occured in the vicinity of 900 - 1400 Hz and 2800 - 8000 Hz. Depressions were located in the neighbourhood of 250 - 400 Hz and 1500 - 2700 Hz.

In Test 3.4 the input voltage into the amplifier was 0.08 volts rms. The results on Fig. 3.6 indicated that the resonances in the loudspeaker response do not shift with a change in environment. This was expected since when white noise excitation was used, a diffuse field was initiated. Thus, in the free field only the resonances of the loudspeaker were measurable.

TABLE III

VARIATION OF LOUDSPEAKER RESONANCES

FIGURE	DISTANCE Loudspeaker to Microphone	PEAKS Frequency Range	PEAKS Maximum Deviation Freq.	PEAKS Maximum Deviation	DEPRESSIONS Frequency Range	DEPRESSIONS Maximum Deviation Freq.	DEPRESSIONS Maximum Deviation
		Hz	Hz	db	Hz	Hz	db
B.1	119"	900 - 1400	1000	8	250 - 350	310	9
		2600 - 8000	6000	8	1400 - 2600	2200	7
B.2	130"	950 - 1400	1250	10	240 - 460	290	12
		2700 - 8000	6000	8	1400 - 2700	2400	6
B.3	93"	900 - 1650	1350	8	280 - 360	320	9
		2600 - 9000	7000	9	600 - 900	780	6
					1650 - 2600	2450	7
B.4	69"	660 - 1450	1100	9	390 - 660	500	7
		2800 - 9000	7000	8	1450 - 2800	2100	7
B.5	97"	900 - 1700	1500	8	260 - 400	300	11
		2800 - 8500	6000	10	1700 - 2800	2400	8
B.6	49"	900 - 1600	1400	9	3800 - 6500	4600	11
		2600 - 8500	6500	10	1600 - 2600	2500	7
B.7	67½"	850 - 1400	1100	7	360 - 600	440	8
		2750 - 800	6000	10	1400 - 2750	2100	6
B.8	121"	950 - 1500	1250	10	250 - 380	280	14
		2800 - 8000	6000	6	1500 - 2800	2200	8

From the tests conducted it was seen that the average loudspeaker frequency response did not vary with input level, change of microphone and loudspeaker position. Due to these tests, linearity can be assumed for the loudspeaker and the effect of the environment disregarded. Hence the loudspeaker frequency response may be used to simulate a loudspeaker by use of a synthesis technique.

3.4 MEASUREMENTS FOR SECOND LOUDSPEAKER

The frequency response of a second loudspeaker was obtained. The apparatus, test setup and method were the same as for tests conducted with the first loudspeaker. The physical characteristics of the second loudspeaker were:

11" (height) x 12" (width) x 8" (depth)

open back baffle

8" speaker

8 ohm impedance

The following test was performed with this loudspeaker:

TEST 3.5 WHITE NOISE FREQUENCY RESPONSE OF LOUDSPEAKER

The frequency response of the loudspeaker was obtained using a white noise excitation. A low impedance amplifier was used.

3.5 RESULTS OF MEASUREMENTS FOR SECOND LOUDSPEAKER

The frequency response of the second loudspeaker is shown on Fig. 3.7 The input voltage of the random noise generator was 0.2 v rms and measurements were conducted with a separation of 165 inches between the microphone and loudspeaker.

A peak was noticeable in the frequency range 2000 Hz to 5000 Hz and a depression existed up to 500 Hz. There were not as many resonances as in the first loudspeaker and the response was more linear than for the first loudspeaker.

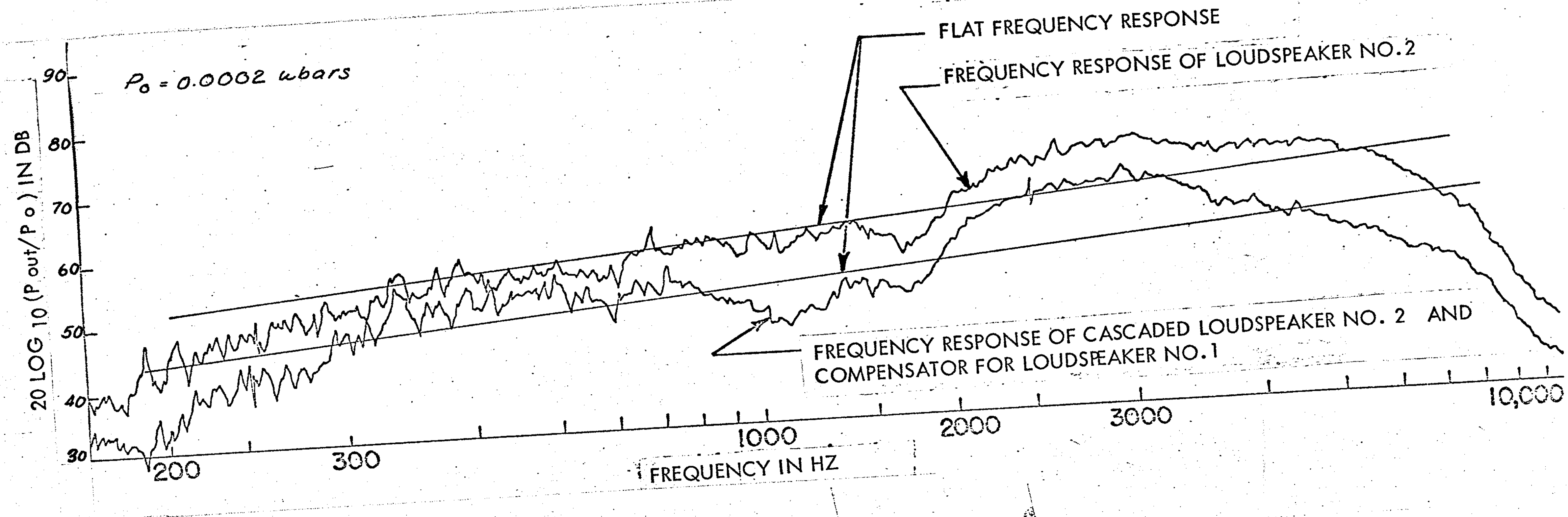


FIG. 3.7 WHITE NOISE FREQUENCY RESPONSE OF SECOND LOUDSPEAKER.

CHAPTER IV

SIMULATOR AND COMPENSATOR DESIGN FOR LOUDSPEAKER

4.1 SIMULATING NETWORK OF A LOUDSPEAKER

From the pure tone frequency response measurements in Chapter 3, the simulator of the loudspeaker was synthesized. The pure tone frequency response was initially approximated by piecewise linear approximations of first order zeros and second order poles, as described in section 3.3. Taking into consideration the psychoacoustic effects listed in Chapter II, the loudspeaker was then simulated.

Initially the sinusoidal excitation response of the first loudspeaker, as shown on Fig. 3.5, was approximated by first order zeros and second order poles. Instead of approximating the loudspeaker by both complex poles and zeros, only complex poles were used. Three main resonance frequencies were found in Chapter 3, Test 3.2 at 225 Hz, 1200 Hz and 4000 Hz, with respective gains of 11 db, 17 db and 8 db referred to the gain at 180 Hz. The response rose with a + 2 slope up to the first resonance (225 Hz) then remained flat up to the next resonance (1200 Hz). Beyond 1200 Hz the gain decreased at a -2 slope up to 1850 Hz, from where it flattened out. At 2340 Hz the plot again had a + 2 slope up till the next resonance at 4000 Hz. Beyond this resonance frequency the response was considered flat. This response was described by an approximated transfer function of the simulator as:

$$G_L = \frac{K_L \quad N_L}{D_L} \qquad \text{--- } 4.1$$

where

K_L = constant

$N_L = S^2(S+2\pi 1850)^2(S+2\pi 2340)^2$

$D_L = \left[S^2+2(.141)2\pi 225\ S+(2\pi 225)^2\right]\left[S^2+2(.07)2\pi 1200\ S+(2\pi 1200)^2\right]$
$\left[S^2+2(.224)2\pi 4000S+(2\pi 4000)^2\right]$

The equations for synthesizing these first order zeros and second order poles are listed in Appendix A. A Fairchild uA709C high performance operational amplifier was used for designing the various networks.

Although equation 4.1 could be synthesized in one stage by methods employing negative impedance converters, three stages were chosen, one for each resonance. The network simulating the loudspeaker is shown in Fig. 4.1. Each network synthesized was checked for stability. In this consideration, the pole inherent to the integrated circuit operational amplifier must be taken into account.

4.2 COMPENSATING NETWORK FOR LOUDSPEAKERS

Having obtained the equation and network of the simulator

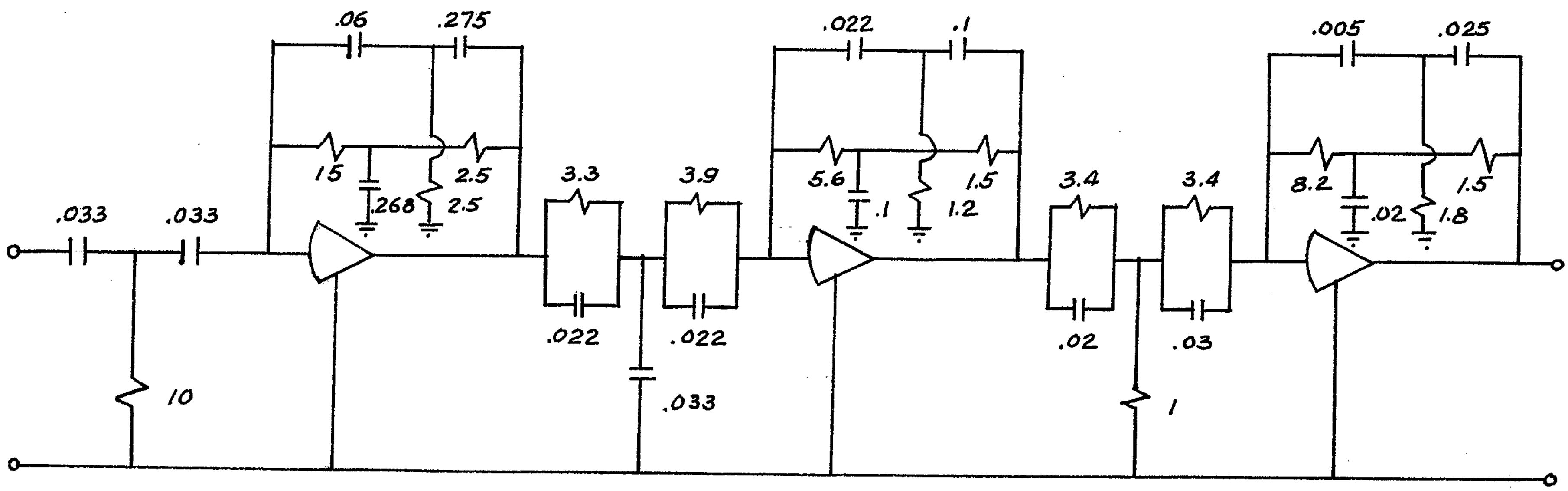


FIG. 4.1 SIMULATOR NETWORK FOR FIRST LOUDSPEAKER

NOTE : RESISTORS ARE IN KΩ AND CAPACITORS IN μF the compensator was synthesized next. Beranek stated that a flat frequency response from 70 Hz to 7000 Hz is desired. For our loudspeaker a flat response at 70 Hz would require a large amount of power and significant distortion would result from obtaining this loudspeaker response at these low frequencies. For these reasons the desired flat transfer function was taken above 180 Hz as described below.

$$G_D(S) = \frac{K_D \quad S^2}{(S+2\pi 180)^2} \qquad \text{---4.2}$$

where G_D = desired frequency response

K_D = constant

From pole zero cancellations of equations 4.2 and 4.1 the transfer function of the compensator was given by:

$$G_{C1} = \frac{K_{C1} \quad N_{C1}}{D_{C1}} \qquad \text{---4.3}$$

where K_{C1} = constant

$N_{C1} = D_L$

$D_{C1} = (S+2\pi 180)^2 (S+2\pi 1850)^2 (S+2\pi 2340)^2$

Three stages were used to synthesize this function. These provided isolation between the three resonant points and allowed for variation of the resonances.

Two types of parameter variation were provided for the compensator. The parameters of the twin T circuit (circuit 6, App. A Table VI) used to synthesize the resonance point were provided with the variations shown in Fig. 4.2.

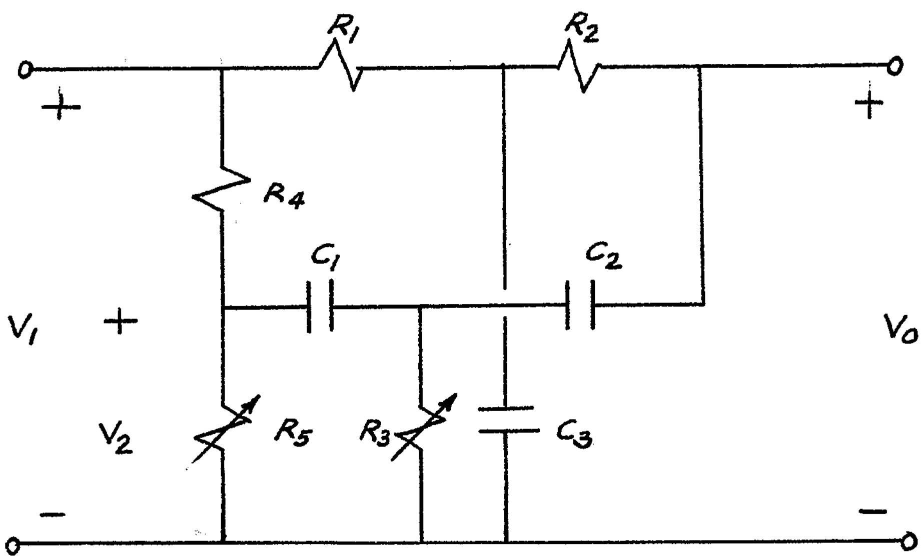


FIG. 4.2 CIRCUIT FOR TRANSFER FUNCTION: $\frac{S^2+\alpha S+1}{S+1}$

Variation of R3 from the calculated value provided a change in the damping factor of the circuit. This is analogous to varying the Q of a circuit (Q and damping factor are inversely proportional). The change in R3 shifted the zero on the pole - zero graph parallel to the real axis. This changes α in the transfer function and thus only the Q of the circuit is changed.

Variation of R5 provides a change in the voltage division ratio at the input. The resistor R5 is chosen approximately ten times as great as R_4. As R_5 decreases, the decrease in V_2 shifts the natural frequency of the resonance to the input. The Q of the circuit is slightly degraded, however the desirable value of Q can be obtained by varying R_3

With the above two types of adjustments, the approximated compensator was varied to provide better compensation for the loudspeaker and was utilized for other loudspeakers. Also, by cascading the simulator and compensator the behaviour of the compensated assembly was tested electrically.

With a minimum of adjustment of parameters for the first loudspeaker compensator, the second loudspeaker was compensated.

Each stage of the compensator should have approximately a unity D.C. gain. A gain greater than unity would not allow higher input voltage levels to be used as the output voltage swing of the u A 709 C operational amplifier is about 5 volts peak to peak. A much lower gain would necessitate the use of a very high output power amplifier with the loudspeaker to provide audible output of the loudspeaker.

As the low frequency response (less than 180 Hz) is unchanged, the distortion of the compensated loudspeaker assembly would not be increased.

A change of pole position of the first loudspeaker compensator from 1500 Hz to 1850 Hz and variation of parameters, as described above, provided compensation for the second loudspeaker. The equation of the compensator transfer function was:

$$G_{C2} = \frac{K_{C2} \quad N_{C2}}{D_{C2}} \qquad \text{--- 4.4}$$

where K_{C2} = constant

$N_{C2} = D_L$

$D_{C2} = (S+2\pi 180)^2(S+2\pi 1500)^2(S+2\pi 2340)^2$

The approximated compensator for the first loudspeaker is shown in Fig. 4.3 and for the second loudspeaker is shown in Fig. 4.5. Upon variation of parameters, as described above, when cascaded with the loudspeaker, the desired frequency response was obtained. The networks obtained are shown on Fig. 4.4 and Fig. 4.6.

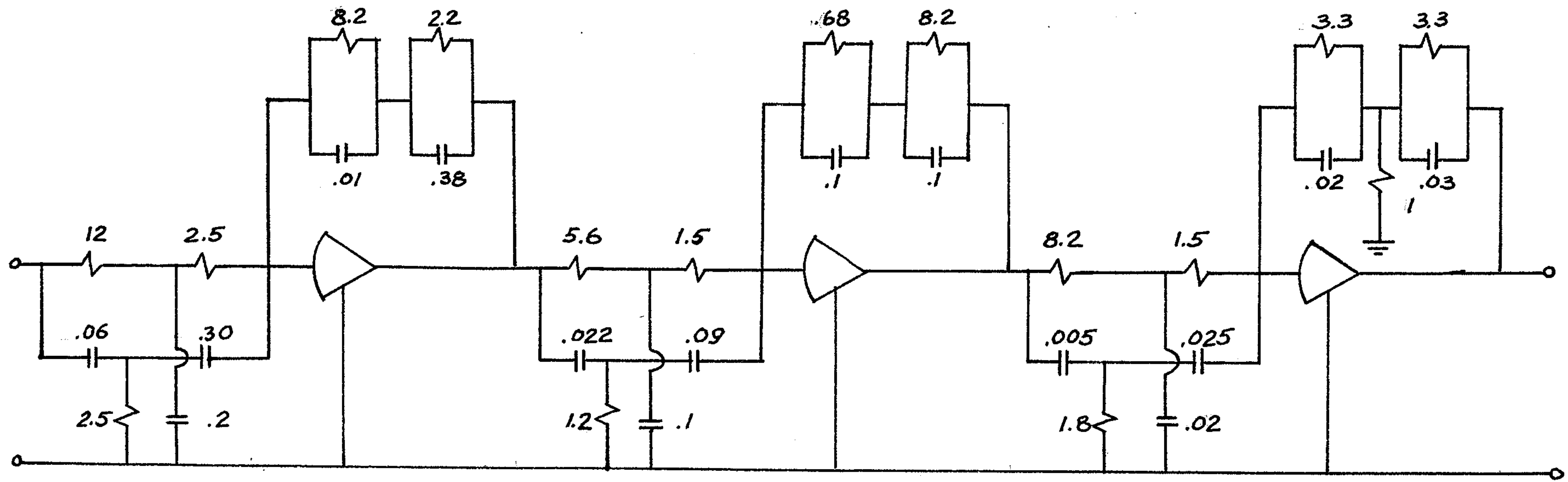


FIG. 4.3 APPROXIMATED COMPENSATED NETWORK FOR FIRST LOUDSPEAKER

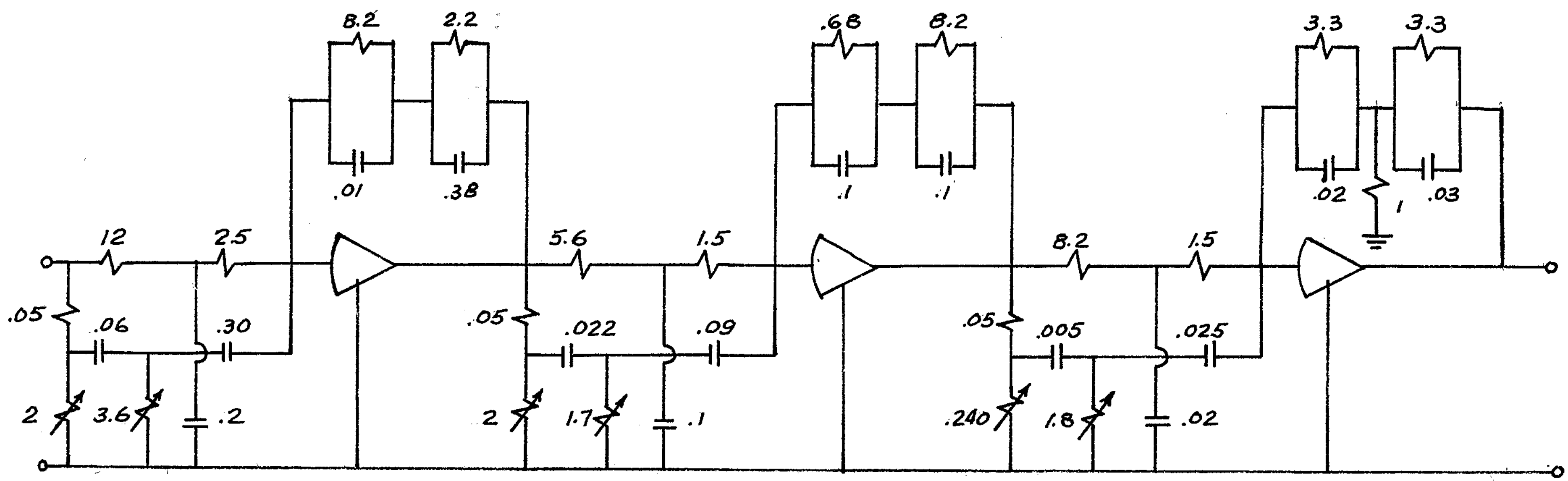


FIG. 4.4 ACTUAL COMPENSATOR NETWORK FOR FIRST LOUDSPEAKER

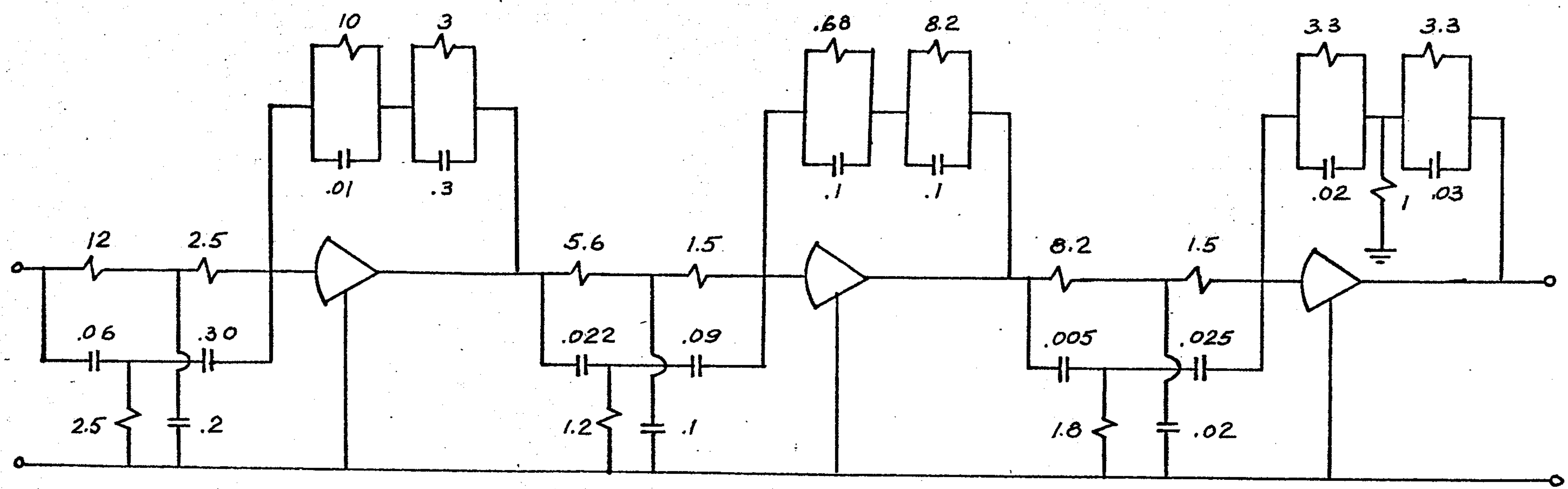


FIG. 4.5 APPROXIMATED COMPENSATOR NETWORK FOR SECOND LOUDSPEAKER

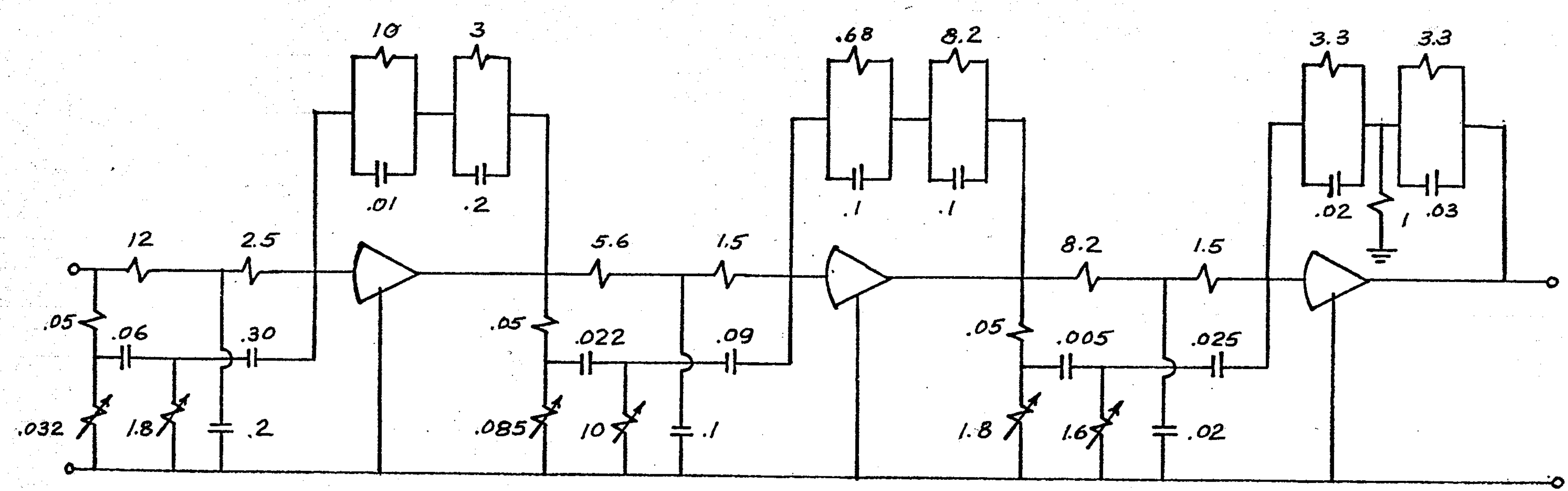


FIG. 4.6 ACTUAL COMPENSATOR NETWORK FOR SECOND LOUDSPEAKER

4.3 FREQUENCY RESPONSE MEASUREMENTS OF SIMULATOR AND COMPENSATOR FOR FIRST LOUDSPEAKER

4.3.1 FREQUENCY RESPONSE OF SIMULATOR

The frequency response of the simulator shown in Fig. 4.1 was obtained by standard experimental methods. The data obtained from these measurements is listed in Appendix C and is also plotted in Fig. 4.7. Initially the frequency response had a + 2 slope. Three resonances were obtained at 220 Hz, 1330 Hz and 4000 Hz with approximate gains of 9 db, 20 db and 8 db referred to the gain at 180 Hz.

4.3.2 FREQUENCY RESPONSE OF APPROXIMATED COMPENSATOR

The frequency response of the compensator network was obtained as shown in Fig. 4.2. Two different input levels were used to test the linearity of the circuit and to check whether the circuit introduced intermodulation noise.

The data obtained from these measurements is listed in Appendix C. A plot of the values obtained is shown in Figures 4.7 and 4.8. As can be seen from these curves, three resonances were present at 210 Hz, 1200 Hz and 4000 Hz. Since the curve in Fig. 4.8 was fairly linear, intermodulation products were negligible.

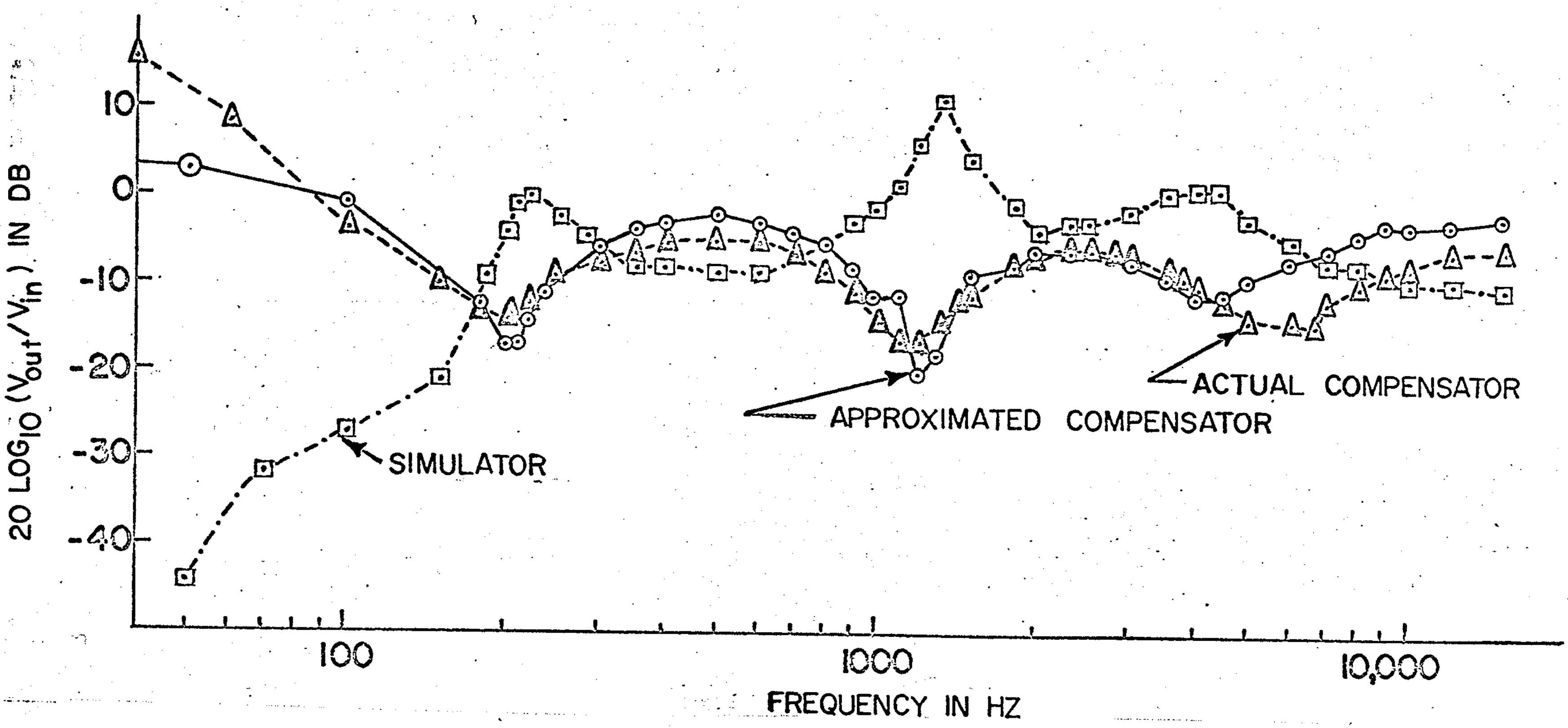


FIG. 4.7 BODE PLOT OF SIMULATOR, APPROXIMATED AND ACTUAL COMPENSATORS FOR FIRST LOUDSPEAKER

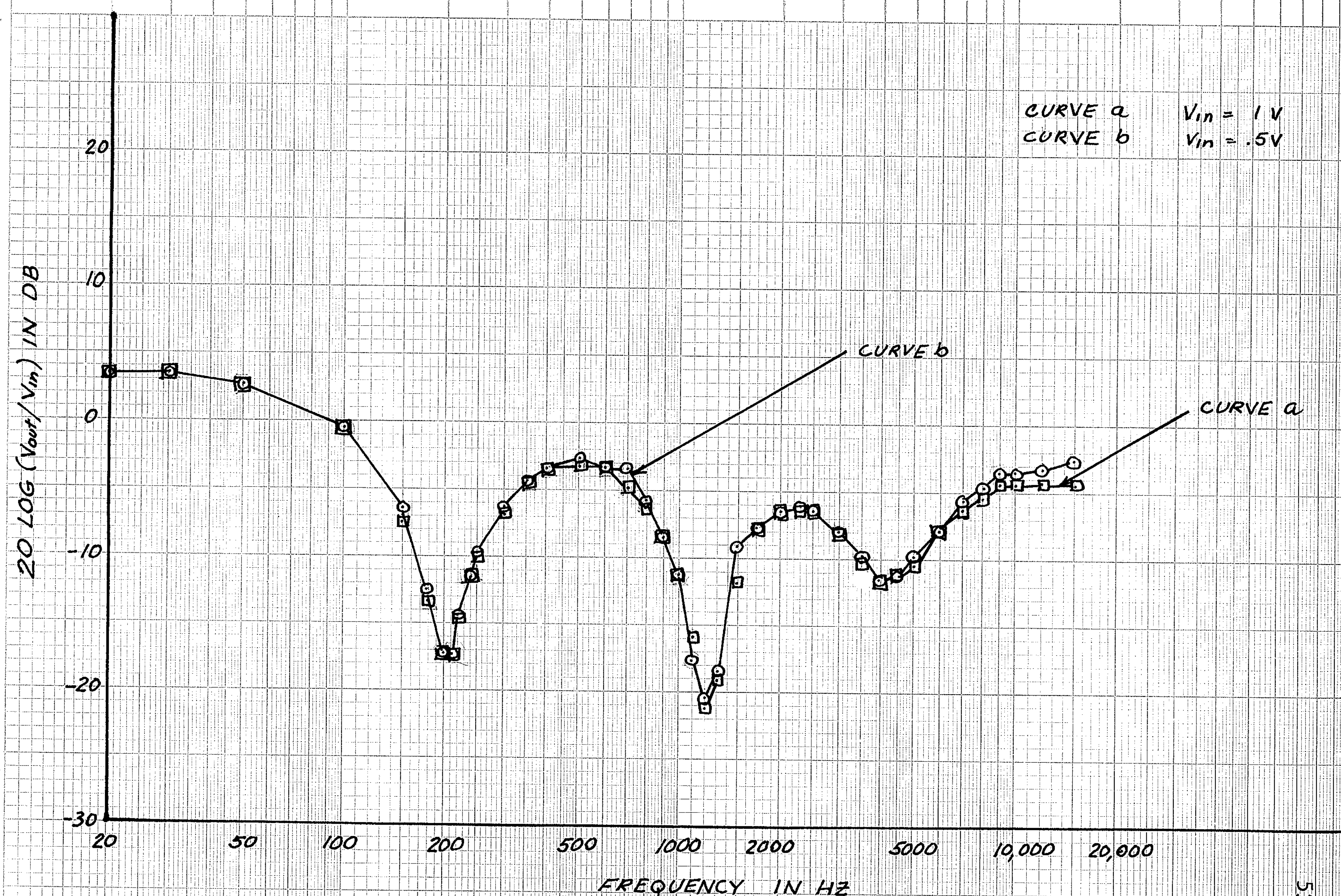


FIG. 4.8 BODE PLOT OF APPROXIMATED COMPENSATOR FOR FIRST LOUDSPEAKER

4.3.3 FREQUENCY RESPONSE OF ACTUAL COMPENSATOR

The frequency response of the circuit shown in Fig. 4.4 was obtained and the data, given in Appendix C, is plotted in Fig. 4.7. Upon comparing this frequency response and that of the approximated compensator, it became evident that the damping factor was greater at 225 Hz, and 1200 Hz for the actual compensator. Also, in order to provide a desired flat response, the third resonance was shifted from 4000 Hz to 6,800 Hz. Hence this network would provide a pleasing sound to the ear when cascaded with the loudspeaker.

4.3.4 FREQUENCY RESPONSE OF CASCADED SIMULATOR AND ACTUAL COMPENSATOR

The frequency response of the simulator and actual compensator was obtained and the results are listed in Appendix C and plotted in Fig. 4.9. As the curve was not flat as desired, some error was involved in approximating the loudspeaker transfer function and then synthesizing this function. The variation from flatness was up to 6 db. This indicates that some error was involved in approximating and synthesizing the simulating network.

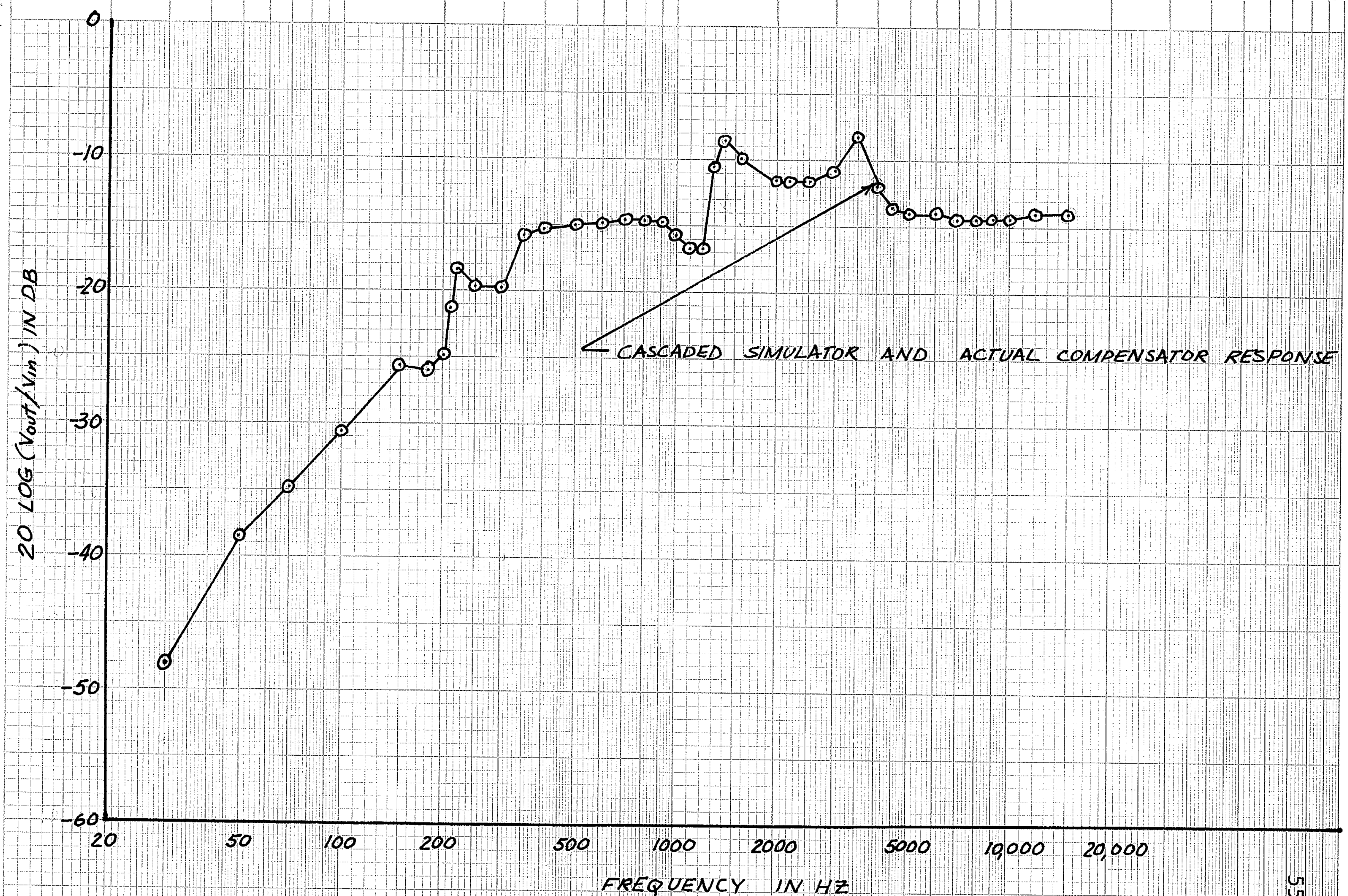


FIG. 4.9 BODE PLOT FOR CASCADED SIMULATOR AND ACTUAL COMPENSATOR

4.4 FREQUENCY RESPONSE MEASUREMENTS OF COMPENSATOR FOR SECOND LOUDSPEAKER

4.4.1 FREQUENCY RESPONSE OF APPROXIMATED COMPENSATOR

The frequency response of the approximated compensator was measured and is shown in Fig. 4.5. The compensator was also tested for linearity. The results are listed in Appendix D and plotted in Fig. 4.10. Three resonances were present at 210 Hz, 2100 Hz and 4000 Hz. The results also indicate that intermodulation products would be minimal as the network was almost perfectly linear.

4.4.2 FREQUENCY RESPONSE OF ACTUAL COMPENSATOR

The frequency response of the actual compensator shown in Fig. 4.6 was obtained. The data is listed in Appendix D and plotted in Fig. 4.11. Comparing this result with the previous test, certain observations were apparent. The natural frequency at 225 Hz was shifted to 250 Hz and the damping factor was greater, the resonance at 1200 Hz was eliminated, and at the higher frequencies the shape remained the same but there was a loss of about 7 db.

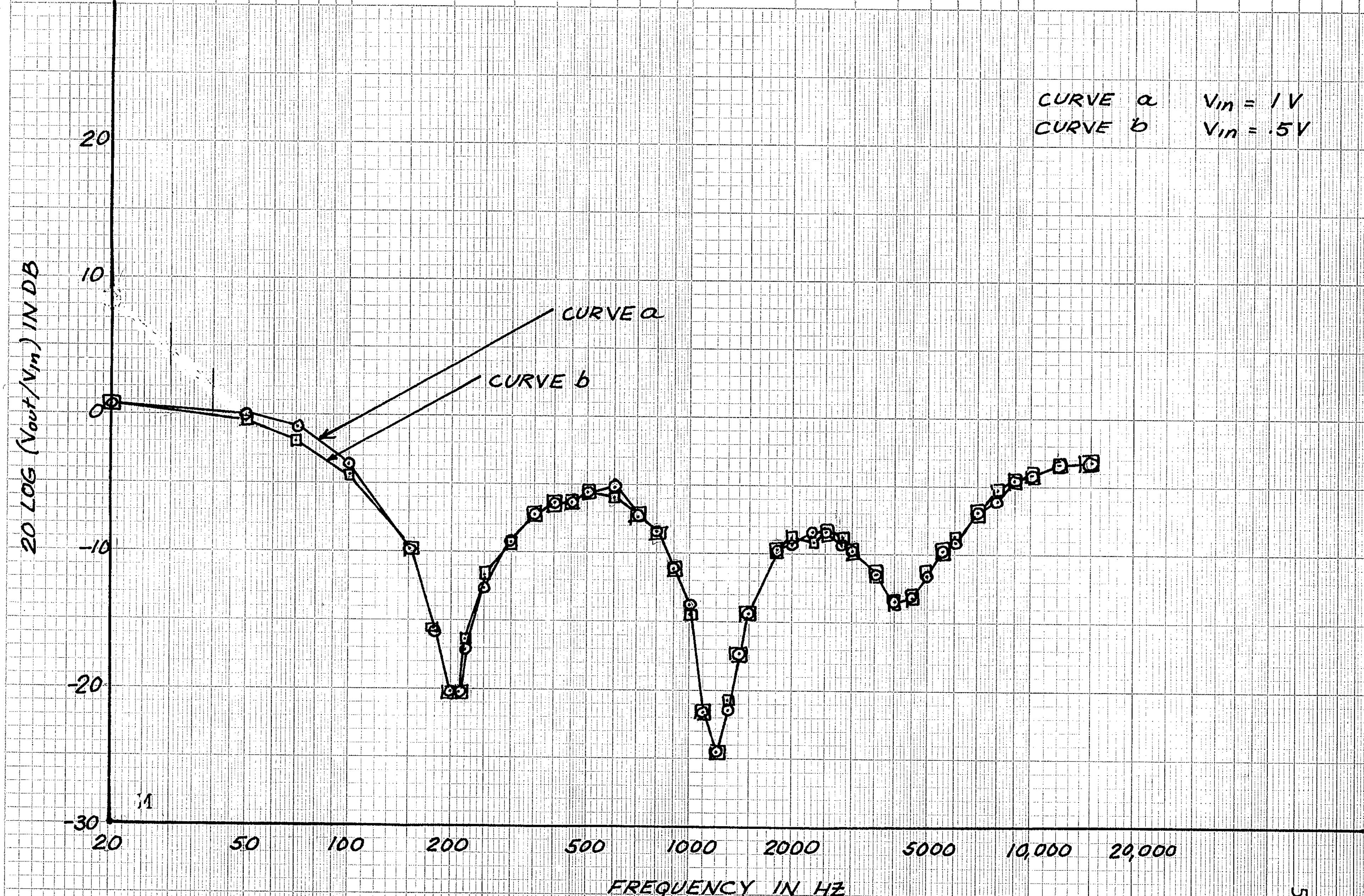


FIG. 4.10 BODE PLOT FOR APPROXIMATED COMPENSATOR FOR SECOND LOUDSPEAKER

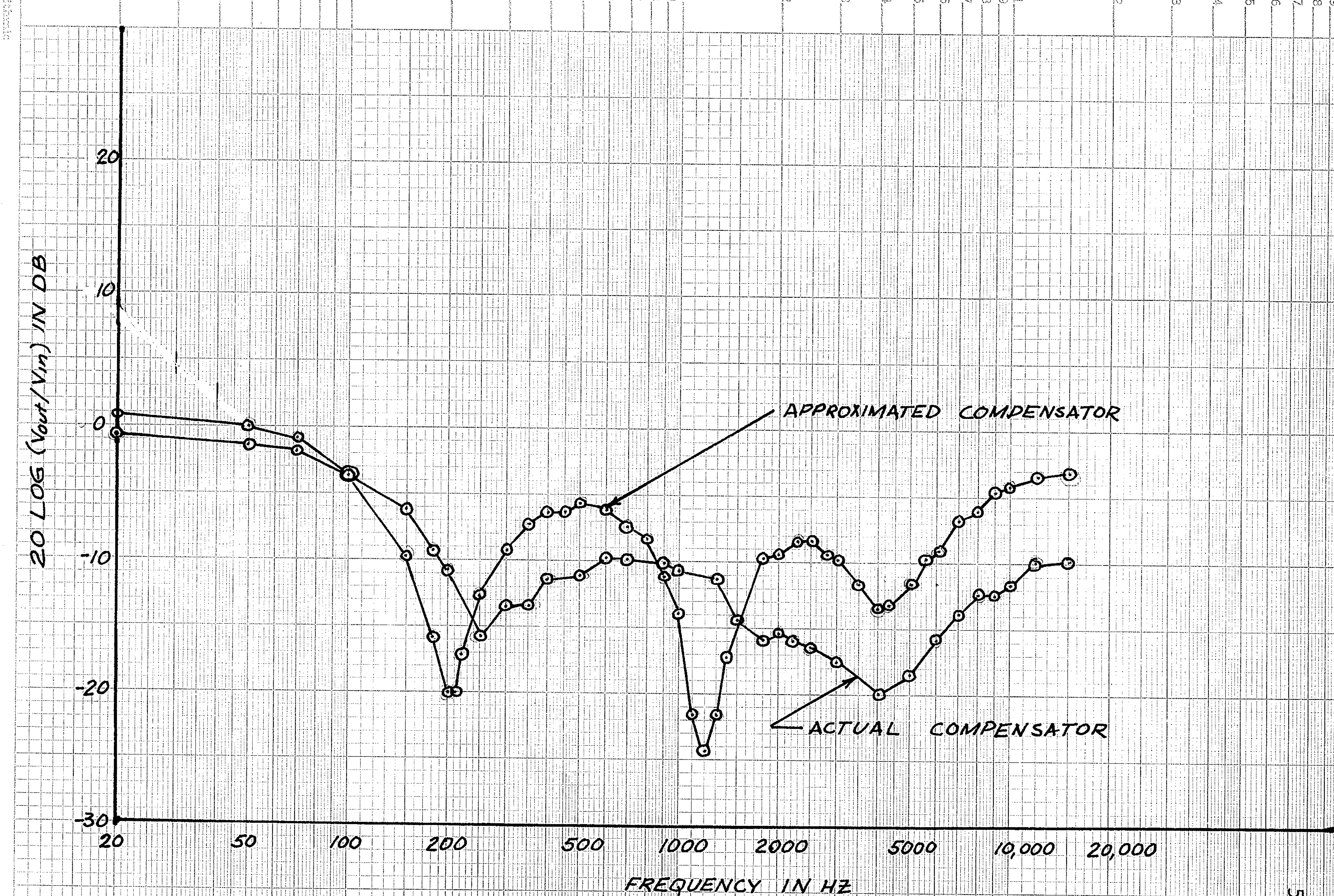


FIG. 4.11 BODE PLOT FOR APPROXIMATED AND ACTUAL COMPENSATORS FOR SECOND LOUDSPEAKER

CHAPTER V

COMPENSATED LOUDSPEAKER TESTS

5.1 TESTS FOR FIRST LOUDSPEAKER

In order to study the operation of the compensated loudspeaker assembly, a white noise excitation frequency response curve was obtained for the compensated loudspeaker. The method was identical to that of Test 3.3 in Chapter 3. The block diagram of the setup is shown in Fig. 5.1.

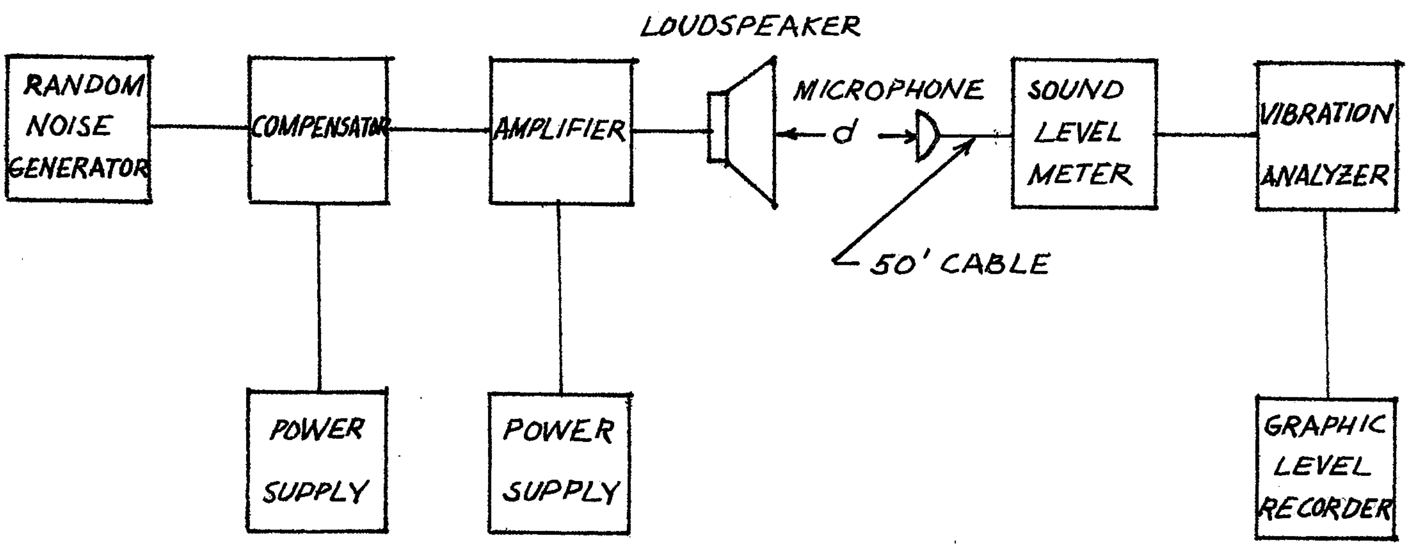


FIG.5.1 EXPERIMENTAL SETUP FOR WHITE NOISE COMPENSATED LOUDSPEAKER FREQUENCY RESPONSE

The amplifier shown in Fig. 5.1 is a low impedance type and the required power supply voltage is 40 V D.C. The power supply voltages for the operational amplifiers were ± 15 V D.C.

The compensator used in the following tests is shown in Fig. 4.3. Different conditions were introduced to study the behaviour of the compensated assembly. The graphs providing the results are included in Appendix E. Table IV lists all the tests conducted. The results were as follows:

TEST 5.1:COMPENSATED AND UNCOMPENSATED LOUDSPEAKER FREQUENCY RESPONSE

This test shows the uncompensated and compensated loudspeaker frequency response. There was a marked improvement in flatness for the compensated frequency response. The resonances at 225 Hz, 1200 Hz and 4000 Hz were flattened. The reading was obtained using 1/3 octave bands, and from the compensated loudspeaker readings, a definite change in fidelity of the loudspeaker is observed.

TESTS 5.2 AND 5.3:COMPENSATED LOUDSPEAKER LINEARITY TESTS

Two tests of the compensated loudspeaker assembly for linearity were carried out. They indicated that the loudspeaker was approximately linear over the frequency band of interest. It was noted that since a white noise excitation was used, the effects of the enclosure were negligible for these measurements.

TABLE IV

TESTS FOR FIRST LOUDSPEAKER

Test	Figure	Distance from loudspeaker to microphone	Vin Vrms.	Special conditions
5.1	E 1	143"	.08	
5.2	E 2	143"	a).08 b).16	
5.3	E 3	143"	a).08 b).16	
5.4	E 4	178"	.16	
5.5	E 5	111"	.16	
5.6	E 6	70"	.16	
5.7	E 7	70"	.16	Ambient noise
5.8	E 8	130"	.16	Loudspeaker position changed.
5.9	E 9	130"	.16	Loudspeaker position same as 5.8 3 chairs introduced 1 behind microphone 2 on side of microphone
5.10	E 10	130"	.16	Loudspeaker position same as 5.8 3 chairs introduced 1 - 2 yards in front of speaker 2 - on side of micro-phone.

All levels of excitation may hence be compensated, since the loudspeaker is approximately linear.

TESTS 5.4, 5.5 AND 5.6 - COMPENSATED LOUDSPEAKER TESTS FOR MICROPHONE POSITION VARIATION

These tests determined the effect of changing the listening position on the frequency response. It may be concluded from the results that the listening position did not affect what the ear detects. This was expected, as the effect of the enclosure was negligible.

TEST 5.7 AMPIENT NOISE LEVEL IN ENCLOSURE

This test provided the level of the ambient noise in the microwave anechoic chamber. As can be observed, the ambient noise in the chamber was of such low level that other readings were not affected.

TEST 5.8 COMPENSATED LOUDSPEAKER TEST FOR LOUDSPEAKER POSITION CHANGE

In this test the loudspeaker position was changed. The compensated frequency response was still, however, very close to the desired response.

TESTS 5.9 AND 5.10. COMPENSATED LOUDSPEAKER TESTS FOR ENCLOSURE CHARACTERISTICS CHANGE

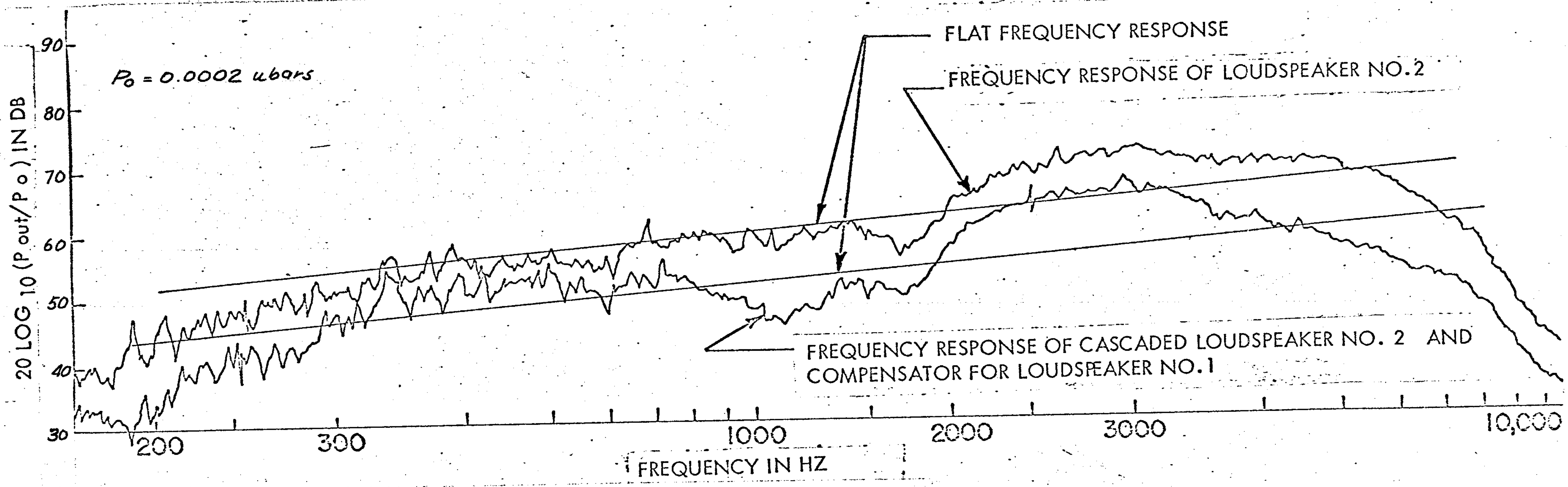
In these tests new objects were introduced into the enclosure at various positions. The compensated loudspeaker response still remained the same as before - very close to the desired flat response.

The fact that the loudspeaker was approximately linear meant that only the Bode plot was required to specify the loudspeaker transfer function, as the phase is related to the gain plot. Thus a flat frequency response indicated a fast transient response, which is very desirable in a loudspeaker

5.2 TESTS FOR SECOND LOUDSPEAKER

In order to show the flexibility of the method, the second loudspeaker was tested. The flat frequency response of the second loudspeaker is shown on Fig. 5.2. In order to compensate the second loudspeaker, the compensator of the first loudspeaker was initially cascaded with the second loudspeaker. The frequency response obtained, as shown in Fig. 5.2, was much worse than for the uncompensated loudspeaker. Parameters were varied, as described in Section 4.2, and a new compensated frequency response was obtained and shown in Fig. 5.3.

As can be seen from Fig. 5.3, a flat response was obtained above 150 Hz, approximately. The response above 4000 Hz dropped below the reference line and there was a depression in



10.

FIG. 5.2 WHITE NOISE FREQUENCY RESPONSE OF SECOND LOUDSPEAKER

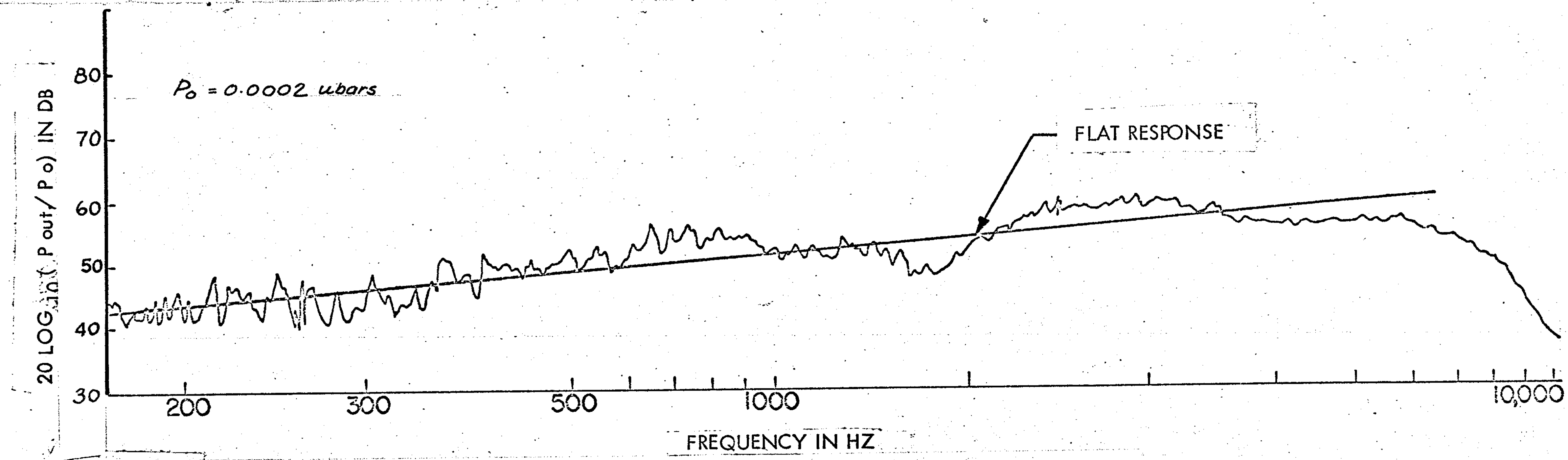


FIG. 5.3 WHITE NOISE FREQUENCY RESPONSE OF SECOND COMPENSATED LOUDSPEAKER

the frequency response between 1500 - 2000 Hz. Although the variation was greater in some cases than the allowable 3 db, the response approximated the desired response much closer than the initial uncompensated response.

5.3 PSYCHOACOUSTIC TESTS

Subjective tests were conducted to provide another measure of the validity of our approach.

The following apparatus was employed in the measurements:

Turntable.

Amplifier with voltage gain of 10

Actual compensator for Second Loudspeaker

Heathkit 25 watt amplifier with A A compensator

Second loudspeaker.

Record - "Getting Romantic" Side 1, by the Swingle Singers.

The equipment was set up as shown in Fig. 5.4.

Eight listeners were brought in, one or two at a time, and asked to judge the quality of the sound. The compensator was switched in manually without knowledge of the observers.

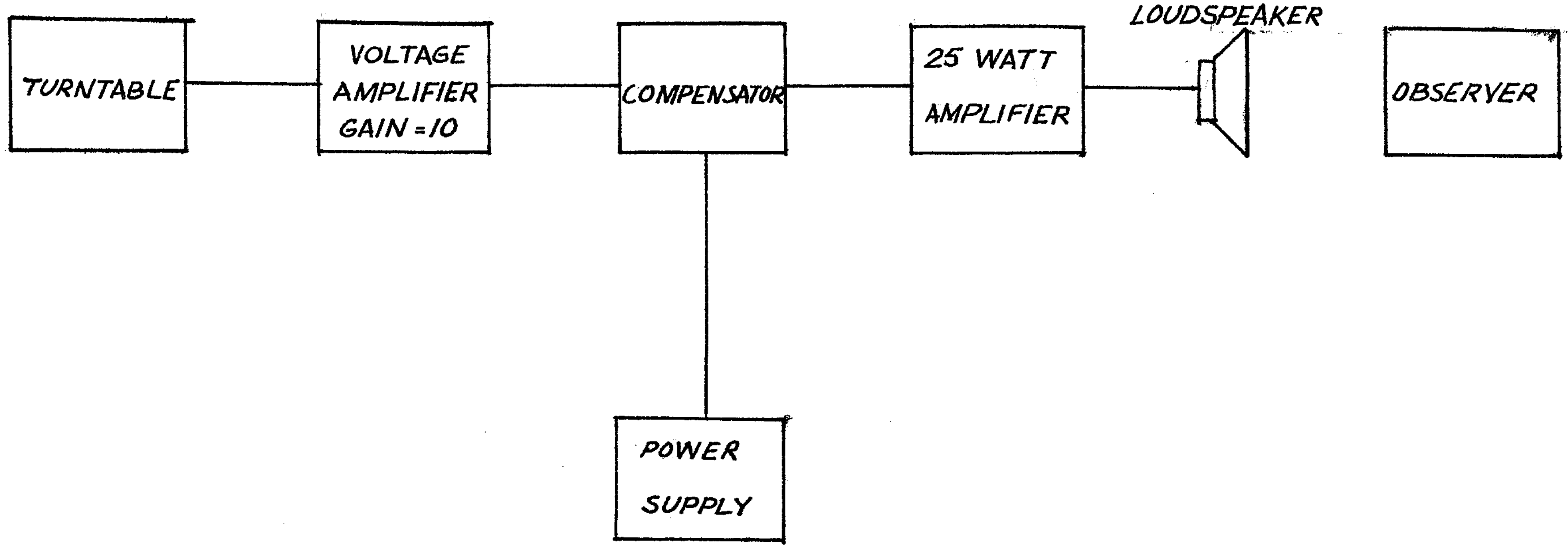


FIG. 5.4 EXPERIMENTAL SETUP FOR SUBJECTIVE TESTS

The listeners were asked whether the sound was of equal loudness in both cases before making their decision. The results obtained are shown in Table V.

The listeners were able to distinguish the compensated assembly and to make definite comments about its performance as shown in Table V. The unanimous decision of all listeners was that the compensated response was much more pleasing to the ear.

TABLE V

PSYCHOACOUSTIC TEST RESULTS

Listeners	Comments
Dr. R. W. Menzies	Showed a marked increase in bass. The sound was more pleasing.
Mrs. R. W. Menzies	Better bass response. Sound is much better.
1 graduate student	Much better response with compensator.
Dr. G. W. Swift	Resonances not present, better bass response.
2 graduate students	Much better bass. Better articulation.
1 graduate student	Much better response.
Dr. H. K. Kim	Immediate change in listening with compensator, for the better. Response much better. High frequencies not as pronounced.

CHAPTER VI

CONCLUSIONS

It has been demonstrated that a loudspeaker may be compensated by means of active circuit synthesis employing RC elements and integrated circuits.

Three operational amplifier stages were used in the compensator mainly to provide isolation and individual adjustment of the damping factors of the resonant twin T circuits and shifting of their natural frequencies. These features were important to provide the desired frequency response and design flexibility which cannot be achieved by a smaller number of stages.

Since the compensated loudspeaker was approximately linear, its flat frequency response meant that it had a fast transient response. This characteristic is very desirable for loudspeakers.

By means of objective and subjective tests, it has been shown that the compensated response is more natural and pleasing to the ear. A compensator was built for one loudspeaker and after adjustment of parameters was applied to another loudspeaker to provide the desired flatness.

It is concluded that this type of compensator should be incorporated with preamplifiers to improve the frequency response of loudspeakers.

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APPENDIX A

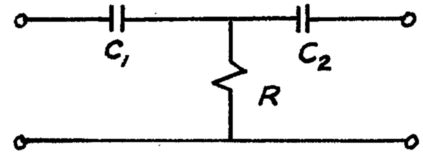
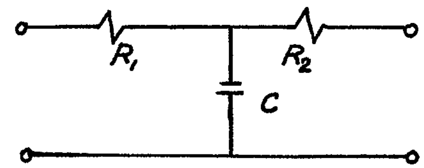
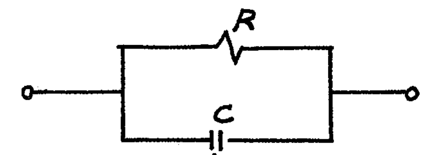
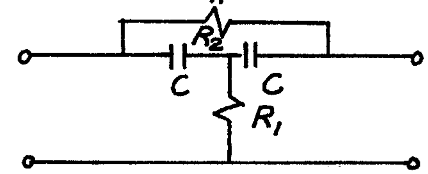
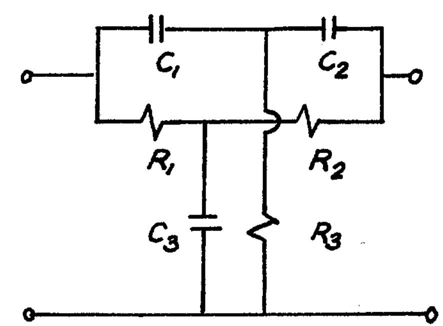
DESIGN EQUATIONS FOR SYNTHESIS OF POLES AND ZEROS

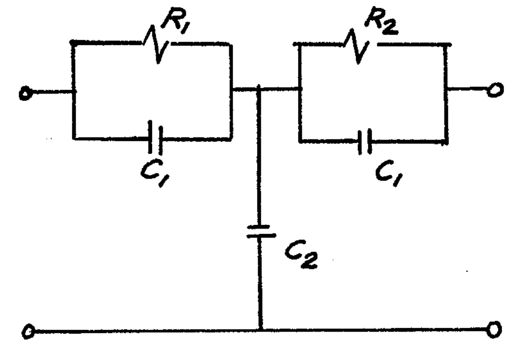
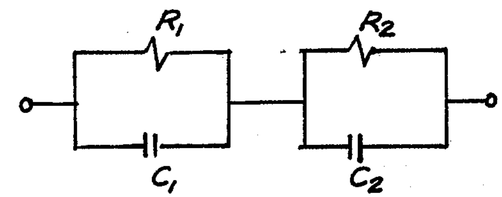
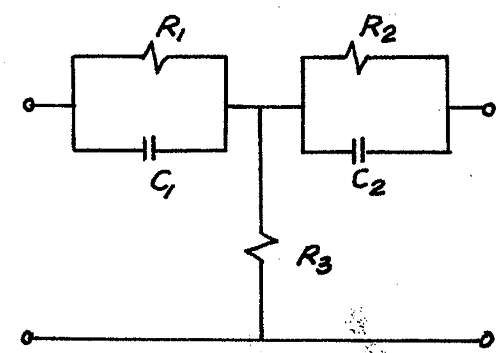
The networks shown in Table VI were considered when designing the loudspeaker simulator and compensator. This table shows the transfer function to be compensated, its short circuit admittance parameter, circuit configuration and design formula.

Further information for designing a complex pair of zeros or poles of a certain damping factor and natural frequency is provided in Fig. A.1.

TABLE VI

DESIGN EQUATIONS

	Transfer Function	Short Circuit Admittance Parameter	Circuit Configuration	Design Equation
1.	$\frac{S^2}{S+a}$	$-Y12 = \frac{S^2 C_1 C_2 / C_1 + C_2}{S + G/C_1 + C_2}$		$a = \frac{G}{C_1 + C_2}$
2.	$\frac{1}{S+a}$	$-Y12 = \frac{G_1 \; G_2/C}{S + G_1 + G_2/C}$		$A = R_1 + R_2$ $a = \frac{G_1 + G_2}{C}$
3.	$\frac{S}{S+a}$	$-Y12 = \frac{S \; G}{S + G/C}$		$a = G/C$
4.	$S + a$	$-Y12 = \frac{S + G/C}{R}$		$A = R$ $a = G/C$
5.	$\frac{S^2 + \alpha S + 1}{S + \alpha}$	$-Y12 = \frac{C}{2} \; \frac{S^2 + S2G/C + G_1 \; G_2}{S + G_1/2C}$		$A = R_2$
6.	$\frac{(S+1)(S^2 + \; S+1)}{(S+\sigma 1)(S+\sigma 2)} \approx \frac{S^2 + \alpha S + 1}{S+1}$	$-Y12 = \frac{S^2 + \alpha S + 1}{S + 1}$		$\alpha = \frac{1}{Q}$ $b = (2.5 - \alpha)\frac{(1+\alpha)}{2+\alpha}$ $C_1 = \frac{b}{2\pi fo}$ $R_1 = \frac{1}{b}$ $C_2 = \frac{b}{b - 1)2\pi fo}$ $R_2 = \frac{b-1}{b}$ $C_3 = \frac{b^2}{(b-1)(1+\alpha) \; 2\pi fo}$ $R_3 = \frac{(b-1)(\alpha+1)}{b^2}$

	Function	Admittance Parameter	Configuration	Equation
7.	$\frac{(S+b)(S+c)}{(S+a)}$ $a < b < c$	$-Y12 = \frac{(S+b)(S+c)}{S+a}$		$A = R1 + R2$ $a = \frac{R1 + R2}{R1 + R2}(2C1 + C2)$ $b = \frac{1}{R2C1}$ $c = \frac{1}{R1C1}$
8.	$\frac{S + b}{(S+a)(S+c)}$ $a < b < c$	$-Y12 = \frac{S + b}{(S + a)(S+c)}$		$A = R1 + R2$ $a = \frac{1}{R3C2}$ $b = \frac{R1 + R2}{R_1R_2}(C1+C2)$ $c = \frac{1}{R1C1}$
9.	$\frac{(S+a)(S+b)}{S+c}$ $a < b < c$	$-Y12 = \frac{(S+a)(S+b)}{S+c}$		$A = R_1 + \frac{R1}{R2}{}^{2}$ $a = \frac{1}{R_1C_2}$ $b = \frac{1}{R_1C_1}$ $c = \frac{R1+2R2}{R1\ R2}(C1+ C2)$

Where A = D.C gain
a, b, c = singularities

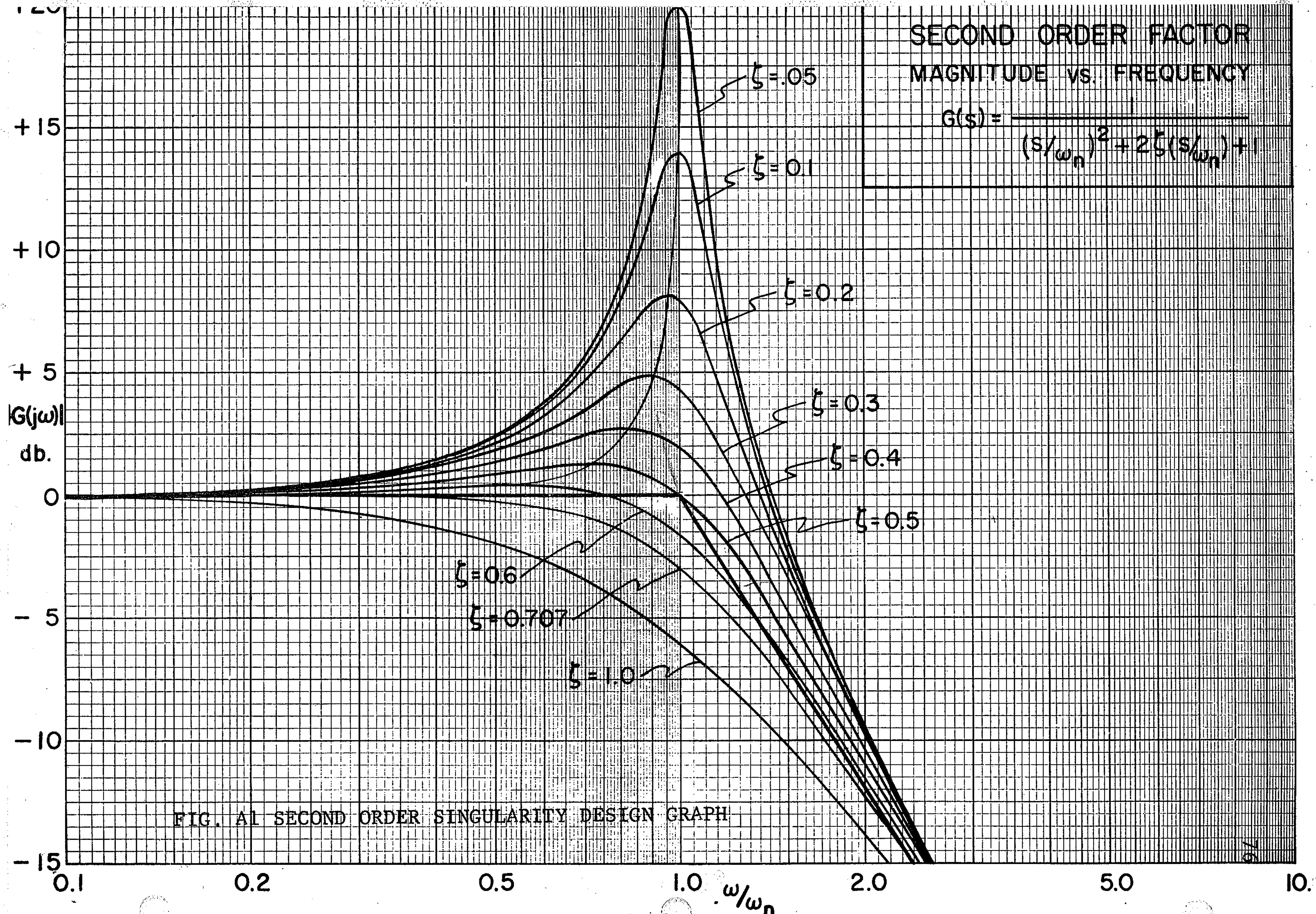


FIG. A1 SECOND ORDER SINGULARITY DESIGN GRAPH

APPENDIX B

FREQUENCY RESPONSE OF THE FIRST LOUDSPEAKER USING WHITE NOISE EXCITATION

The following data was obtained from Test 3.3. A matched impedance amplifier was used and the input voltage was measured at the input to this amplifier. The following were the conditions under which the readings were obtained.

$V_{D.C.}$ power supply = 40 V

Vin = .015 Vrms

Figure	Distance to microphone
B.1	119 "
B.2	130 "
B.3	93 "
B.4	69 "
B.5	97 "
B.6	49 "
B.7	67½"
B.8	121 "

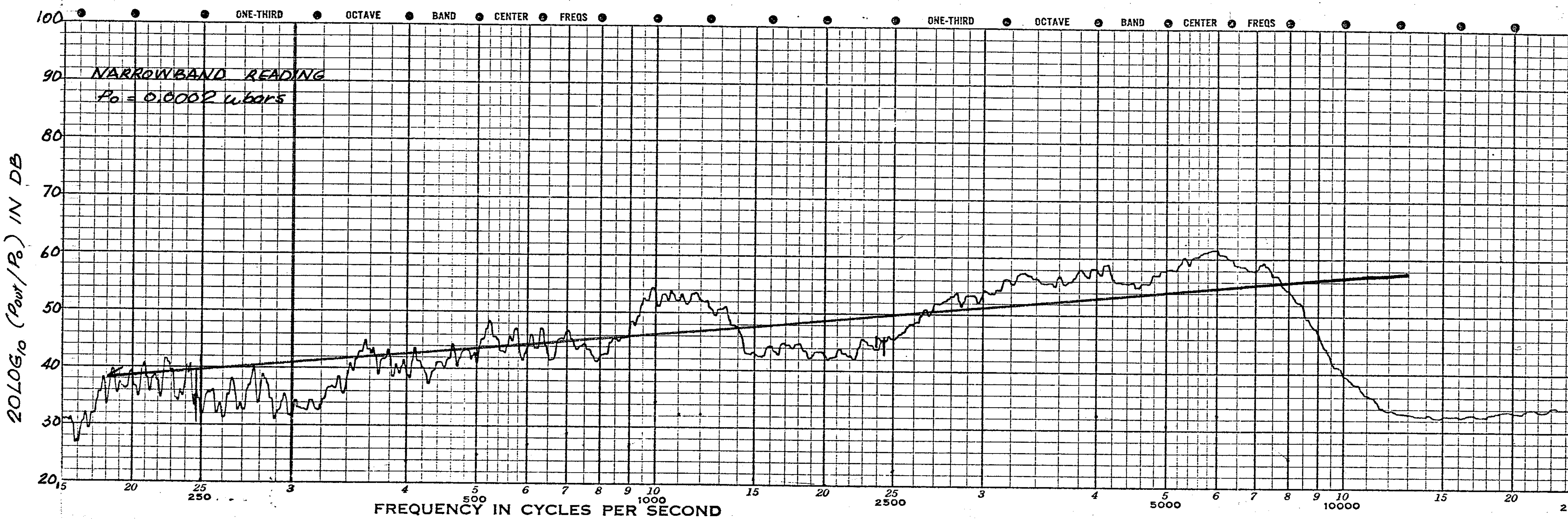


FIG. B1 FREQUENCY RESPONSE OF FIRST LOUDSPEAKER (d = 119")

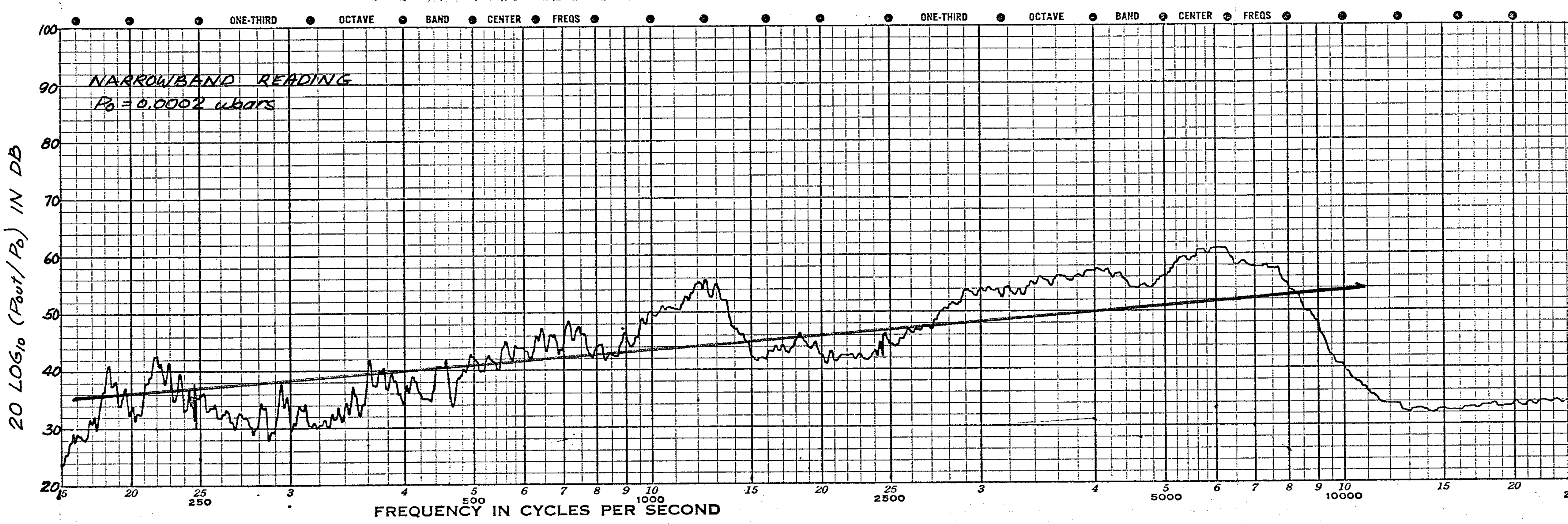


FIG. B2 FREQUENCY RESPONSE OF FIRST LOUDSPEAKER (d = 130")

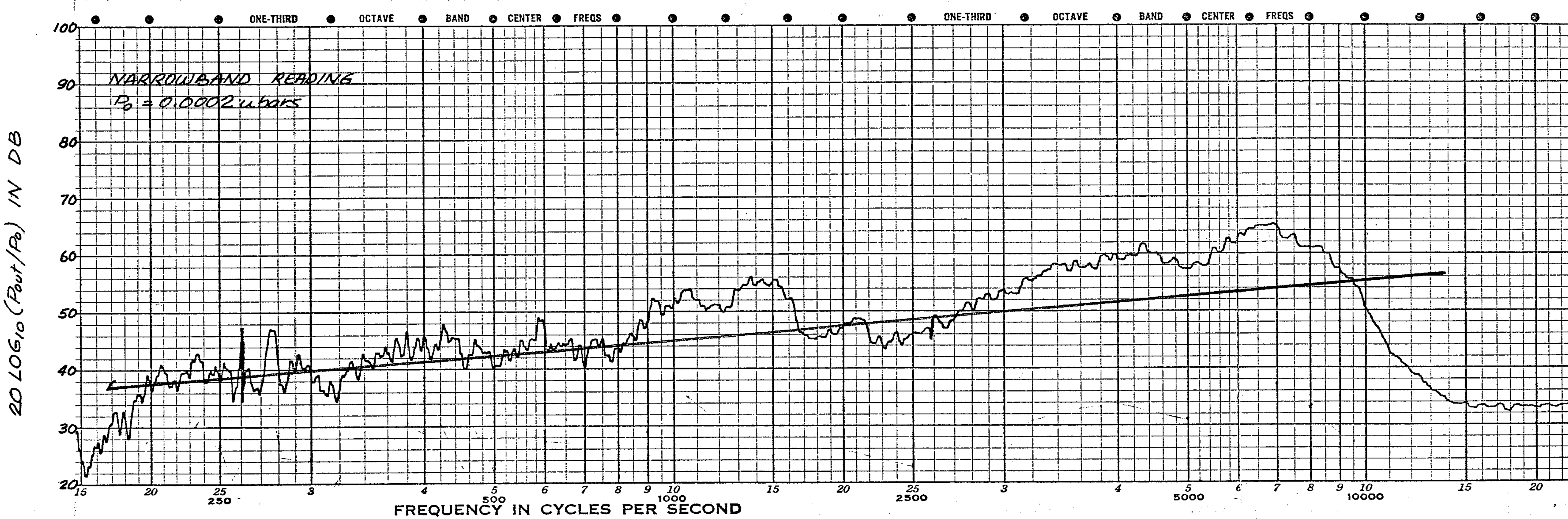


FIG. B3 FREQUENCY RESPONSE OF FIRST LOUDSPEAKER (d = 93")

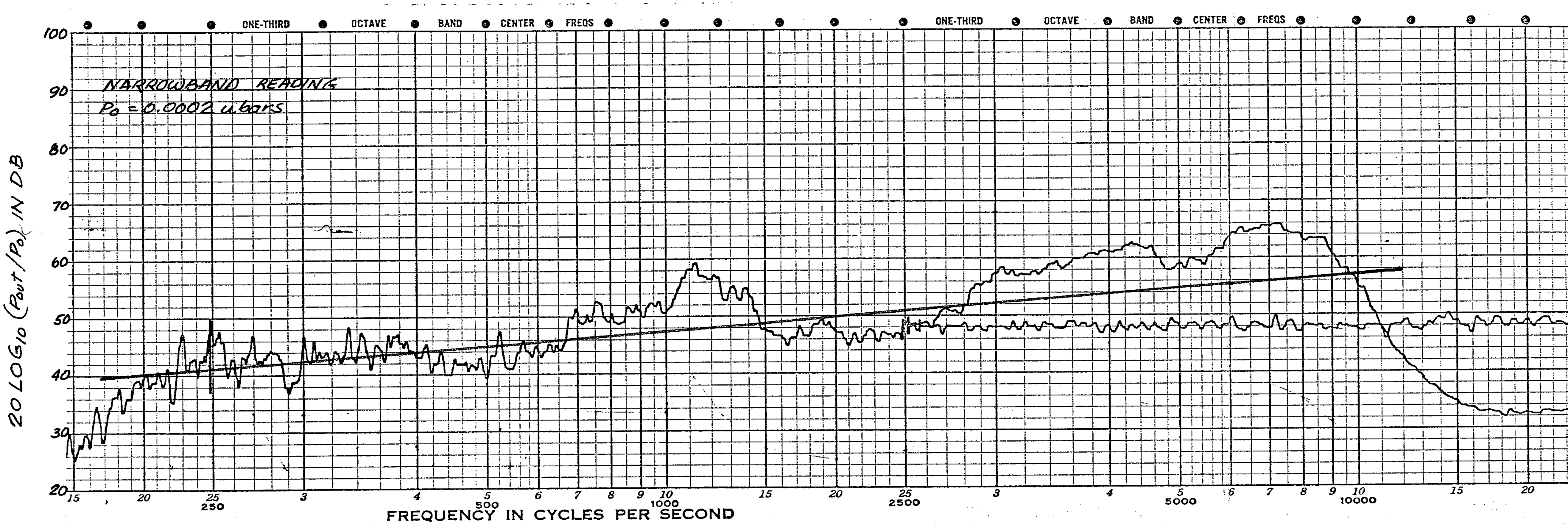


FIG. B4 FREQUENCY RESPONSE OF FIRST LOUDSPEAKER (d = 69")

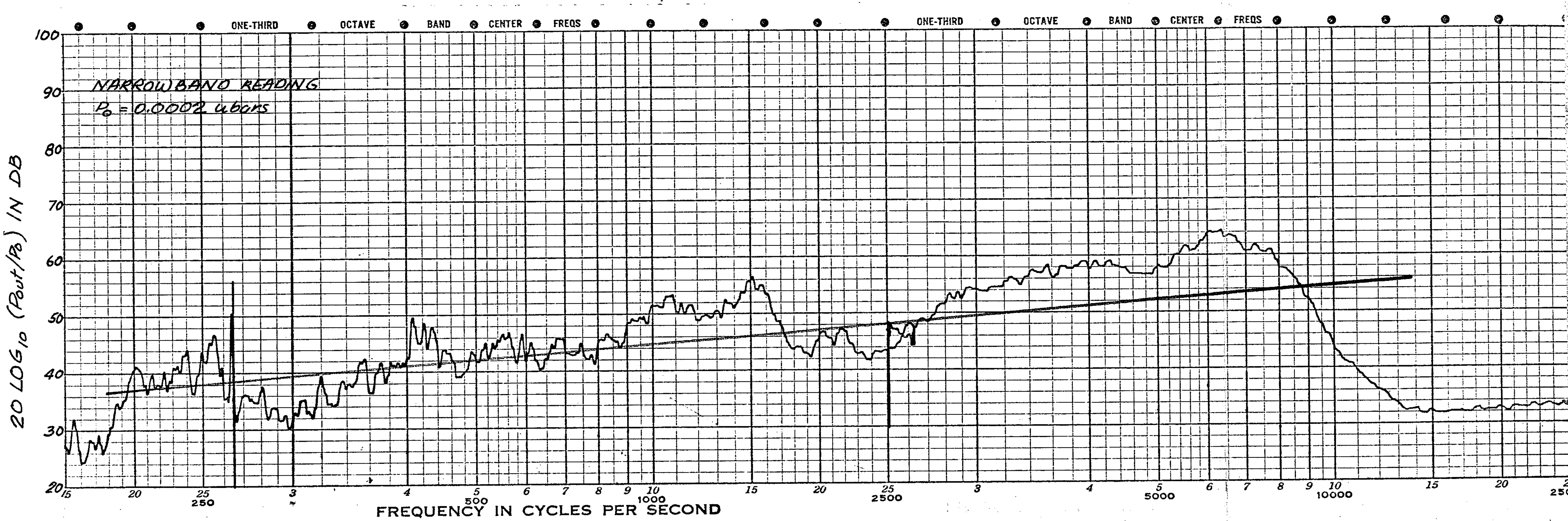


FIG. B5 FREQUENCY RESPONSE OF FIRST LOUDSPEAKER (d = 97")

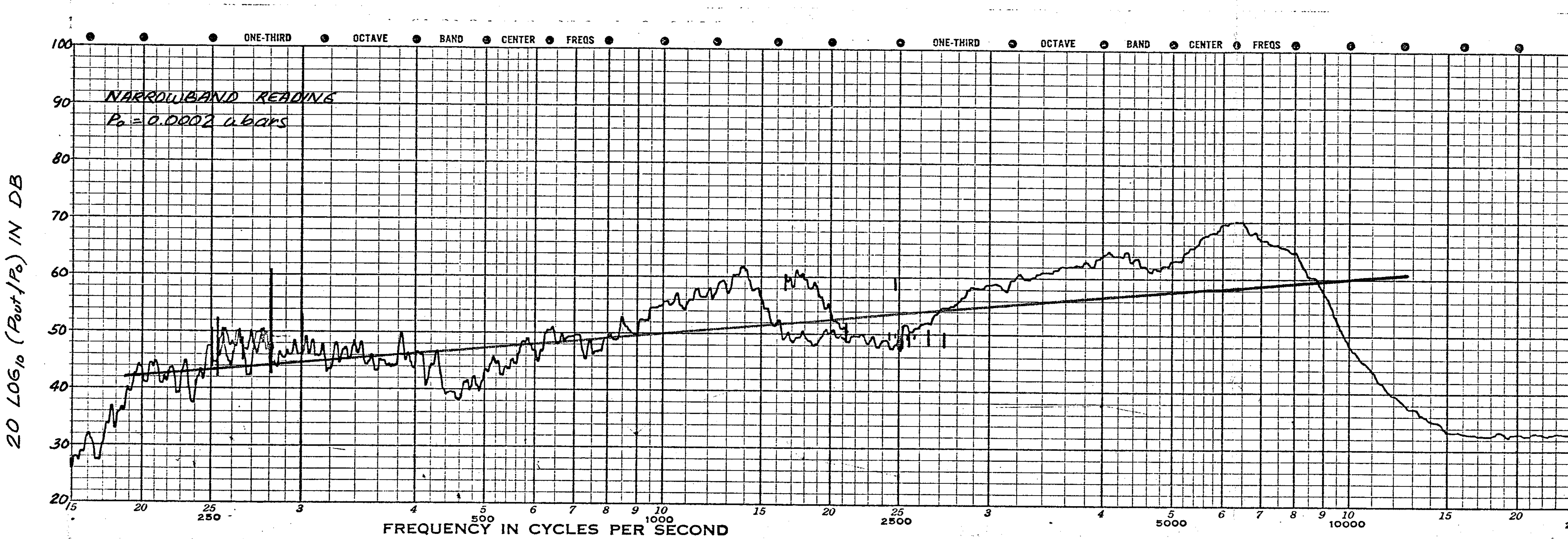


FIG. B.6 FREQUENCY RESPONSE OF FIRST LOUDSPEAKER (d = 49")

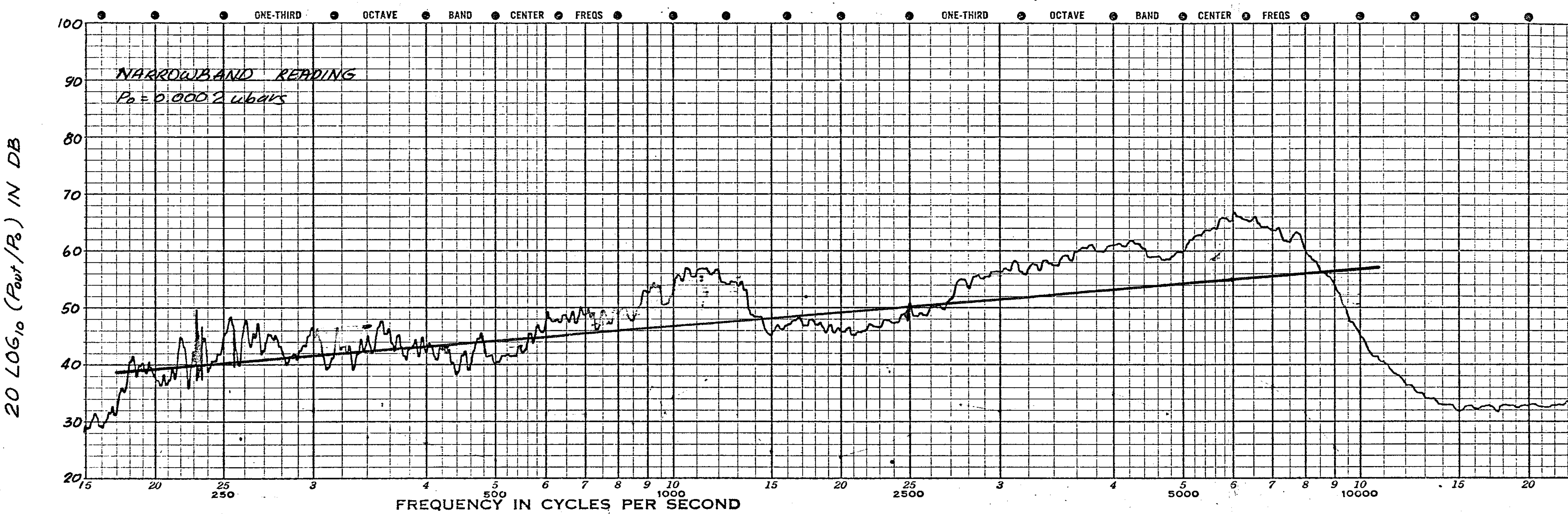


FIG. B.7 FREQUENCY RESPONSE OF FIRST LOUDSPEAKER (d = 67½")

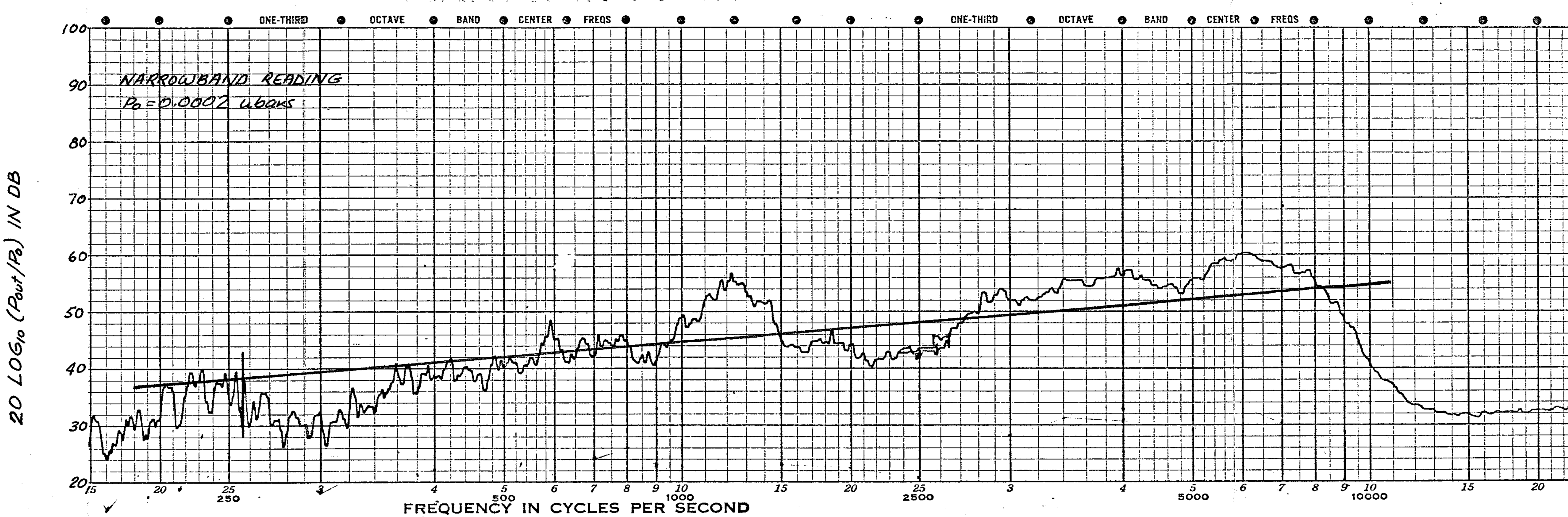


FIG. B8 FREQUENCY RESPONSE OF FIRST LOUDSPEAKER (d = 121")

APPENDIX C

SINE WAVE EXCITATION FREQUENCY RESPONSE DATA FOR SIMULATOR AND COMPENSATOR OF FIRST LOUDSPEAKER

Section 4.3.1 Frequency Response of Simulator

Vin = 1 x .5v peak to peak

Power Supply Voltages for Operational Amplifier = ± 15V

f Hz	Vout v peak to peak	20 log Vo/Vin	f Hz	Vout v peak to peak	20 log Vo/Vin
20	0.	- ∞	1200	1.050	6.44
50	.003	-44.43	1330	1.775	11.00
70	.012	-32.40	1500	.800	4.08
100	.020	-27.96	1800	.450	- .92
150	.075	-20.92	2000	.400	- 3.94
180	.170	- 9.37	2300	.375	- 2.50
200	.300	- 4.44	2500	.375	- 2.50
210	.440	- .11	3000	.425	- 1.41
220	.500	0.00	3500	.530	0.51
250	.380	- 2.38	4000	.560	0.99
280	.280	- 5.04	4300	.520	0.34
350	.200	- 7.96	5000	.380	- 2.38
400	.190	- 8.18	6000	.280	- 5.04
500	.180	- 8.87	7000	.220	- 7.13
600	.180	- 8.87	8000	.190	- 8.40
700	.220	- 7.10	9000	.180	- 8.87
800	.260	- 5.68	10000	.160	- 9.90
900	.320	- 3.88	12000	.160	- 9.90
1000	.400	- 1.94	15000	.150	-10.46
1100	.625	1.94			

Section 4.3.2 Frequency Response of Approximated Compensator

a) Vin = 1 volt peak to peak

Power Supply Voltages for Operational Amplifier = ± 10V

f Hz	Vout v peak to peak	20 log Vo/Vin	f Hz	Vout v peak to peak	20 log Vo/Vin
20	1.50	3.52	1100	.16	-15.92
30	1.45	3.23	1200	.085	-21.
50	1.35	2.60	1300	.11	-19.17
100	.90	- 0.92	1500	.25	-12.04
150	.42	- 7.54	1800	.395	- 8.07
180	.22	-13.17	2000	.465	- 6.65
200	.14	-17.08	2300	.48	- 6.38
210	.14	-17.08	2500	.48	- 6.38
220	.18	-14.87	3000	.40	- 7.96
240	.26	-11.70	3500	.31	-10.02
250	.30	-10.04	4000	.26	-11.70
300	.45	- 6.93	4500	.27	-11.372
350	.39	- 4.88	5000	.29	-10.75
400	.64	- 3.84	6000	.40	- 7.96
500	.68	- 3.16	7000	.50	- 6.19
600	.64	- 3.84	8000	.54	- 5.35
700	.56	- 5.04	9000	.60	- 4.44
800	.48	- 6.37	10000	.60	- 4.44
900	.36	- 8.89	12000	.60	- 4.44
1000	.26	-11.70	15000	.60	- 4.44

b) Vin = .5 volt peak to peak

Power Supply Voltages for Operational Amplifier = ± 10v

f Hz	Vout v peak to peak	20 log Vo/Vin	f Hz	Vout v peak to peak	20 log Vo/Vin
20	.750	3.52	1100	.080	-17.70
30	.750	3.52	1200	.0475	-20.45
50	.700	2.92	1300	.060	-18.42
100	.475	- .46	1500	.1675	- 9.00
150	.240	- 6.38	1800	.2025	- 7.85
180	.120	-12.39	2000	.240	- 6.38
200	.070	-17.08	2300	.250	- 6.02
210	.070	-17.08	2500	.240	- 6.38
220	.095	-14.42	3000	.200	- 7.96
240	.130	-11.70	3500	.160	- 9.90
250	.160	- 9.90	4000	.135	-11.37
300	.245	- 6.20	4500	.140	-11.06
350	.300	- 4.43	5000	.160	- 9.90
400	.340	- 3.35	6000	.200	- 7.96
500	.360	- 2.85	7000	.260	- 5.68
600	.345	- 3.22	8000	.295	- 4.58
700	.300	- 4.43	9000	.330	- 3.61
800	.255	- 5.83	10000	.330	- 3.61
900	.190	- 8.40	12000	.345	- 3.22
1000	.140	-11.05	15000	.380	- 2.38

Section 4.3.3 Frequency Response of Actual Compensator

Vin = 1 x .5v peak to peak

Power Supply Voltages for Operational Amplifier = ± 15V

f Hz	Vout v peak to peak	20 log Vo/Vin	f Hz	Vout v peak to peak	20 log Vo/Vin
20	1.2	15.90	1400	.24	-12.39
50	1.2	15.90	1500	.28	-11.10
70	1.1	8.40	1800	.39	- 8.18
100	.65	3.75	2000	.45	- 6.95
150	.32	9.81	2300	.48	- 6.37
180	.22	-13.17	2500	.48	- 6.37
200	.20	-13.99	2800	.46	- 6.75
210	.20	-13.99	3000	.44	- 7.14
220	.24	-12.39	3500	.38	- 8.40
250	.32	- 9.81	3800	.32	- 9.81
300	.42	- 7.75	4000	.30	-10.47
350	.49	- 6.20	4500	.24	-12.40
400	.54	- 5.35	5000	.20	-13.99
500	.55	- 5.19	6000	.19	-14.45
600	.32	- 5.68	6500	.20	-13.99
700	.45	- 6.95	7000	.24	-12.38
800	.38	- 8.40	8000	.30	-10.48
900	.28	-11.08	9000	.32	- 9.81
1000	.20	-13.99	10000	.36	- 8.48
1100	.16	-15.92	12000	.46	- 6.75
1200	.15	-16.50	15000	.46	- 6.75
1300	.19	-14.42			

Section 4.3.4 Frequency Response of Cascaded Simulator - Actual Compensator

Vin = 1v peak to peak

Power Supply Voltages for Operational Amplifier = $\pm$ 10v

f Hz	Vout v peak to peak	20 log Vo/Vi	f Hz	Vout v peak to peak	20 log Vo/Vi
20	0.	$-\infty$	1100	.145	-16.77
30	.004	-47.96	1200	.145	-16.77
50	.012	-38.42	1300	.300	-10.46
70	.018	-34.89	1400	.370	- 8.64
100	.030	-30.46	1550	.320	- 9.85
150	.052	-25.68	2000	.260	-11.70
180	.050	-26.02	2200	.260	-11.70
200	.056	-25.04	2500	.260	-11.70
210	.088	-21.11	3000	.285	-10.90
220	.125	-18.27	3500	.390	- 8.18
250	.160	-19.92	4000	.250	-12.04
300	.160	-19.92	4500	.210	-13.56
350	.165	-15.65	5000	.200	-13.98
400	.170	-15.39	6000	.200	-13.98
500	.180	-14.89	7000	.190	-14.42
600	.1825	-14.75	8000	.190	-14.42
700	.185	-14.66	9000	.190	-14.42
800	.185	-14.66	10000	.190	-14.42
900	.180	-14.89	12000	.200	-13.98
1000	.165	-15.65	15000	.200	-13.98

APPENDIX D

SINE WAVE EXCITATION FREQUENCY RESPONSE DATA FOR COMPENSATOR OF SECOND LOUDSPEAKER

Section 4.4.1 Frequency Response of Approximated Compensator

a) Vin = 1v peak to peak

Power Supply Voltages for Operational Amplifier = ± 15V

f Hz	Vout v peak to peak	20 log Vo/Vin	f Hz	Vout v peak to peak	20 log Vo/Vin
20	1.10	.84	1300	.09	-20.90
50	1.00	0.00	1400	.14	-17.10
70	.90	- .92	1500	.19	-14.45
100	.65	- 3.75	1800	.32	- 9.89
150	.32	- 9.89	2000	.34	- 9.35
180	.16	-15.92	2300	.38	- 8.40
200	.10	-20.00	2500	.38	- 8.40
210	.10	-20.00	2800	.34	- 9.35
220	.14	-17.10	3000	.32	- 9.89
250	.23	-12.76	3500	.26	-11.70
300	.35	- 9.11	4000	.21	-13.60
350	.44	- 7.14	4300	.22	-13.16
400	.48	- 6.37	5000	.26	-11.70
450	.48	- 6.37	5500	.32	- 9.89
500	.52	- 5.67	6000	.35	- 9.12
600	.50	- 6.02	7000	.45	- 6.94
700	.42	- 7.36	8000	.50	- 6.02
800	.38	- 8.20	9000	.58	- 4.72
900	.28	-11.10	10000	.62	- 4.16
1000	.20	-13.99	12000	.68	- 3.36
1100	.12	-18.44	15000	.70	- 3.10
1200	.06	-24.40			

b) Vin = .5v peak to peak

Power Supply Voltages for Operational Amplifier = ± 15V

f Hz	Vout v peak to peak	20 log Vo/Vin	f Hz	Vout v peak to peak	20 log Vo/Vin
20	.550	.84	1300	.045	-20.92
50	.475	- .40	1400	.070	-17.10
70	.400	- 1.95	1500	.095	-14.44
100	.300	- 4.40	1800	.160	- 9.81
150	.160	- 9.89	2000	.180	- 8.88
180	.080	-15.91	2300	.190	- 9.20
200	.0475	-20.40	2500	.190	- 8.40
210	.050	-20.00	2800	.175	- 8.68
220	.060	-18.44	3000	.165	- 9.60
250	.115	-12.76	3500	.135	-11.40
300	.175	- 9.12	4000	.110	-13.10
350	. 20	- 7.12	4300	.110	-13.10
400	.240	- 6.36	5000	.140	-11.10
450	.240	- 6.36	5500	.160	- 9.81
500	.260	- 5.67	6000	.180	- 8.88
600	.250	- 6.02	7000	.220	- 7.12
700	.220	- 7.12	8000	.260	- 5.16
800	.180	- 8.88	9000	.290	- 4.72
900	.140	-11.10	10000	.305	- 4.40
1000	.095	-14.43	12000	.330	- 3.60
1100	.060	-18.44	15000	.350	- 3.10
1200	.030	-24.44			

Section 4.4.2 Frequency Response of Actual Compensator

Vin = .1 V peak to peak

Power Supply Voltages for Operational Amplifier = ± 15V

f Hz	Vout v peak to peak	20 log Vo/Vi	f Hz	Vout v peak to peak	20 log Vo/Vi
20	.090	- .92	1300	.022	-13.16
50	.085	- 1.43	1500	.019	-14.43
70	.080	- 1.95	1800	.016	-15.90
100	.065	- 3.75	2000	.017	-15.37
150	.050	- 6.02	2200	.016	-15.90
180	.035	- 9.12	2500	.015	-16.47
200	.029	-10.75	3000	.013	-17.70
250	.016	-15.90	4000	.010	-20.00
300	.021	-13.54	5000	.012	-18.40
355	.021	-13.54	6000	.016	-15.90
400	.024	-12.40	7000	.020	-13.98
500	.028	-11.04	8000	.024	-12.40
600	.032	- 9.90	9000	.024	-12.40
700	.032	- 9.90	10000	.026	-11.70
900	.031	-10.16	12000	.032	- 9.90
1000	.029	-10.76	15000	.032	- 9.90

APPENDIX E

TESTS FOR COMPENSATED FIRST LOUDSPEAKER

Various tests were conducted to study the behaviour of the compensated loudspeaker. Special consideration was given to a person's listening. The various tests conducted were:

Test 5.1	Compensated and Uncompensated Loudspeaker Frequency Response.
Test 5.2 and 5.3	Compensated Loudspeaker Linearity tests.
Tests 5.4, 5.5 and 5.6	Compensated Loudspeaker Tests for Microphone Position Variation.
Test 5.7	Ambient Noise Level in Enclosure.
Test 5.8	Compensated Loudspeaker Test for Loudspeaker Position Change.
Test 5.9 and 5.10	Compensated Loudspeaker Test for Enclosure Characteristics Change.

The various conditions under which the above tests were performed are listed in Table IV.

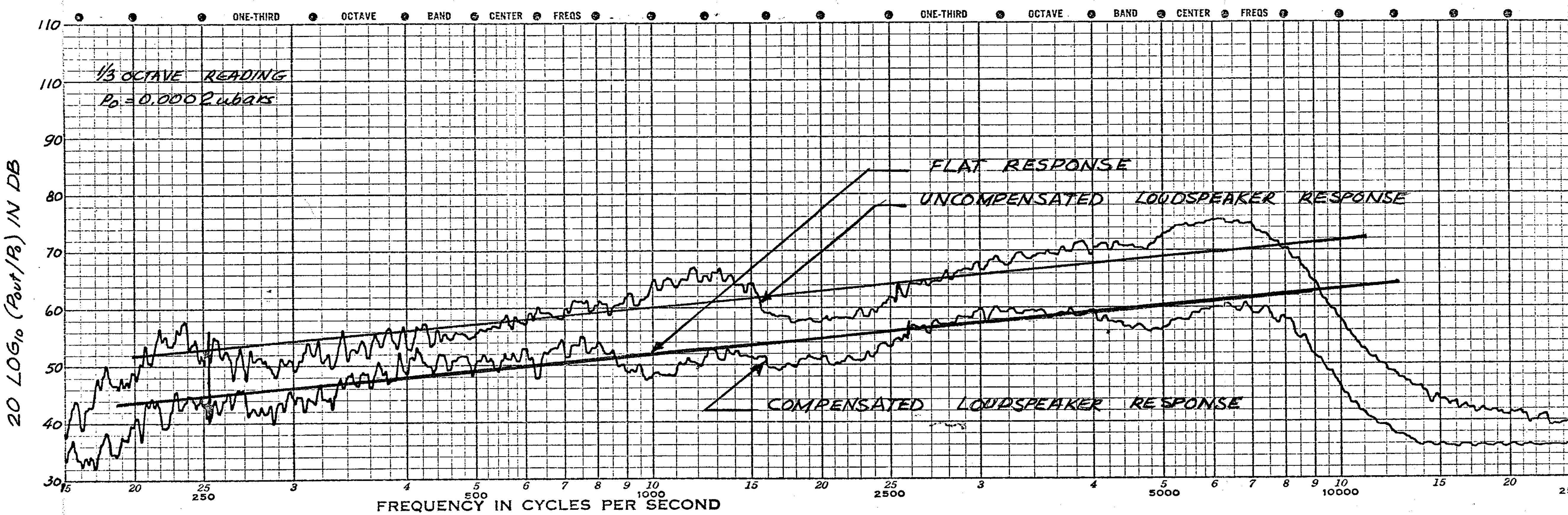


FIG. E1 FREQUENCY RESPONSE OF COMPENSATED AND UNCOMPENSATED LOUDSPEAKER

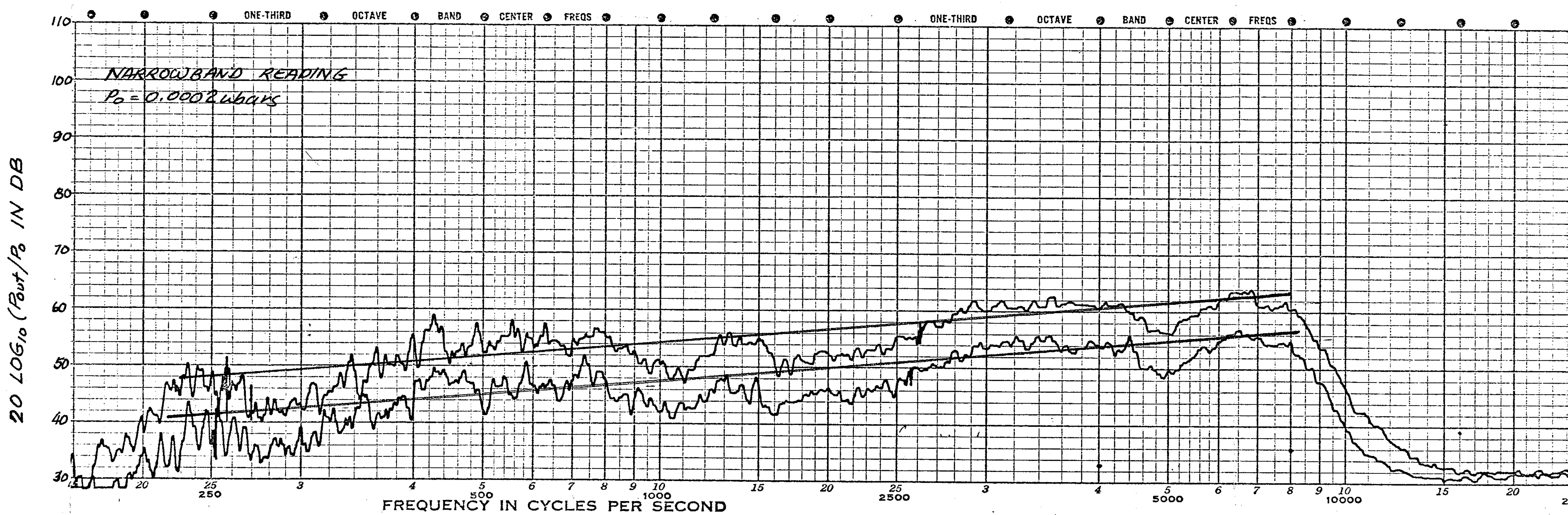


FIG. E2 FREQUENCY RESPONSE FOR LINEARITY TEST OF COMPENSATED LOUDSPEAKER

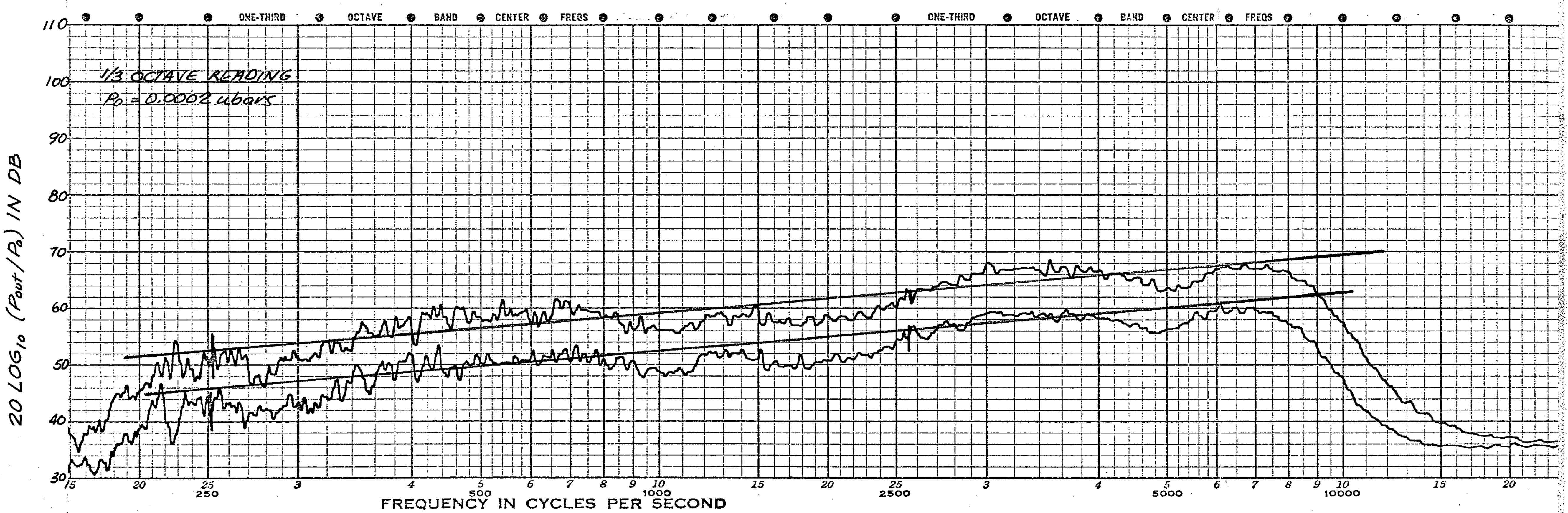


FIG. E3 FREQUENCY RESPONSE FOR LINEARITY TEST OF COMPENSATED LOUDSPEAKER

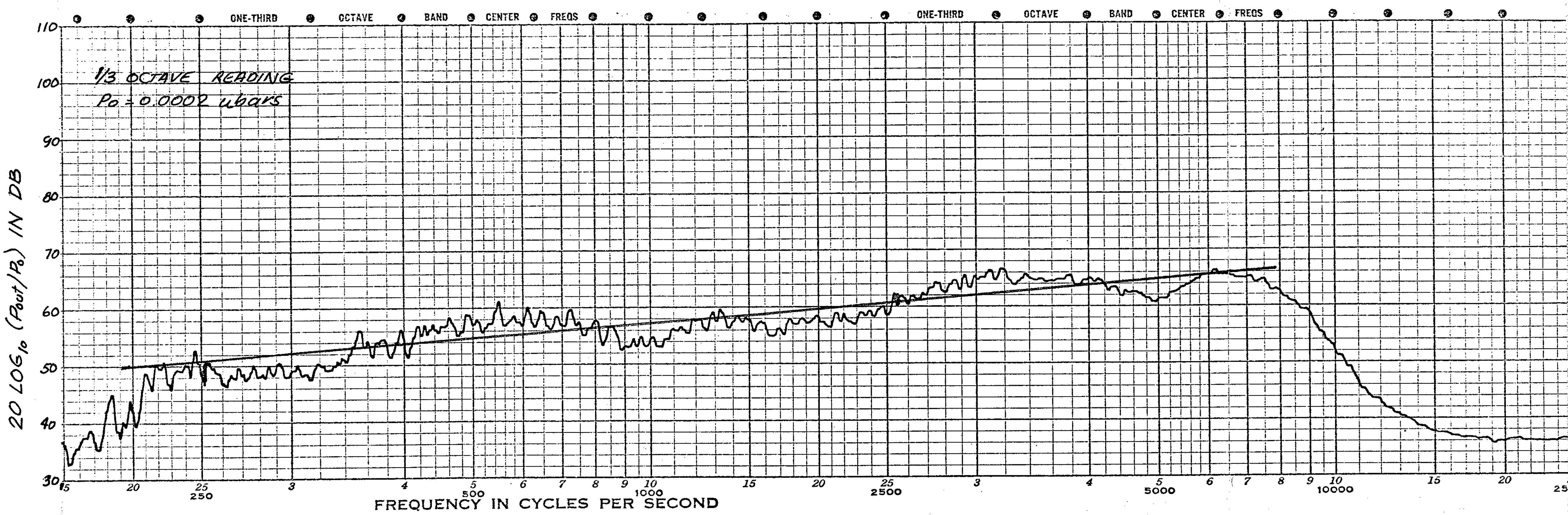


FIG. E4 FREQUENCY RESPONSE FOR MICROPHONE POSITION VARIATION FOR COMPENSATED LOUDSPEAKER

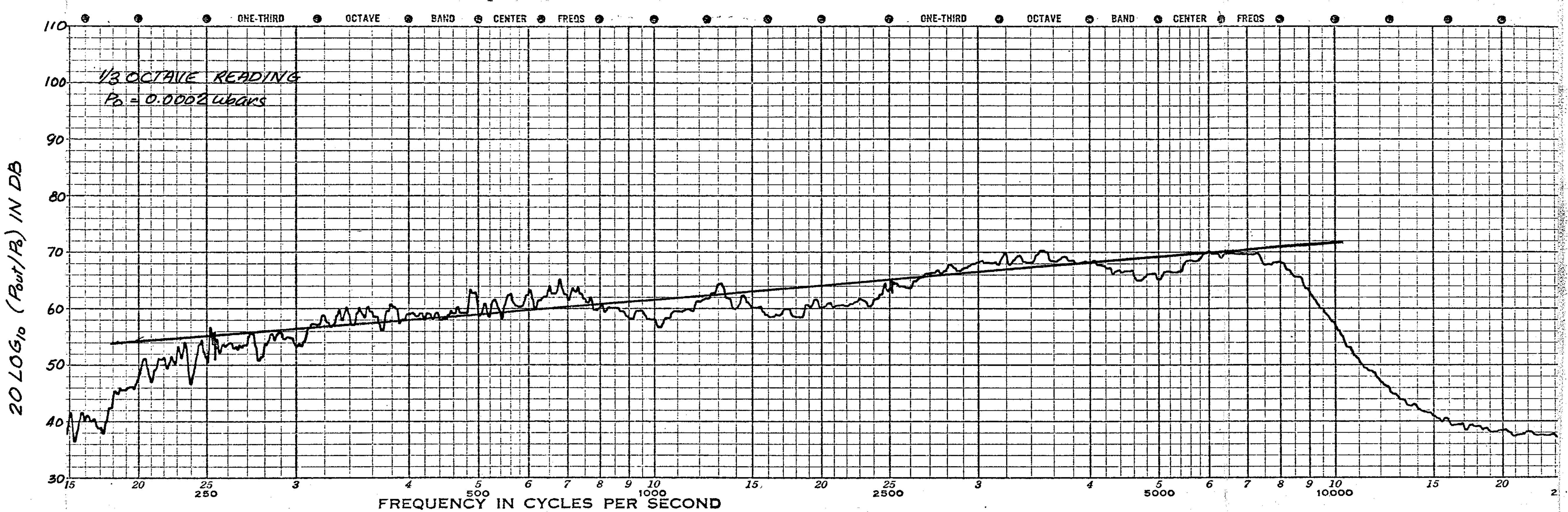


FIG. E5 FREQUENCY RESPONSE FOR MICROPHONE POSITION VARIATION FOR COMPENSATED LOUDSPEAKER

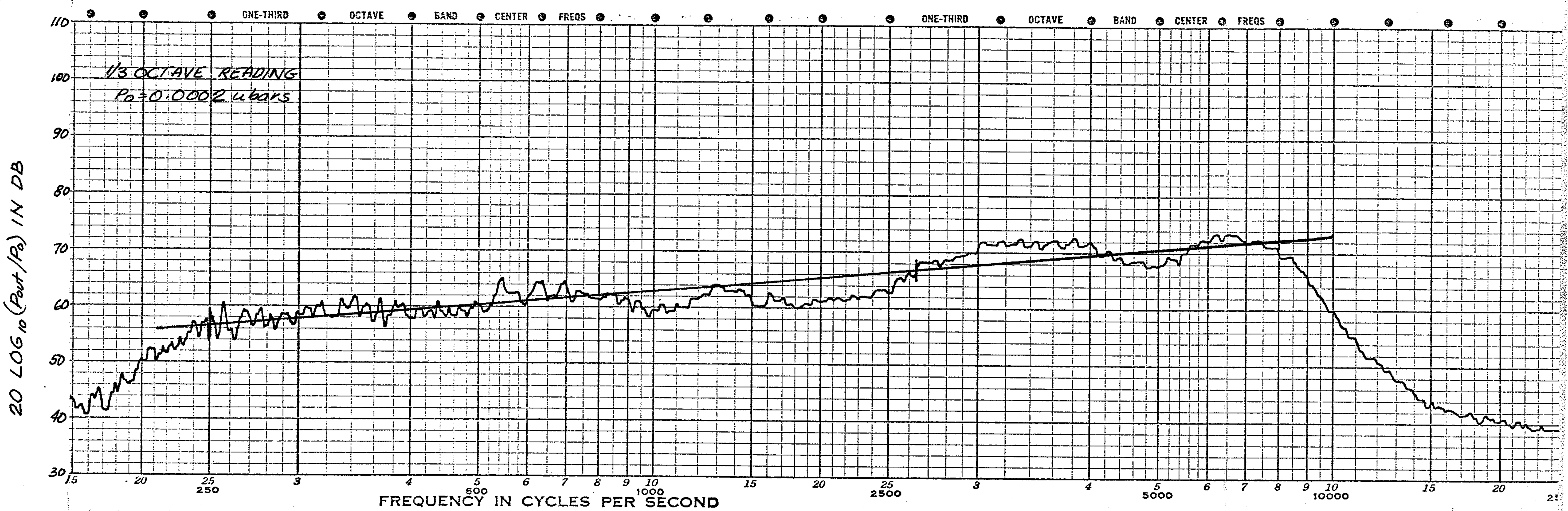


FIG. E.6 FREQUENCY RESPONSE FOR MICROPHONE POSITION VARIATION FOR COMPENSATED LOUDSPEAKER

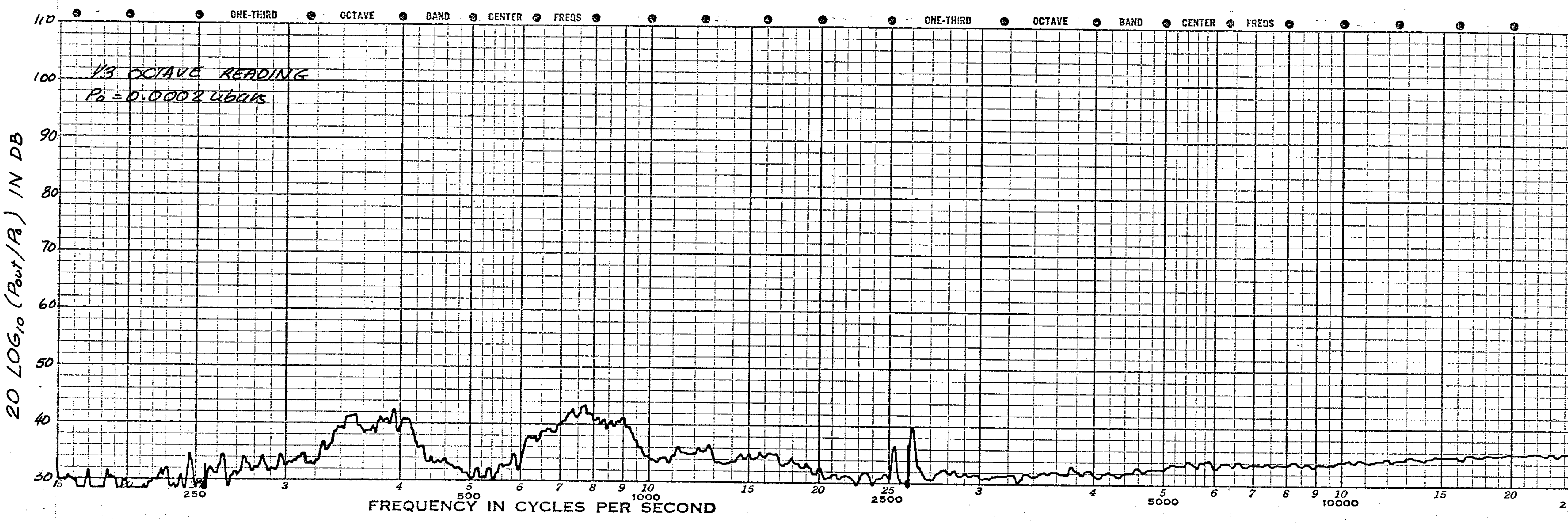


FIG. E7 FREQUENCY RESPONSE OF AMBIENT NOISE LEVEL IN ENCLOSURE

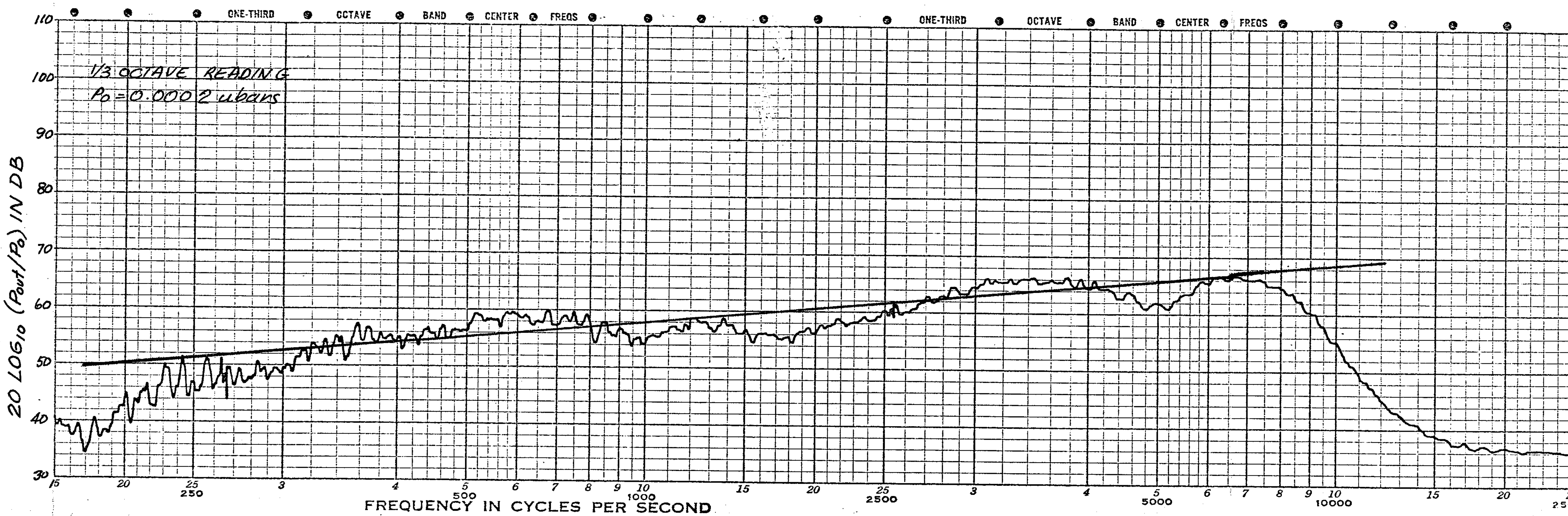


FIG. E8 FREQUENCY RESPONSE FOR LOUDSPEAKER POSITION CHANGE FOR COMPENSATED LOUDSPEAKER

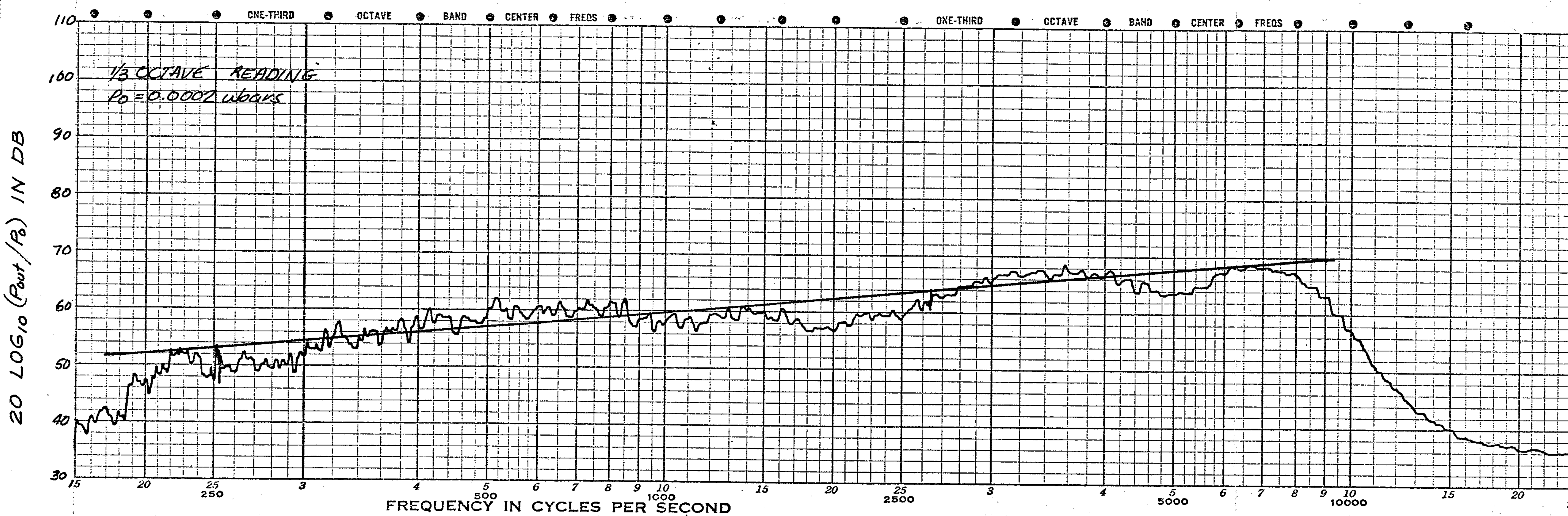


FIG. E9 FREQUENCY RESPONSE FOR ENCLOSURE CHARACTERISTICS CHANGE FOR COMPENSATED LOUDSPEAKER

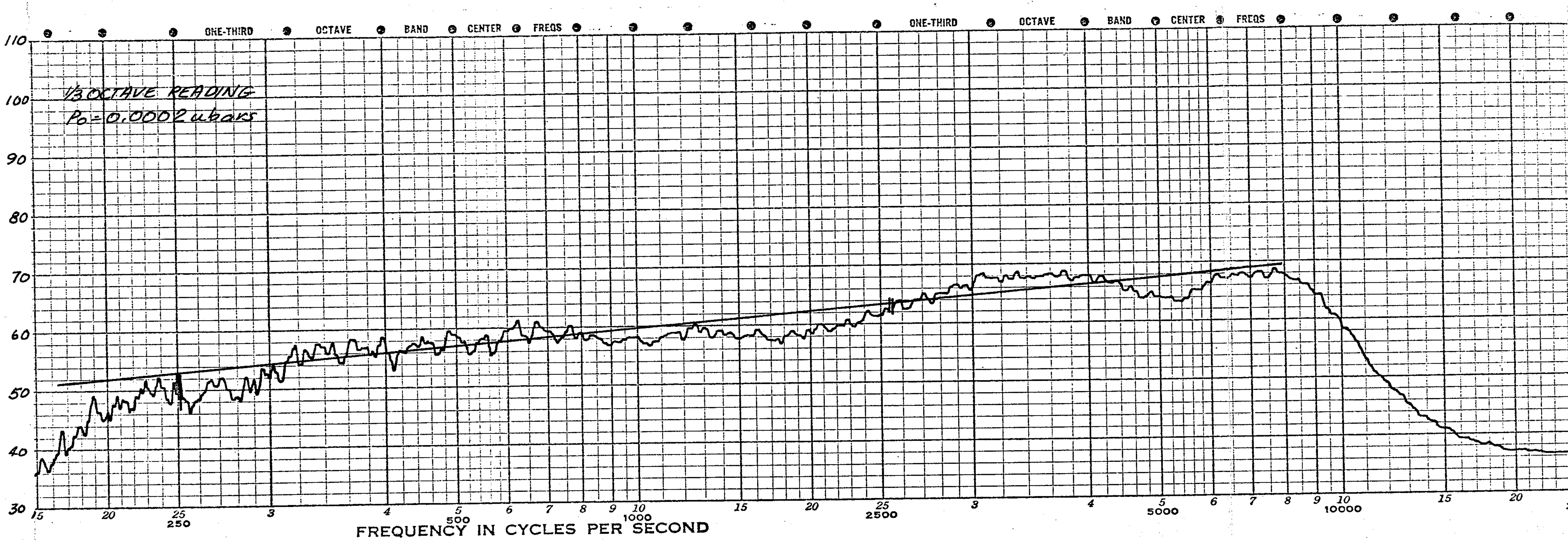


FIG. E10 FREQUENCY RESPONSE FOR ENCLOSURE CHARACTERISTICS CHANGE FOR COMPENSATED LOUDSPEAKER