APPENDIX I

COIL DESIGN

The theory of coil design is based on the work of Campbell[1] (1959) and others. Time varying magnetic flux, Φ_m, cutting a coil will induce an e.m.f. across the coil terminals which according to Faraday's Law of induction is

$$\text{e.m.f.} = -\frac{d\Phi_m}{dt}$$

In our case there are N terms, or N circuits in series so that the voltage across the coil terminals is

$$V = -N\frac{d\Phi_m}{dt}$$

Since $$\Phi_m = \int \vec{B} \cdot d\vec{s}$$

the voltage output from a circular coil with area A is

$$V = -NA\frac{dB}{dt}$$

Assuming B to oscillate sinudoidally at frequency ω

$$V = NA\omega B \qquad (1)$$

This equation is generally true for induction coils so long as ω is well below the resonant frequency of the coil in a frequency range where the coil acts as a purely resistance circuit element.

In practical units, the voltage can be expressed as

$$V = NA\ 10^{-7}\ 2\pi f B \qquad (2)$$

---

[1] Campbell, op. cit., p. 7.

Where V is in μV, A is in cm^2, and B is in γ $[1\gamma = 10^{-5}]$
The coils that we built each had 20,100 turns on a two-meter diameter circular frame so that the NA product is 6.315×10^8 turn-cm^2 the Eq.2 becomes

$$V = 396.8 \, fB \, \mu V \qquad (3)$$

We designed the coils to be sensitive in the Frequency range of Pc 1 and they can detect the signals from 0.001 to 10 Hz.

The resonant frequency of the coil is approximately

$$\omega_o = \left(\frac{1}{LC}\right)^{\frac{1}{2}}$$

To fix ω_o well above the frequencies of interest, the coil inductance or capacitance must be kept resonably small. Decreasing of value of L can only be done by reducing the number of turns (L varies as N^2) but this has the unfavorable result of loss of sensitivity at the frequencies of interest. On the other hand, C can be decreased, with no loss of sensitivity, by careful winding. One practice is to keep small the number of turns in a winding layer so that the number of layers will increase but the layer-to-layer capacitance between adjacent layer will decrease. The total capacitance also decreased because, in the coil, it looks like capacitors connected in series; so,

$$C = \frac{C_1}{M}$$

where C = total capacitance of the coil
C_1 = the individual layer-to-layer capacitance
M = the number of layer

Hence when M is larger the total capacitance will be a small value.

APPENDIX II

COIL CALIBRATION

The calibration technique used to determine the inductance, capacitance, and resonant frequency consists of first measuring the coil resistance (R_c) on a bridge, and then applying a voltage V, over a wide range of frequencies alternately to the coil and to a dummy resistor R_D, $R_D \approx R_c$. The voltage drop V_2 across a resistor R_g in series with the source is recorded at each frequency and a plot of the ratio

$$n = \frac{V_2(\text{coil})}{V_2(\text{dummy})} \qquad (1)$$

From this curve we can estimate values of L and C, as described below. The measuring circuit used is shown in Figure 11

The ratio n can be shown equal to the ratio of two impedances. At any frequency, ω,

$$n(\omega) = \frac{R_g + Z(\omega)}{R_g + R_D}$$

where Z is the coil impedance, and R_g is selected to be much larger than R_C,

$$|Z| = \frac{L}{R_c\, C} \left[\frac{1 + \dfrac{R_c^{\,2}}{\omega^2\, L^2}}{1 + \left(\dfrac{\omega L - 1/\omega C}{R_c}\right)} \right]^{\frac{1}{2}}$$

At frequencies approaching DC, $Z \longrightarrow R_c$ and

$$\underset{\omega \to 0}{n} = \frac{1 + \dfrac{Z}{R_g}}{1 + \dfrac{R_D}{R_g}} \longrightarrow \frac{1 + \dfrac{R_c}{R_g}}{1 + \dfrac{R_D}{R_g}} \longrightarrow 1$$

On the other hand, at very high frequencies coil inductive reactance also becomes very large so that

$$Z \longrightarrow -i\left(\frac{1}{\omega C}\right)$$

and

$$\underset{\omega \to \infty}{n} = \frac{\left|R_g - i\left(\frac{1}{\omega C}\right)\right|}{R_g + R_D} = \frac{\left(1 + \frac{1}{R^2 \omega^2 C^2}\right)^{\frac{1}{2}}}{1 + \frac{R_D}{R_g}}$$

So long as R_g is very large

$$\underset{\omega \to \infty}{n} \longrightarrow 1$$

Between these extremes there will exist a frequency, the resonant frequency, where $\left|R_g + Z\right|$, and thus n, is a maximum. It can be shown that Z takes on its largest value,

$$Z = \frac{L}{R_c C}$$

at

$$\omega_o = \left[\frac{1}{LC} - \left(\frac{R_c}{L}\right)^2\right]^{\frac{1}{2}} \qquad (2)$$

where

$$n = n_{max} = 1 + \frac{L}{R_c R_g C} \qquad (3)$$

We find through simple algebraic manipulation that

$$L - (n_{max} - 1) R_c R_g C$$

As ω_o can be determined by finding the ω at which n is a maximum, the coil C may now be found using values of ω_o, R_c, and L in Eqs. (2) and (3).

$$C = \frac{\left[\frac{\left(n_{max} - 1\right) R_g}{R_c} - 1\right]^{\frac{1}{2}}}{\omega_o \left(n_{max} - 1\right) R_g}$$

As Campbell points out, in actual measurement there exists an effective series resistance of the voltage source and a shunt capacitance of the measuring device. These two circuit parameters tend to cause n to become less than unity at high frequencies, but they do not change the L and C estimates.

APPENDIX III

CHOICE OF SAMPLING INTERVAL AND OTHER PARAMETER

The data to be analyzed is recorded continuously and must be digitized prior to machine analysis.

Sampling Interval: The sampling interval $h = \Delta t$ is usually chosen such that

$$h = \frac{1}{2f_{max}}$$

Since $\frac{1}{f_{max}}$ is the smallest period that can be observed in the record, h must be chosen sufficiently small so that aliasing[1] will not be a problem.

By difinition there will be only 2 points per cycle of the f_{max} oscillation, but if signal frequencies of large amplitude exist near f_{max}, one should choose $h = \frac{1}{4f_{max}}$. If power spectra measurements are the prime consideration, then choosing $h = \frac{2}{5f_{max}}$ is sufficient, but for reasons of computation economy $h = \frac{1}{2f_{max}}$ can be chosen.

Number of Correlation Lag Values: The maximum number of correlation lag values, m, to be computed depends on the resolution bandwidth, B_e, desired in the power spectra, as well as the sampling interval, h, chosen;

$$m = \frac{1}{B_e h}$$

thus B_e will be small for a given h when m is large.

Sample Size N and Record Length Tr: In choosing sample size N we must consider the standard error of the spectral calculation. In this case N is expressed as

---

[1] Bendat and Piersol, op. cit., p. 23.

$$N = \frac{m}{\epsilon^2}$$

ϵ is the normalized standard error desired for spectral calculations. As the associated record length, Tr, is

$$Tr = Nh$$

we can easily express the error of autocorrelation or power spectrum estimate in terms of m and N,

$$\epsilon = \sqrt{\frac{m}{N}}$$

Thus, ϵ will be small for a given N when m is small. In practice it is desirable to keep the maximum lag,

$$m \leqslant 0.1N$$

APPENDIX IV

HANNING METHOD

The Hanning method is one way of smoothing periodograms (raw estimates). The power spectral density, $\tilde{G}_x(f)$, is given by equation:

$$\tilde{G}_x(f) = 4\int_0^m R_x(\tau)\cos(2\pi f\tau)\,d\tau$$

However, this is an inefficient estimate of the true spectral density and smoothing is necessary.

Let $$\tilde{G}_k = \tilde{G}_x(f) = \tilde{G}_x\left(\frac{kf_{max}}{m}\right)$$

when the index k is called the harmonic number, and $\tilde{G}_k$ is the "raw" estimate of the power spectral density function at harmonic k, corresponding to the frequency $f = \frac{kf_{max}}{m}$.

Let $\hat{G}_k$ represent the "smooth" estimate at harmonic k, where the $\wedge$ replaces the $\sim$. Then at the m + 1 frequencies $f = \frac{kf_{max}}{m}$; k = 0, 1, 2, 3 ..., m one obtains

$$\hat{G}_o = 0.5\,\tilde{G}_o + 0.5\,\tilde{G}_1$$

$$\hat{G}_k = 0.25\,\tilde{G}_{k-1} + 0.5\,\tilde{G}_k + 0.25\,\tilde{G}_{k+1} \quad k = 1,2,3,\ldots,m-1.$$

and $$\hat{G}_m = 0.5\,\tilde{G}_{m-1} + 0.5\,\tilde{G}_m$$

The upper equation is implemented easily on a binary digital computer compared to other smoothing procedures. These other procedures provide different bias uncertainly errors which may be preferred for certain applications. In general, the Hanning method should be satisfactory for our uses.

REFERENCES

Angenheister, G. 1954. Registrierungen erdmagnetischer pulsationen, Goettingen 1952/53. Gerlands Beitr. ur Geophs., 64: 108-132.

Balser, M., and Wagner, C.A. 1960. Observations of Earth-Ionosphere Cavity resonances. Nature, 188: 638-640.

Bendat, J.S., and Piersol, A.G. 1966. Digital Computer Techniques, p.p. 278-320. Measurement and Analysis of Random data. New York: John Wiley and Sons.

Bibl, K. 1960. Dynamic Characteristic of the Ionosphere and their Coherency with the local and planetory magnetic index. Journal of Geophysical Research, 65: 2333-2342.

Bleil, D.F. 1964. Natural Electromagnetic Phenomena Below 30 KC/S. New York: Plenum Press.

Campbell, W.H. 1959. "A study of Micropulsations in the earth's magnetic field". Unpublished Doctorial's Thesis, Institute of Geophysics, University of California, Los Angeles.

Campbell, W.H., and Stiltner, E.C. 1965. Some Characteristics of Geomagnetic pulsations at frequencies near 1 Hz. J. Res. NBS., Radio Sci., 69D: 1117-1132.

Chapman, S., and Bartels, J. 1962. Geomagnetism. 2 vols., 1 ed., London: Oxford University Press.

Davies, K. 1965. Ionospheric Radio Propagation. United States Department of Commerce.

Dawson, J.A. 1965. "Geomagnetic Micropulsations with emphasis on the properties and interpretation of Pearls." Unpublished Doctorial's Thesis, Department of Physics, Alaska University.

Dessler, A.J. 1959. Ionospheric Heating by Hydromagnetic Waves. Journal of Geophysical Research, 64: 379-401.

Duffus, H.J., and Shand, J.A. 1958. Some observations of Geomagnetic Micropulsations. Canadian Journal of Physics, 36: 508-526.

Fejer, J.A. 1960. Hydromagnetic Wave Propagation in the Ionosphere. J. Atmosph. Terrest. Phys., 18: 135-146.

Francis, W.E., and Karplus, R. 1960. Hydromagnetic Waves in the Ionosphere. Journal of Geophysical Research, 65: 3593-3600.

Gendrin, R.E., and Troitskaya, V.A. 1965. Preliminary results of a Micropulsation experiment at conjugate points. Radio Sci., 69D: 1107-1116.

Greifinger, C., and Greifinger, P. 1965. Transmission of Micropulsations through the lower ionosphere. Journal of Geophysical Research, 70: 2217-2231.

Harang, L. 1936. Oscillation and Vibrations in magnetic records at high-lattitude stations. Terrest. Magn. Atmosph. Elec., 41: 329-336.

Heacock, R.R. 1966. The 4-second summertime Micropulsation band at College. Journal of Geophysical Research, 71: 2763-2775.

Heacock, R.R. and Hessler, V.P. 1962. Pearl-type telluric current Micropulsations at College. Journal of Geophysical Research, 67: 3985-3995.

Helliwell, R.A. 1969. Low-frequency wave in the Magnetosphere. Reviews of Geophysics, 7, No. 1 and 2, Feb.-May.

Hirasawa, T., and Nagata, T. 1966. Spectral analysis of Geomagnetic Pulsations from 0.5 to 100 seconds in period for the quiet sun condition. PAGEPM., 65: 102-124.

Holmberg, E.R.R. 1953. Rapid periodic fluctuations of the Geomagnetic field. Geophysical Supplement, Monthly Notices of the Royal Astronomical Society, 6: 467-481.

Hutton, R.M.S. 1965. Equatorial Effects. J. Res. NBS. Radio Sci., 68: 1169-1177.

Jacobs, J.A., Kato, Y., Matsushita, S., and Troitskaya, V.A. 1964. Classification of Geomagnetic Micropulsations. Journal of Geophysical Research, 69: 180-183.

Jacobs, J.A., and Wright, C.S. 1965. Geomagnetic Micropulsation results from Byrd station and Great Whale River. Canadian Journal of Physics, 43: 2099-2122.

Karplus, R., Francis, W.E. and Dragt, A.J. 1962. The Attenuation of Hydromagnetic Waves in the Ionosphere. Planet. Space Sci., 9: 771-786.

Kato, Y. 1962. Geomagnetic Pulsations. Sci Rept. Tohoku Univ., 13: 141-163.

Kato, Y., and Okuda, M. 1956. The Effect of the Solar Eclipse on the rapid pulsations of the earth's magnetic field. Sci. Rept. Tohoku Univ., Fifth Ser., 7: 37-43.

Kato, Y., Ossaka, J., Okuda, M., Watanabe, T., and Tamao, T. 1957. Investigation on the Magnetic disturbance by the induction magnetograph, VI, on the daily variation and the 27-day recurrence tendency in the Geomagnetic pulsation. Sci. Rept. Tohoku Univ., Fifth Ser., 8: 19-23.

Kato, Y., and Saito, T. 1959. Preliminary studies on the daily behavior of Rapid Pulsation. J. Geomag. Geoelectr., 20: 220-221.

Keller, G.V., and Frischknecht, F.C. 1966. Electrical Methods in Geophysical Prospecting. London: Pergamon Press Ltd.

Kelso, J.M. 1964. Physics of the Ionosphere, p.p. 66-110, Radio Ray Propagation in the Ionosphere. New York: McGraw-Hill Book Co. Inc.

Lokken, J.E., Shand, J.A., and Wright, C.S. 1963. Some Characteristic of Electromagnetic background signals in the vicinity of one cycle per second. Journal of Geophysical Research, 60: 789-794.

Matsushita, S., and Campbell, W.H. 1968. Physics of Geomagnetic Phenomena. 2 vols. New York: McGraw-Hill Book Co. Inc.

Meyerhoff, M.J. 1968. Realization of Sharp Cut-off Frequency Characteristics on dizital computers part I, II. Geophysical Prospecting, XVI: 208-246.

Prince, C.E., Bostick, Jr., F.X., and Smith, H.W. 1964. A study of the transmission of plane Hydromagnetic Waves through the upper atmosphere. Elec. Eng. Res. Lab., Univ. Texas, Rept., 134: 1-221.

Rower, K. 1956. The Ionosphere. New York: Frederick Ungar Publishing Co.

Sacksdoff, E. 1936. Occurrences of Rapid Micropulsations at Sodankyla during 1932 to 1935. Terrest. Magn. Atmosph. Elec., 41: 337-344.

Sandstrom, A.E. 1965. The Radiation Belt of the Earth, p. 359, Cosmic Ray Physics. New York: John Wiley and Sons.

Schumann, W.O. 1952. Uber die Ausbreit sehr Langer elektrischer Wellenund der Blitzentladung um die Erede. Zeits. fur Ange. Phys., 4: 474-480.

Tepley, L. 1964. Low latitude observations of fine structured Hydromagnetic Emissions. Journal of Geophysical Research, 69: 2273-2290.

Tepley, L. 1965. Regular oscillations near 1 C/S observed at Middle and Low lattitudes. J. Res. NBS., Radio Sci., 69D: 1089-1105.

Troitskaya, V.A. 1961. Pulsation of the earth's Electromagnetic field with periods of 1 to 15 seconds and their connection with Phenomena at the High Atmosphere. Journal of Geophysical Research, 66: 5-18.

Wentworth, R.C. 1964a. Enhancement of Hydromagnetic Emissions after Geomagnetic Storms. Journal of Geophysical Research, 69: 2291-2298.

Wentworth, R.C. 1964b. Evidence for maximum production of Hydromagnetic Emission above the afternoon hemisphere of the earth, I and II. Journal of Geophysical Research, 63: 2298-2705.

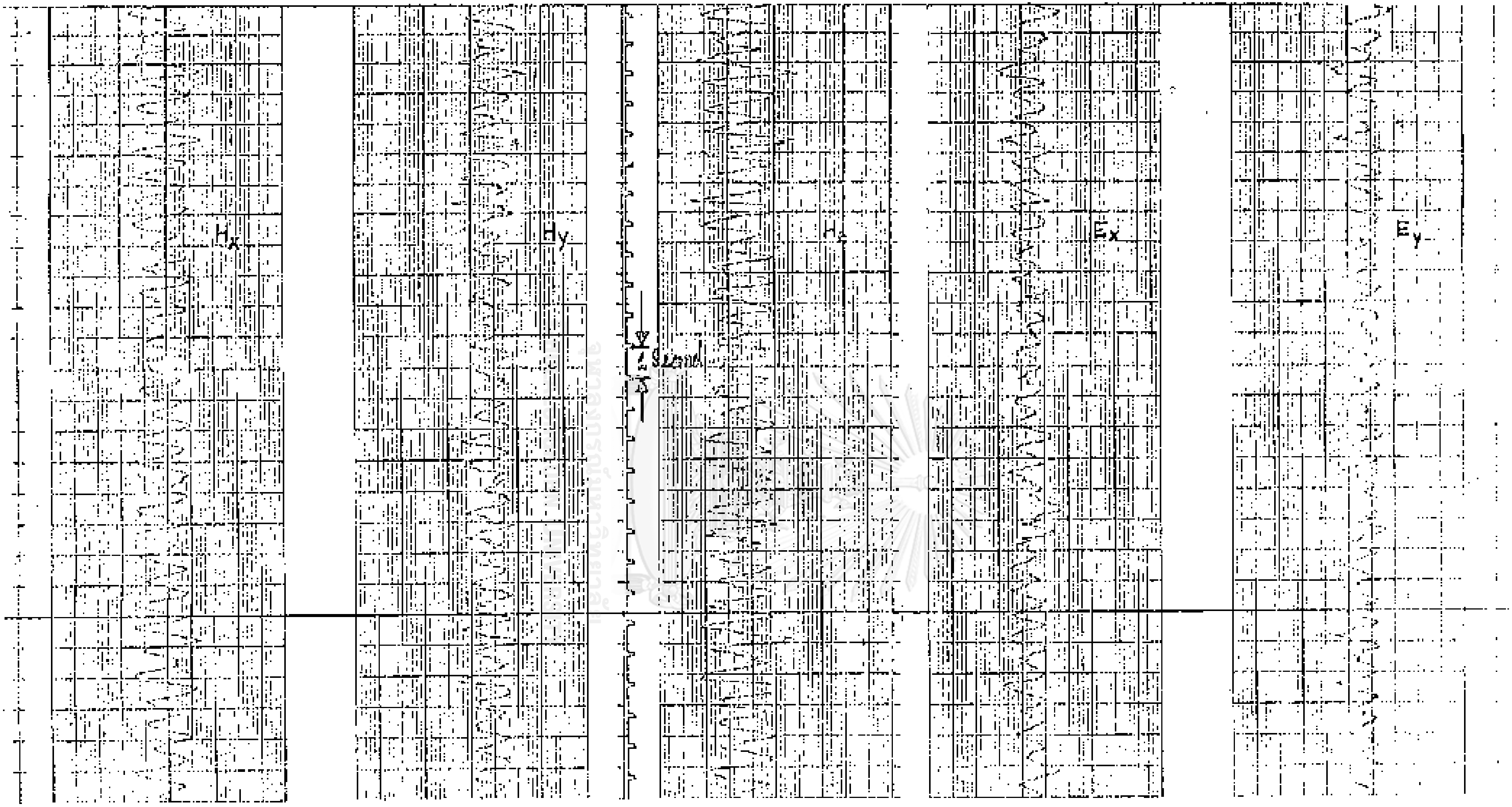


FIG. 1 EXAMPLE OF Pc TYPE MICROPULSATION

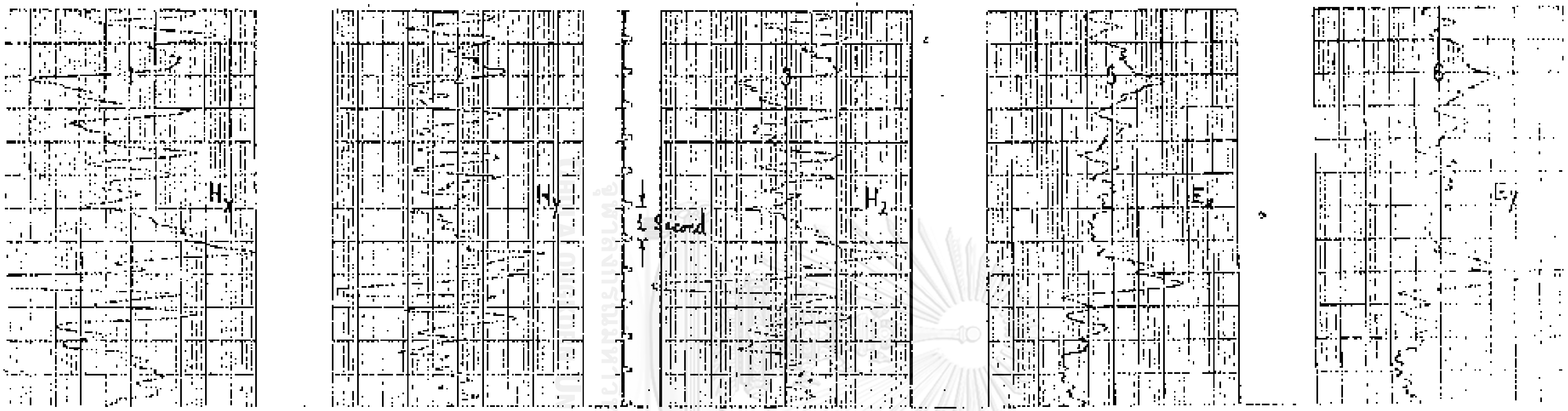


FIG. 2 EXAMPLE OF Pi TYPE MICROPULSATION

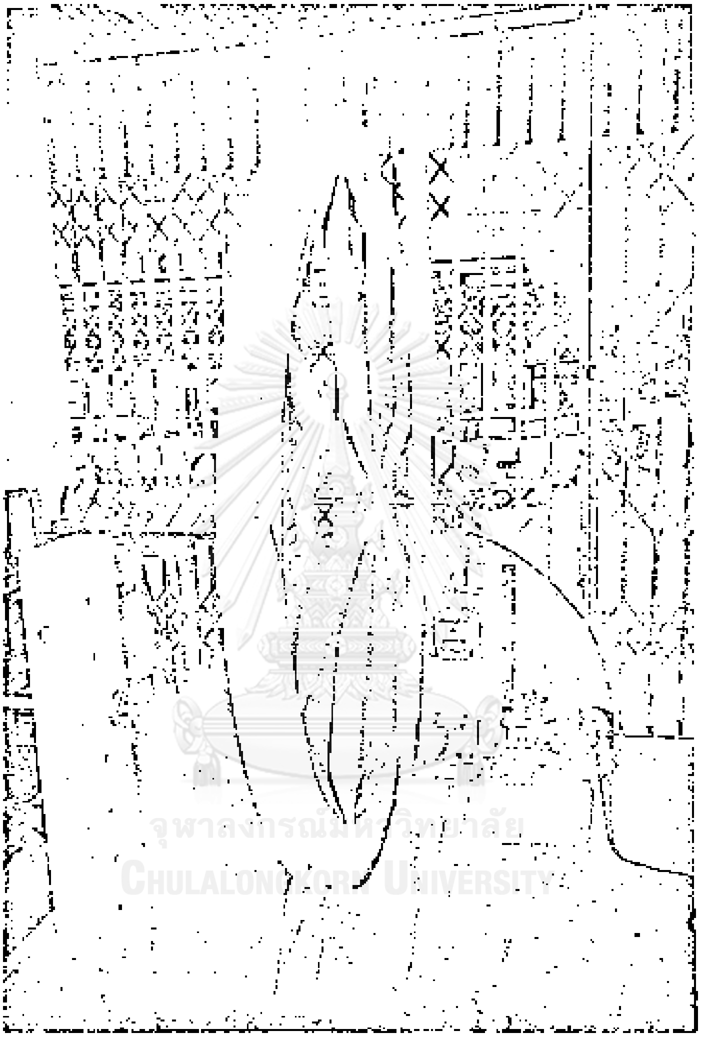


FIG. 3 CLOSE-UP VIEW OF ELECTRIC MOTOR, PULLEY ARRANGEMENT AND TURNS COUNTER

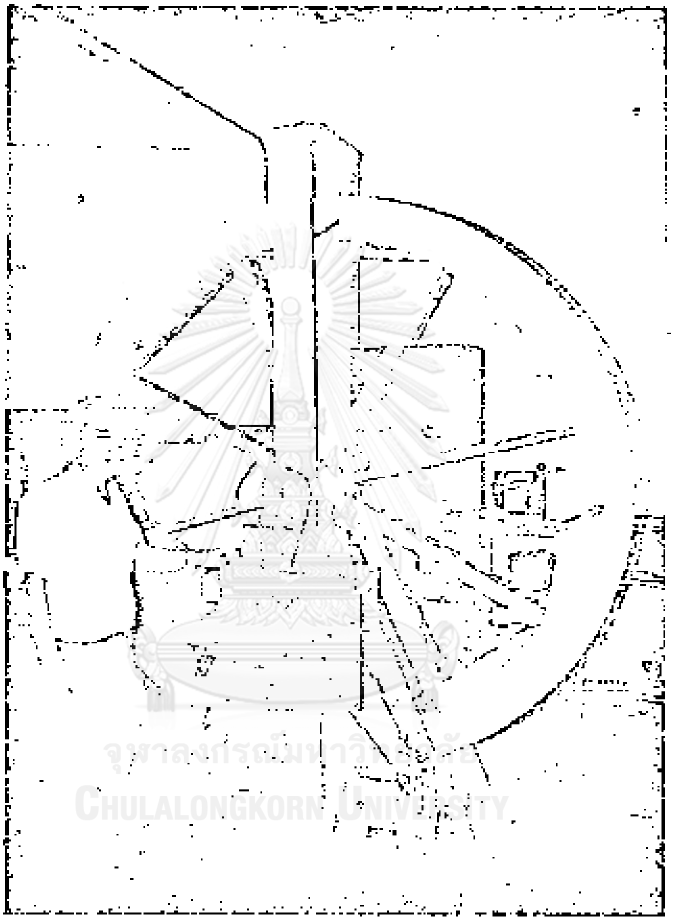
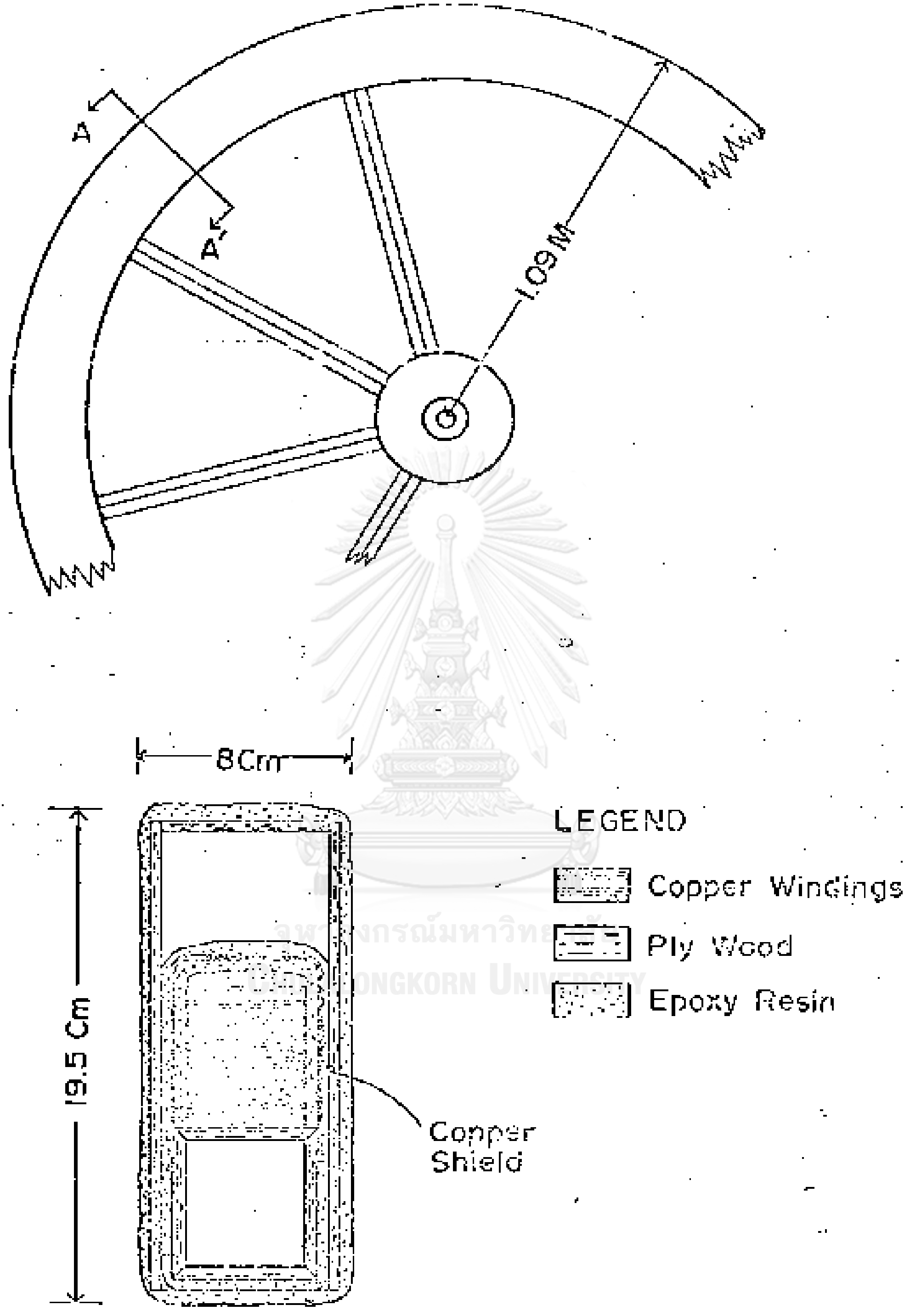


FIG. 4 COIL FRAME MOUNTED IN WINDING FRAME



SECTION A-A'

FIG. 5 COIL SCHEMATIC

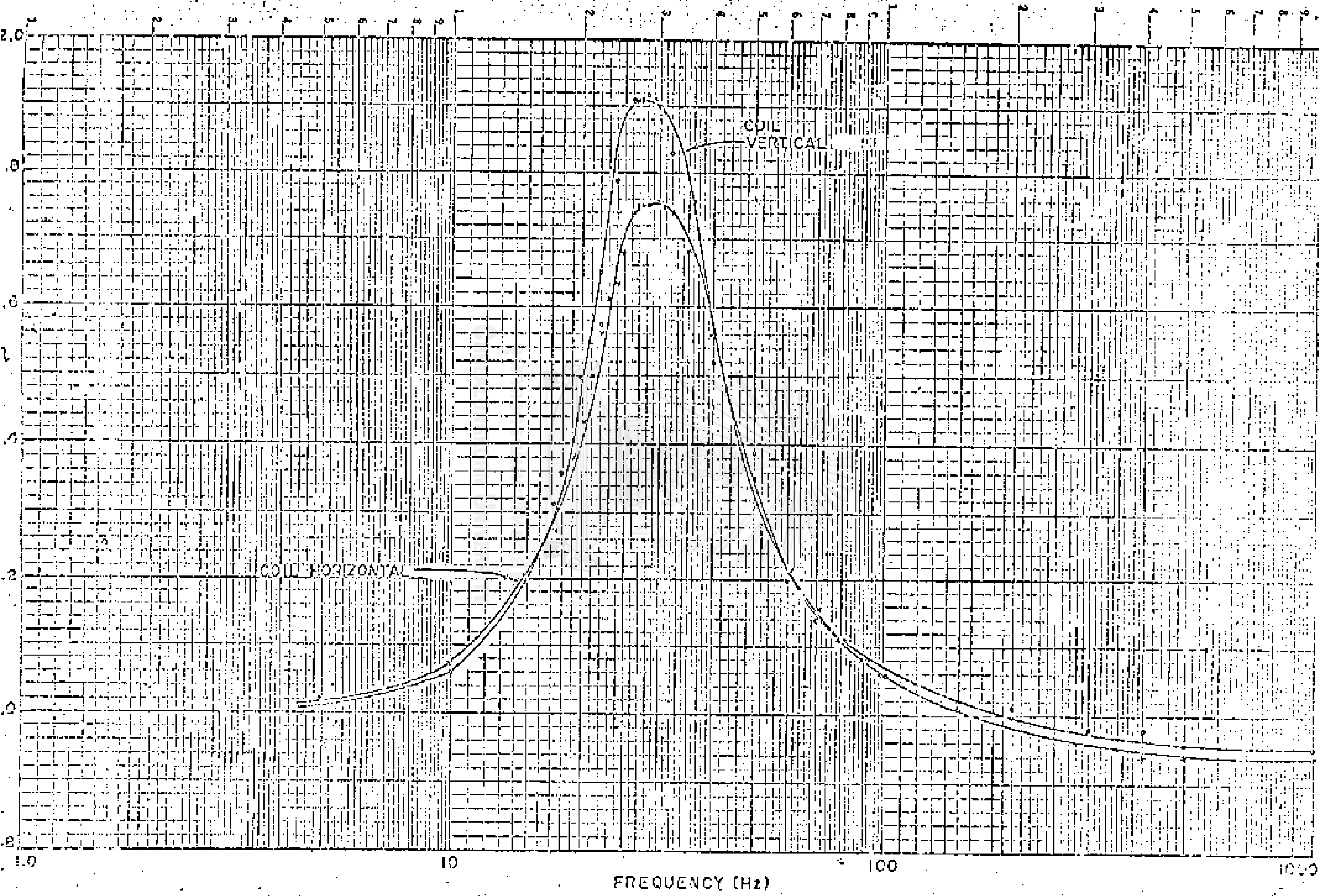


FIG. 6 CALIBRATION CURVE, COIL 2

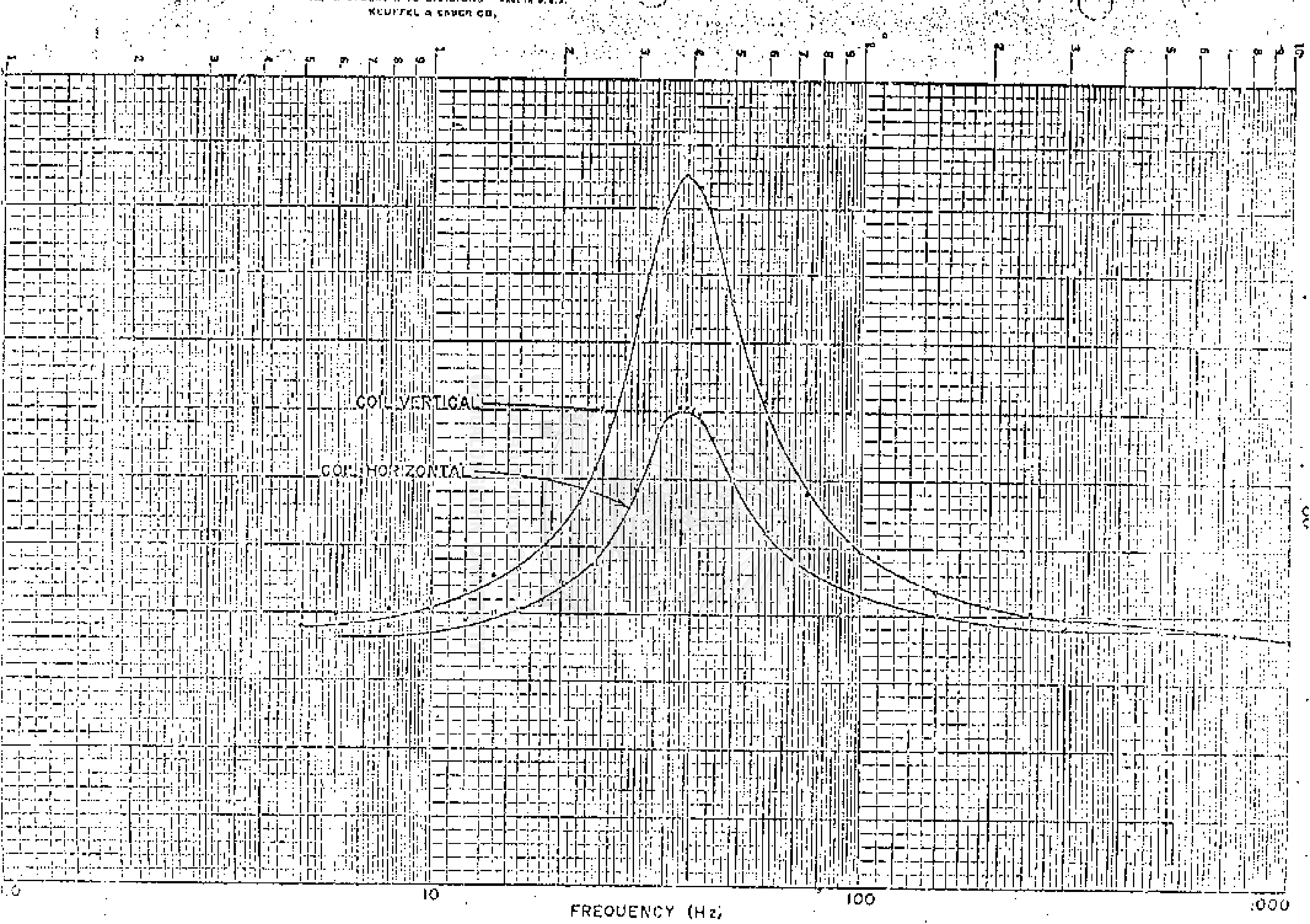


FIG. 7 CALIBRATION CURVE, COIL 3

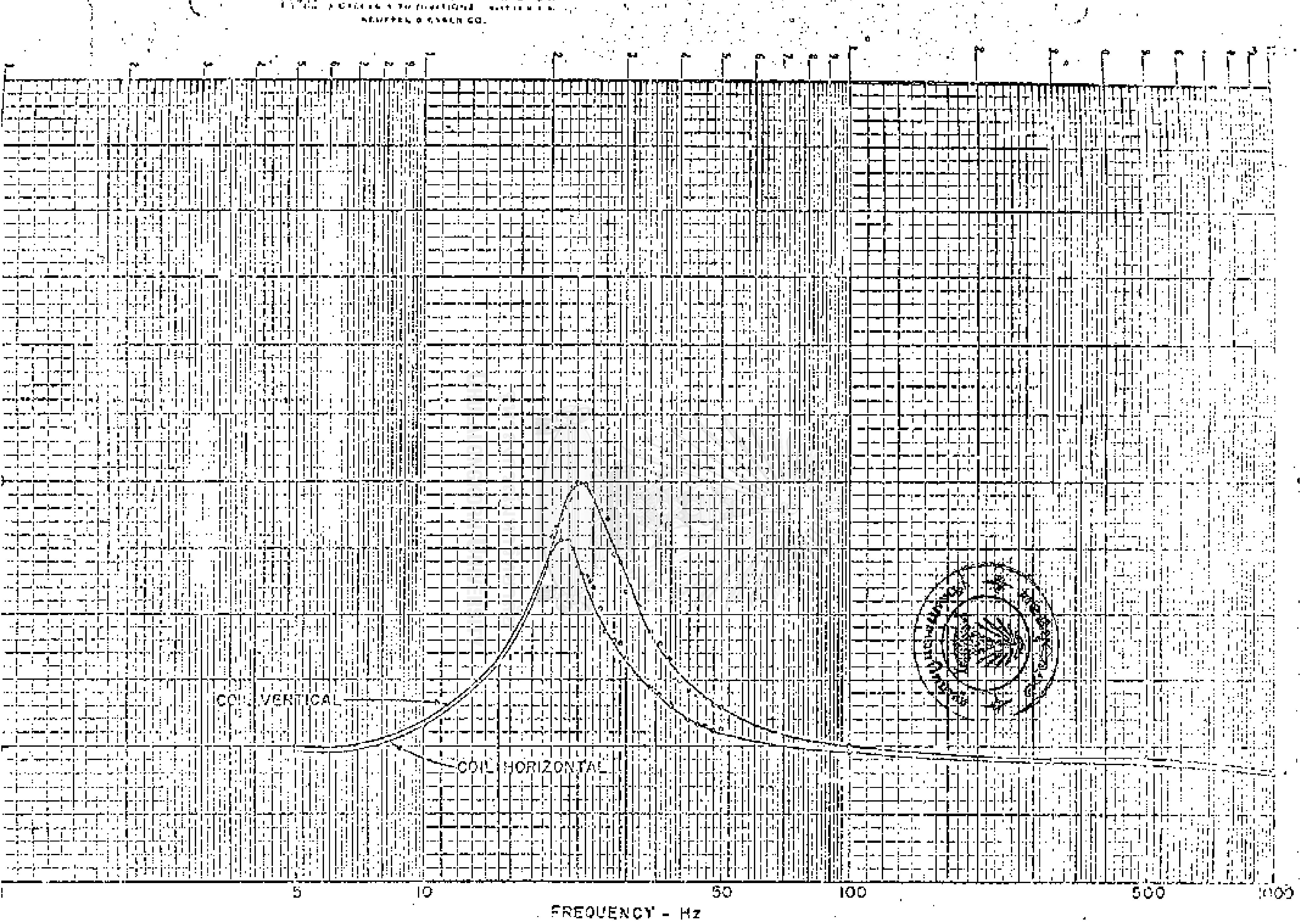


FIG. 8 CALIBRATION CURVE, COIL 4

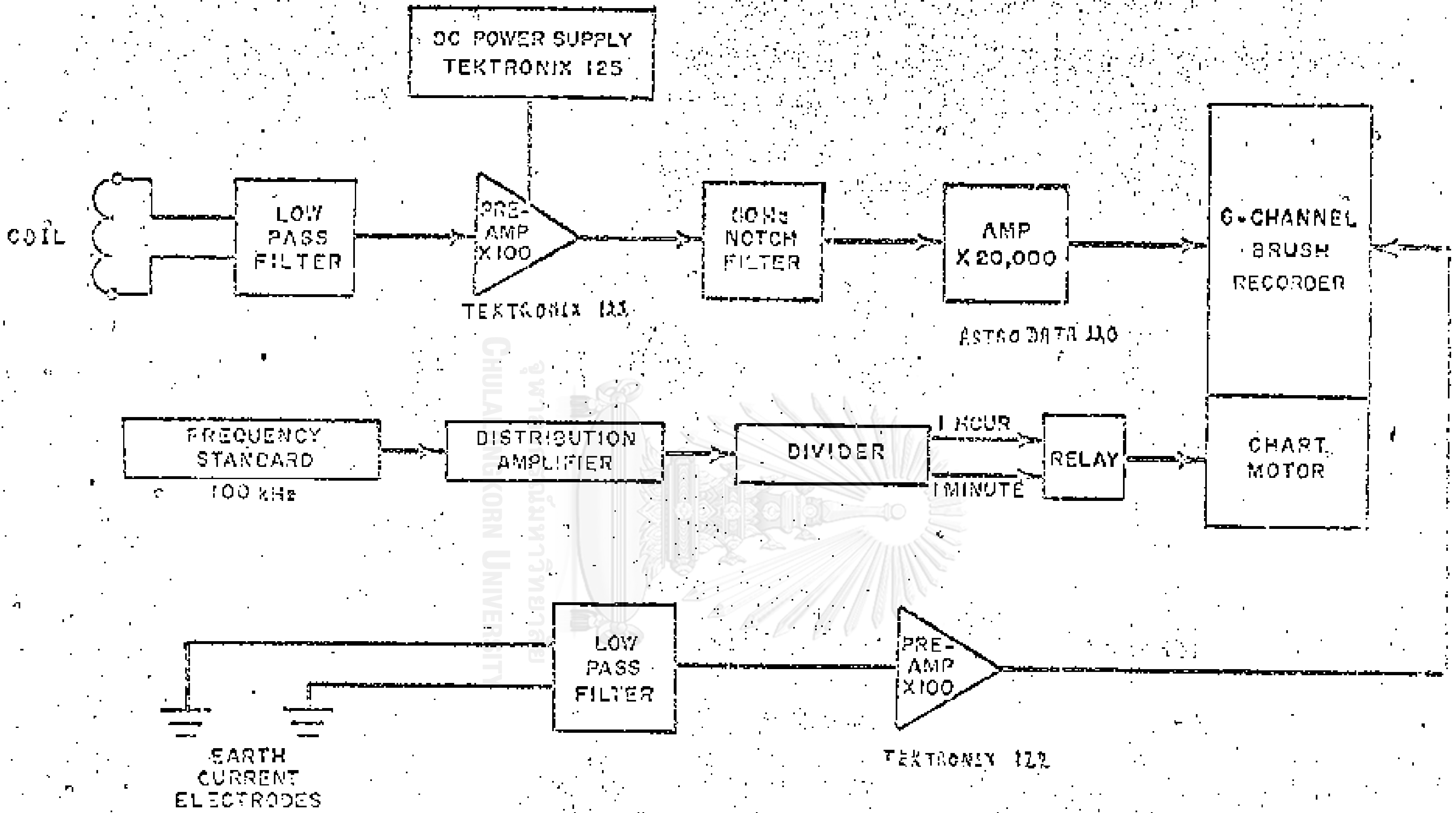


FIG. 9a. BLOCK DIAGRAM OF MAGNETIC AND ELECTRIC FIELD MEASURING SYSTEM

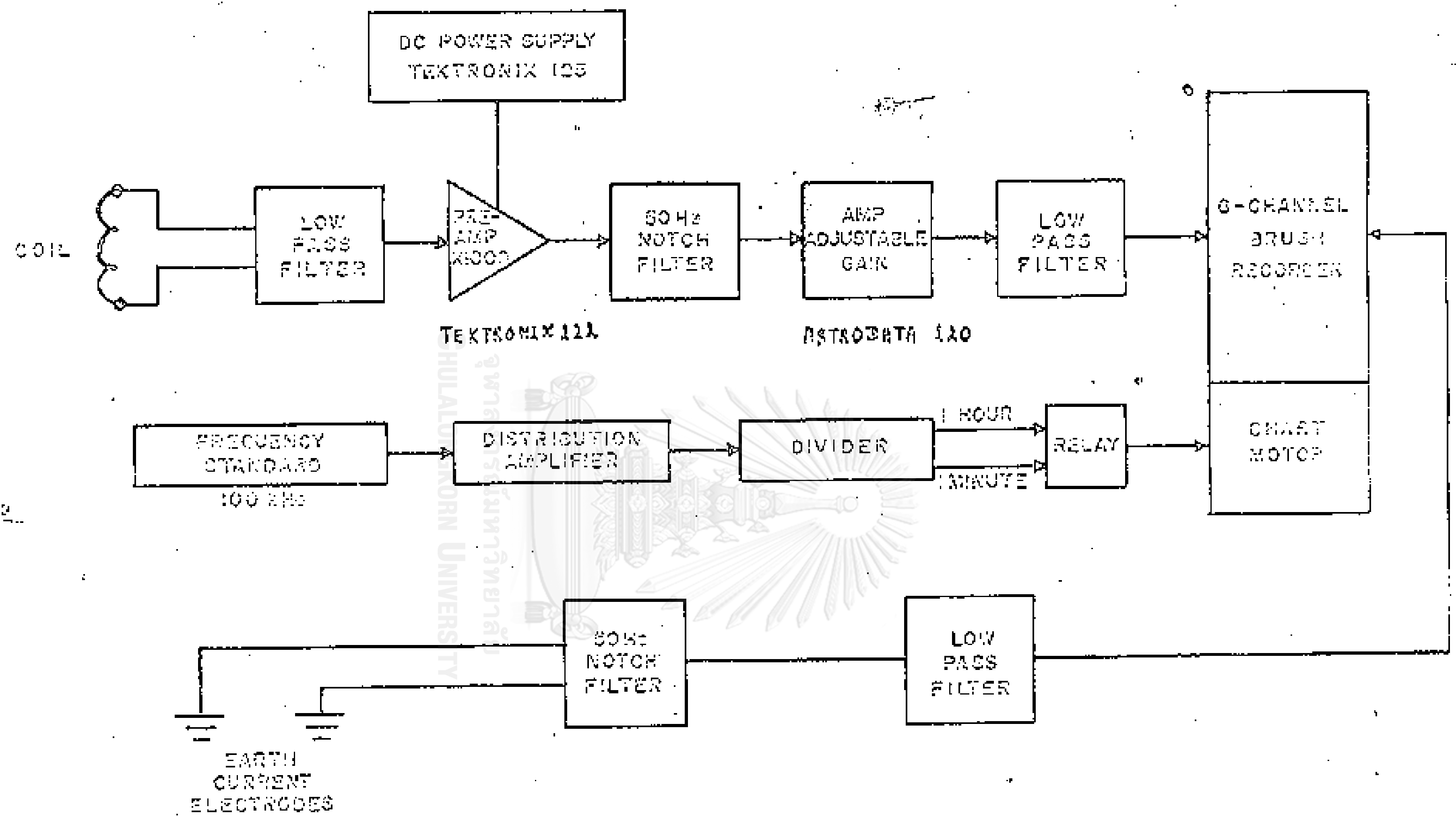


FIG. 9b. BLOCK DIAGRAM OF MAGNETIC AND ELECTRIC FIELD MEASURING SYSTEM

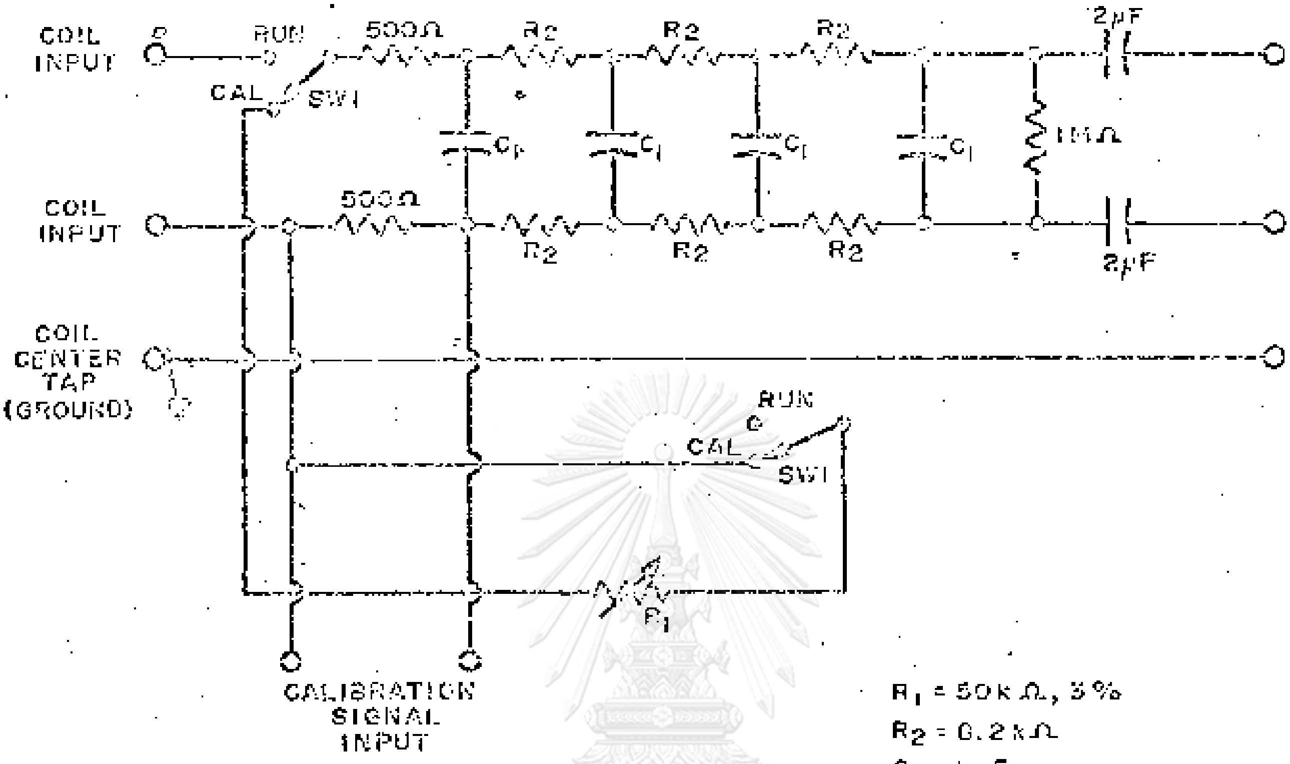


FIG. 10 INITIAL LOW PASS FILTER AND CALIBRATION CIRCUIT FOR COIL MAGNETOMETERS

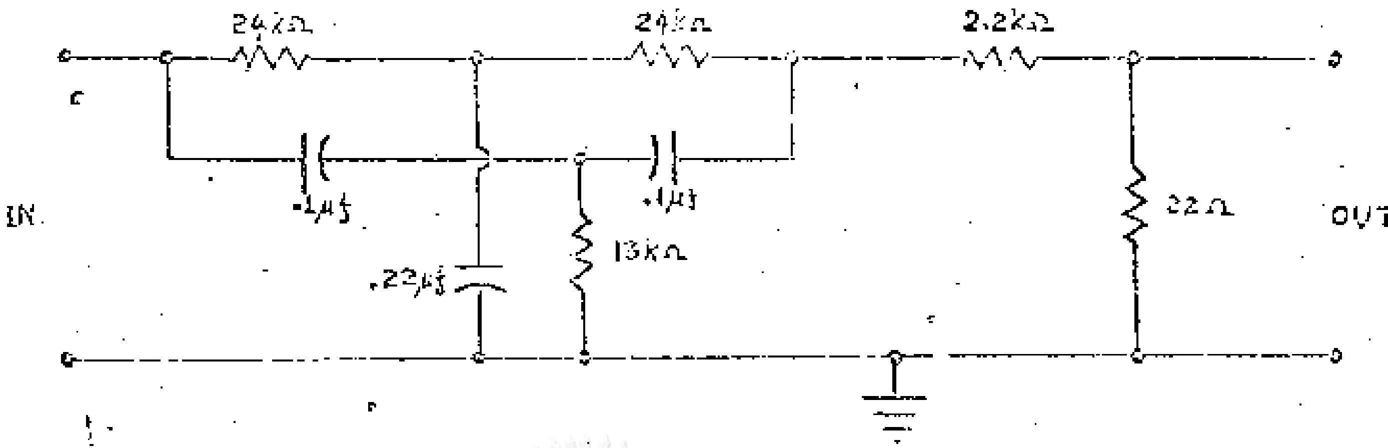


FIG. 11a. 60 Hz NOTCH FILTER AND ATTENUATOR

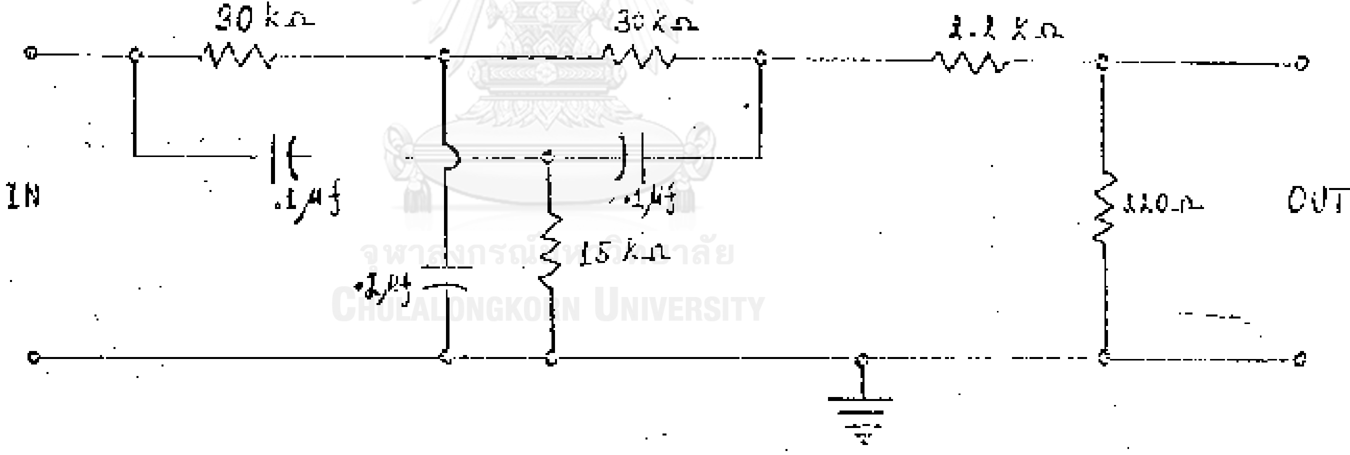


FIG. 11b. 50 Hz NOTCH FILTER AND ATTENUATOR

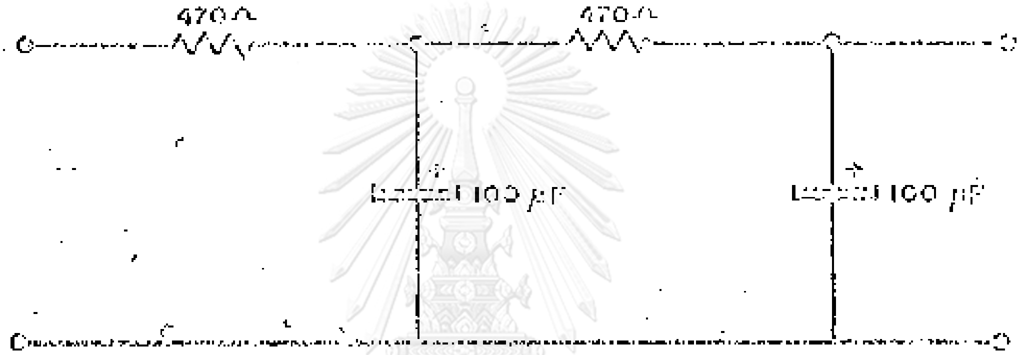


FIG. 12 PRE-RECORDING LOW-PASS FILTER

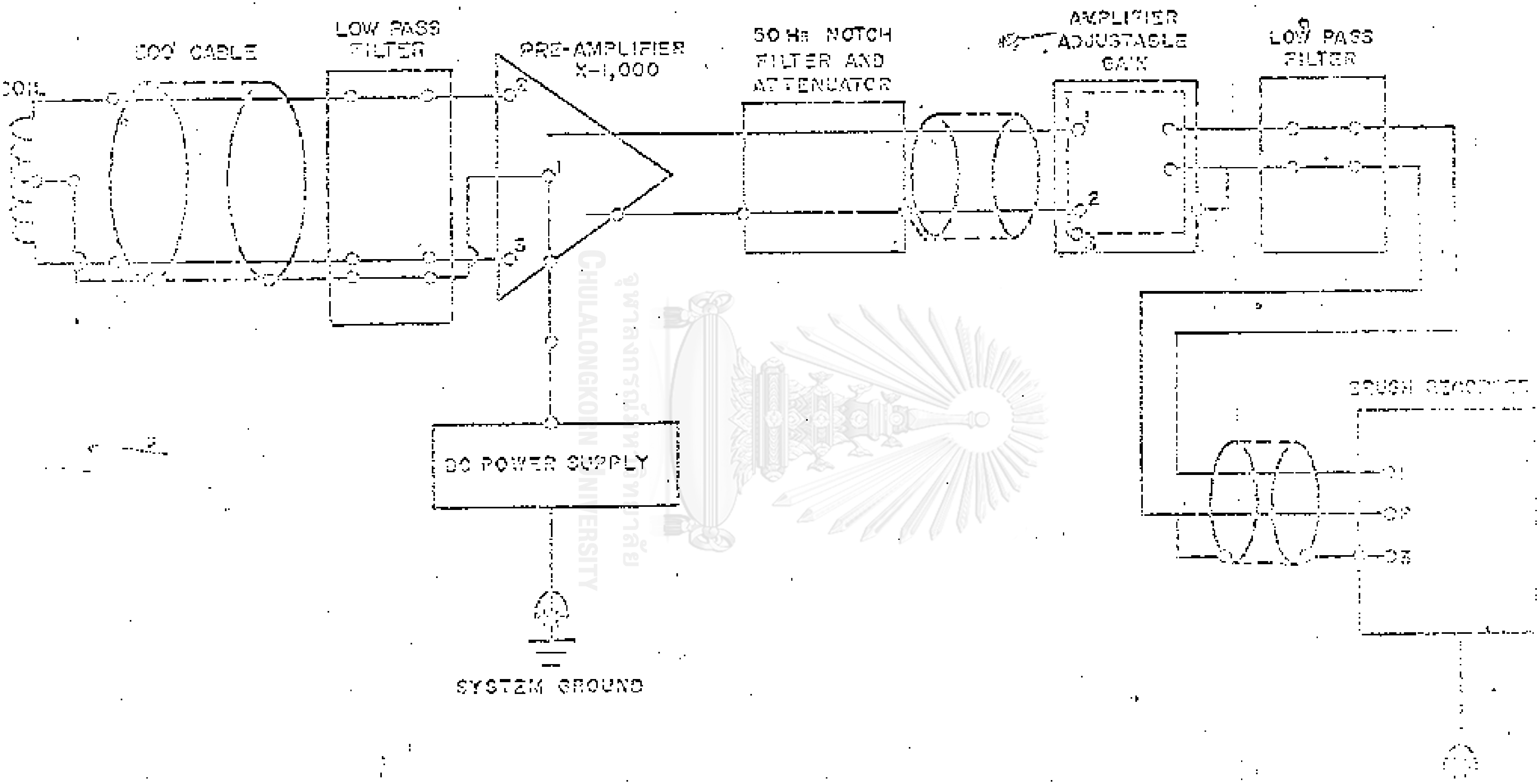
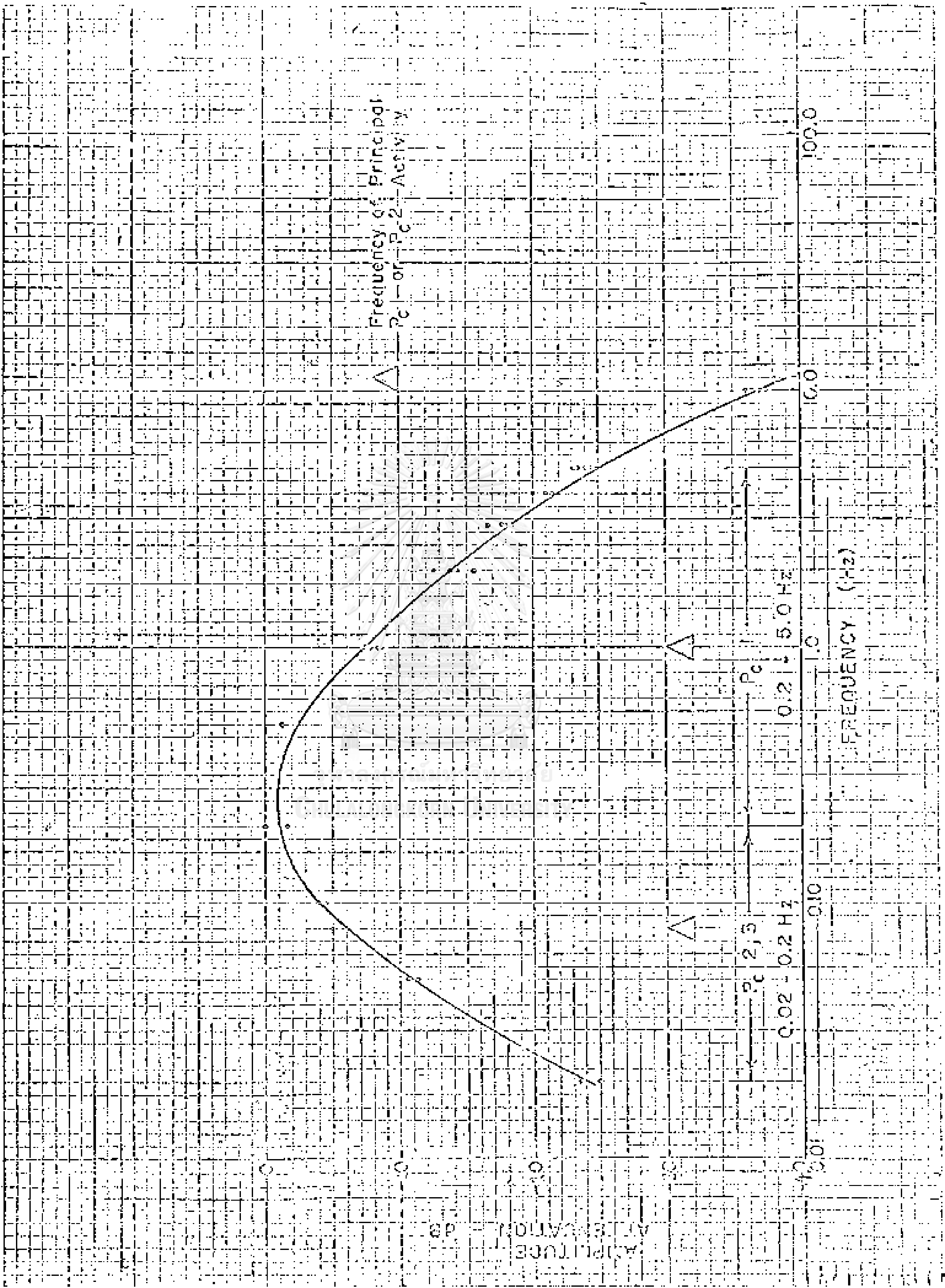


FIG. 13 BLOCK DIAGRAM OF INDUCTION COIL MAGNETOMETER CIRCUIT


Frequency of Principal
Pc or Pc2 Activity
Pc 2,3
0.02 - 0.2 Hz
Pc 1
0.2 - 5.0 Hz
0.01
0.10
1.0
10.0
100.0
FREQUENCY (Hz)
0
-10
-20
-30
-40
AMPLITUDE ATTENUATION dB

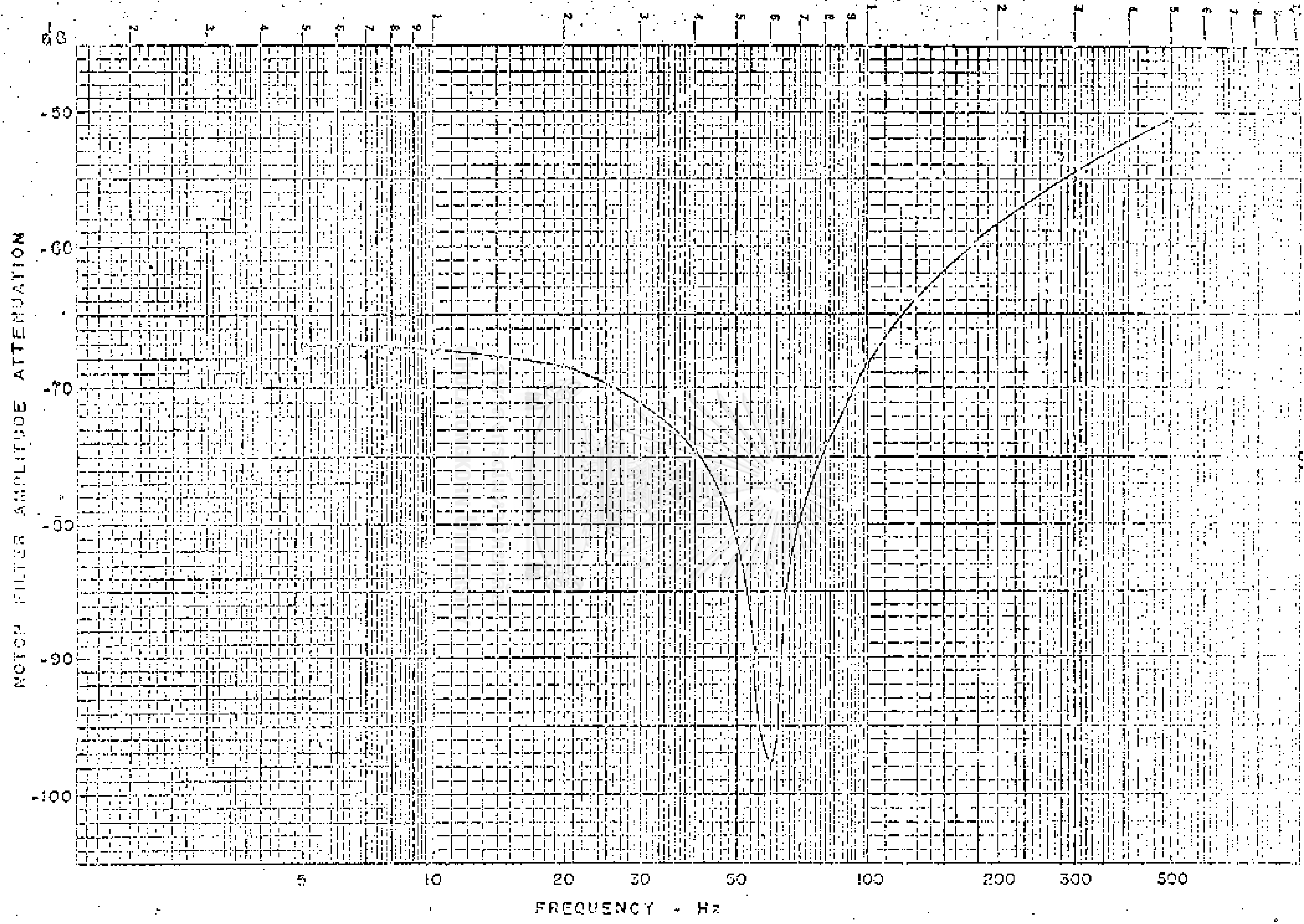
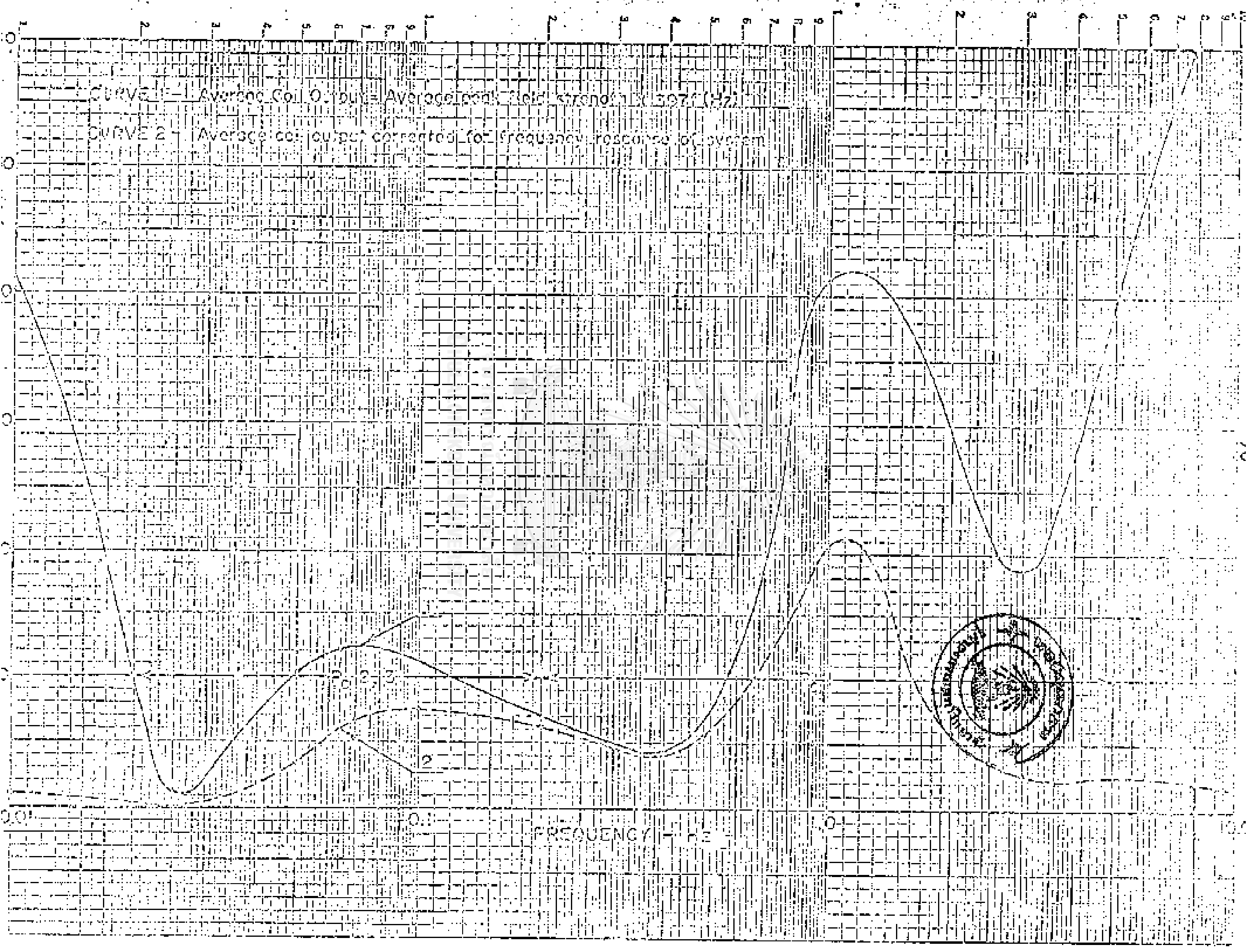
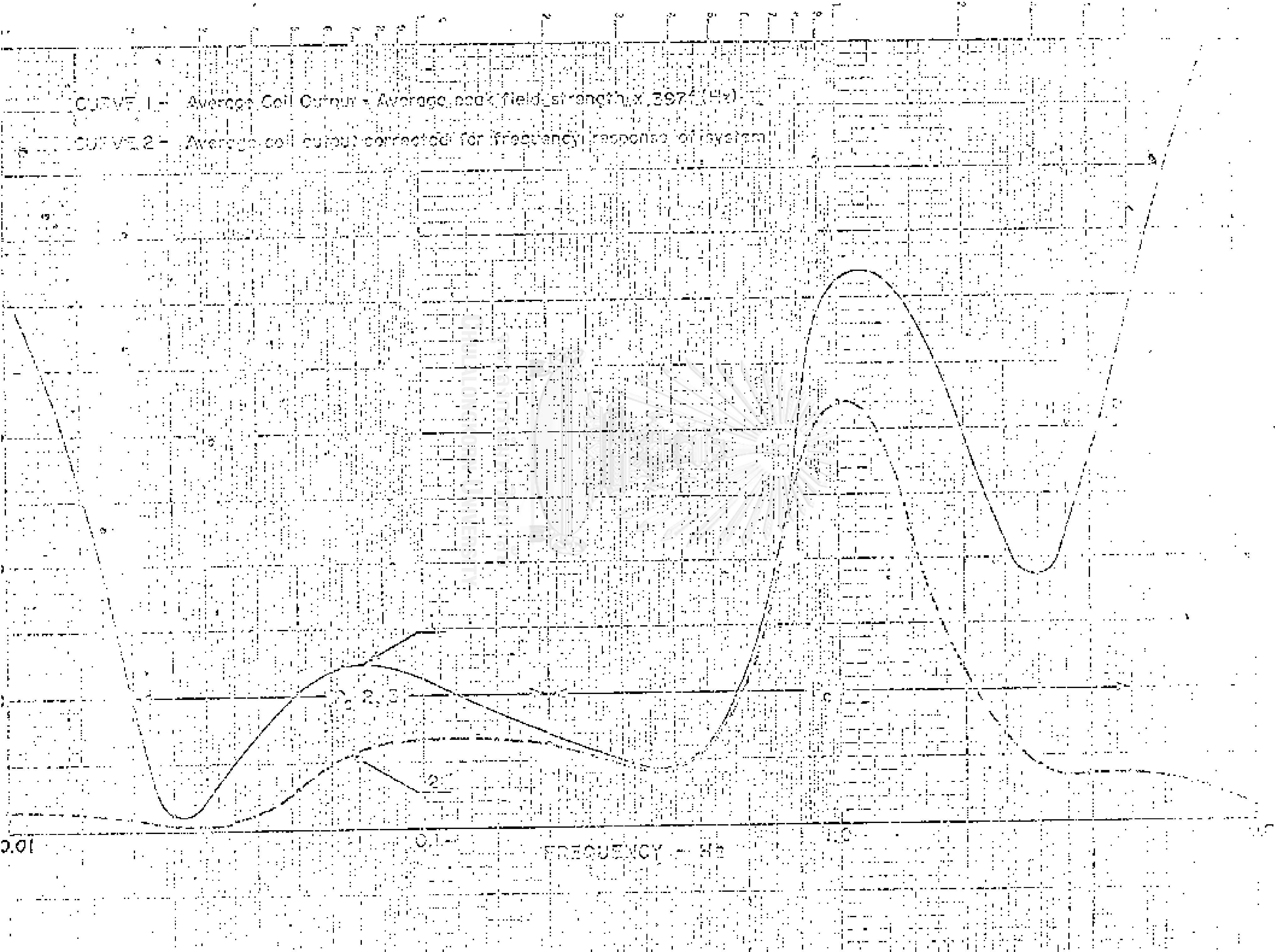


FIG. 15. FREQUENCY RESPONSE OF 60 Hz NOTCH FILTER AND ATTENUATOR


CURVE 1 – Average Coil Output / Average peak field strength X 3971 (Hz)
CURVE 2 – Average coil output corrected for frequency response of system
1
2
2
3
0.01
0.1
1.0
10.0
FREQUENCY – Hz


CURVE 1 – Average Coil Output = Average peak field strength x .397 (Hz)
CURVE 2 – Average coil output corrected for frequency response of system
1
2
2
0.01
0.1
1.0
FREQUENCY – Hz

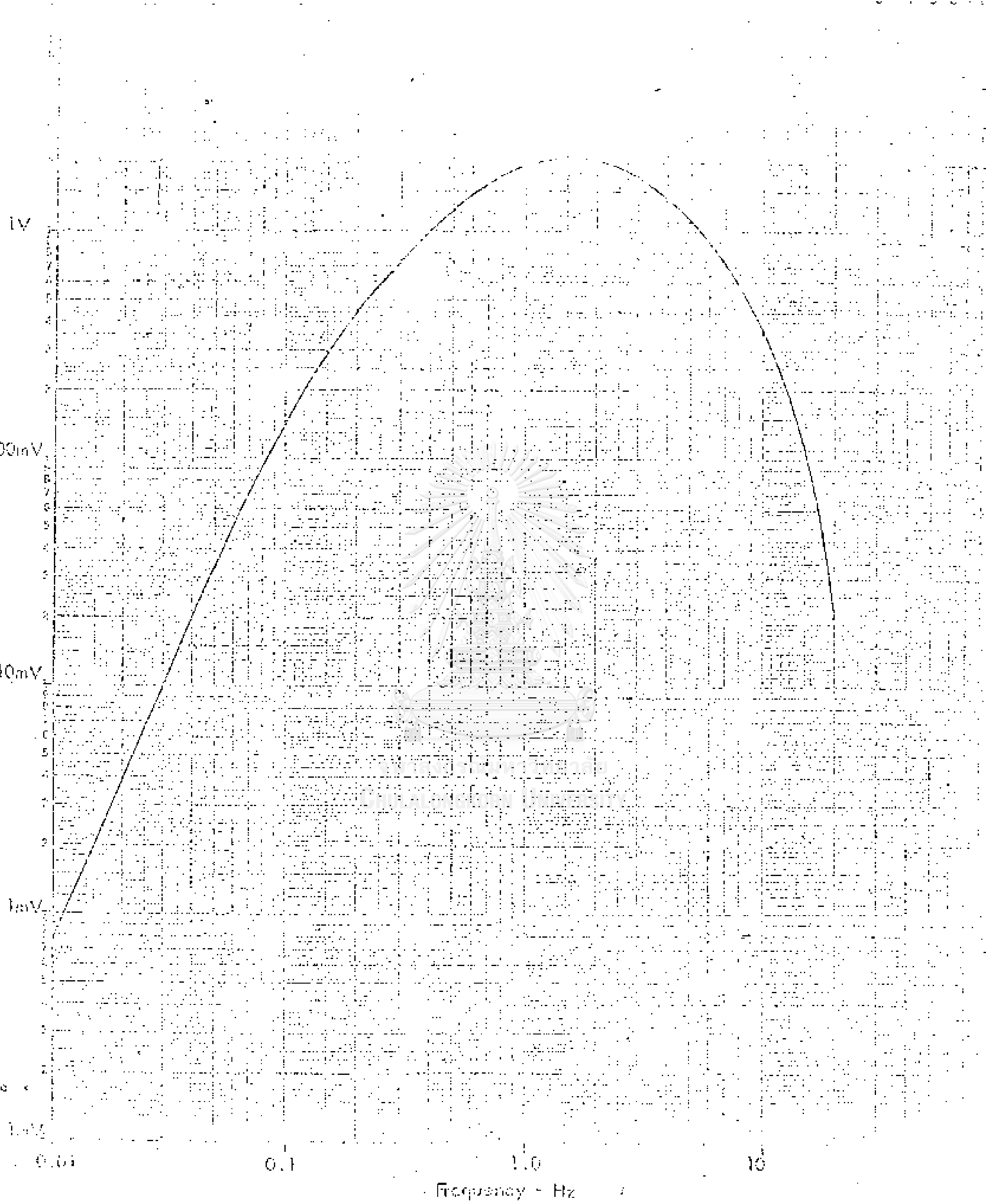


FIG. 17a. MAGNETIC RESPONSE OF MAGNETIC RECORDING SYSTEM
Output Level Produced By 1V Oscillation - Total Amplification of 10^6

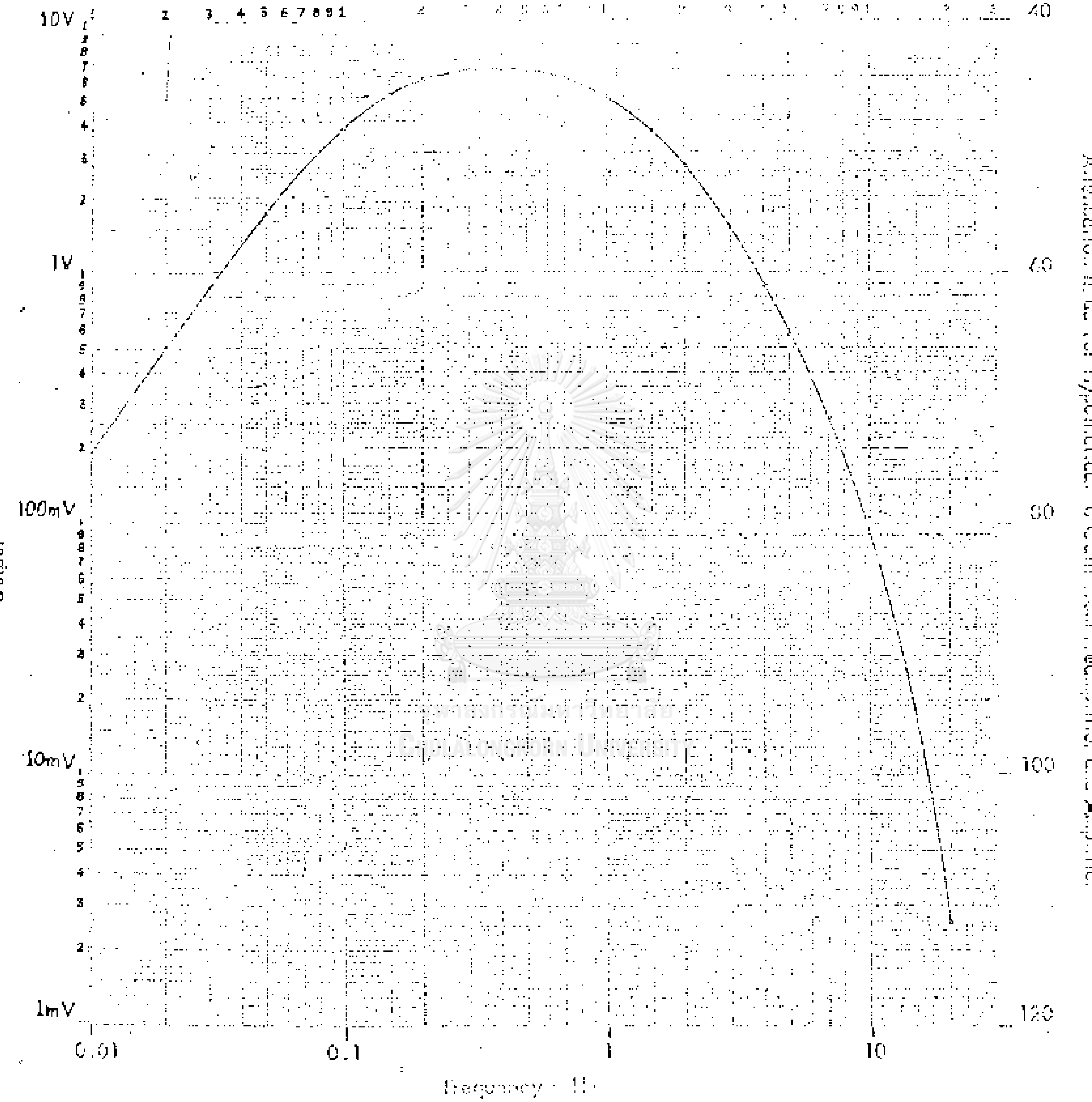


FIG. 17b. ELECTRICAL RESPONSE OF MAGNETIC RECORDING SYSTEM

Output for Input Oscillation of 1mV and Total Amplification of 10^6

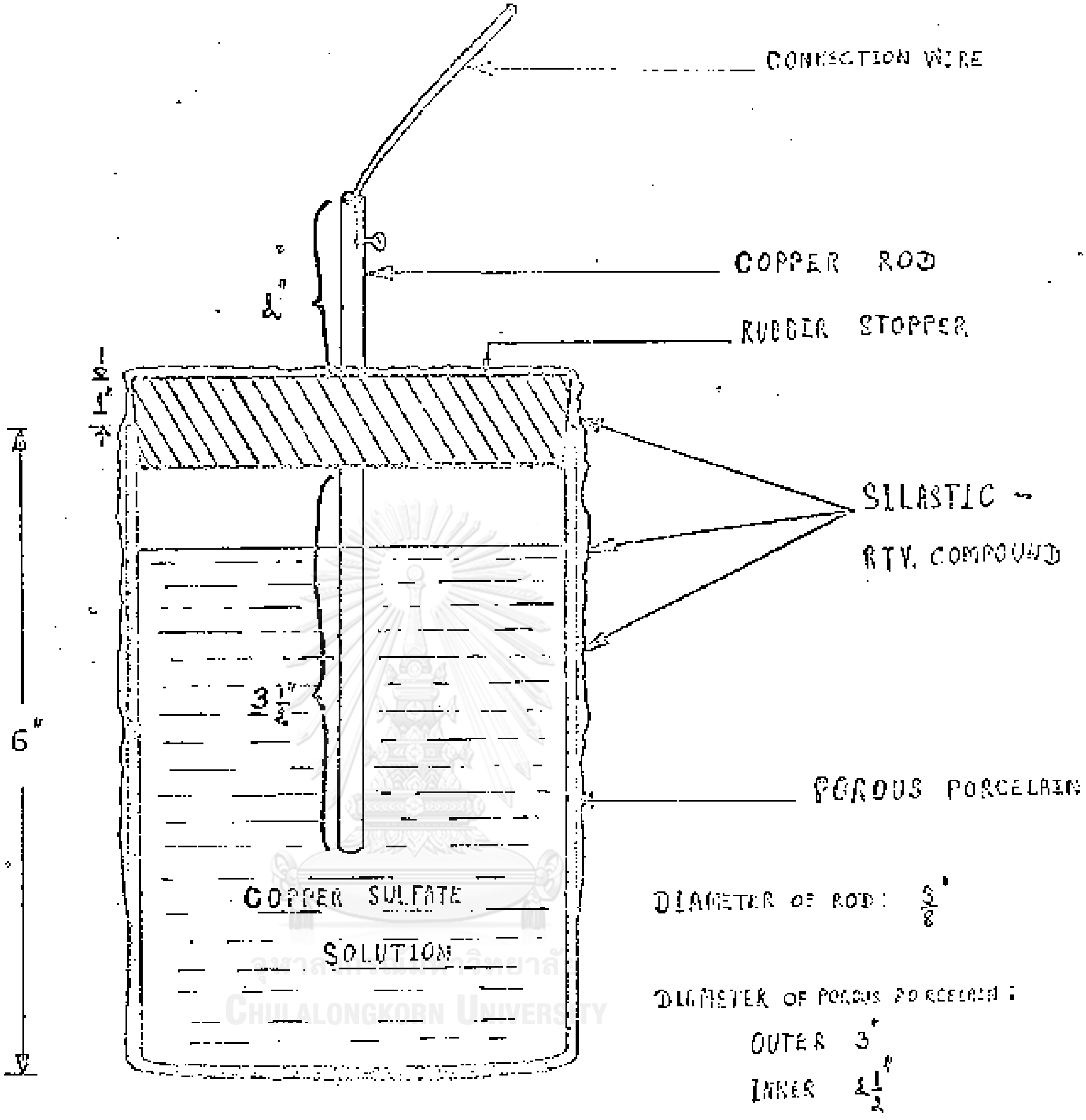


FIG. 18 a. NON-POLARIZING ELECTRODE. (COPPER ELECTRODE)

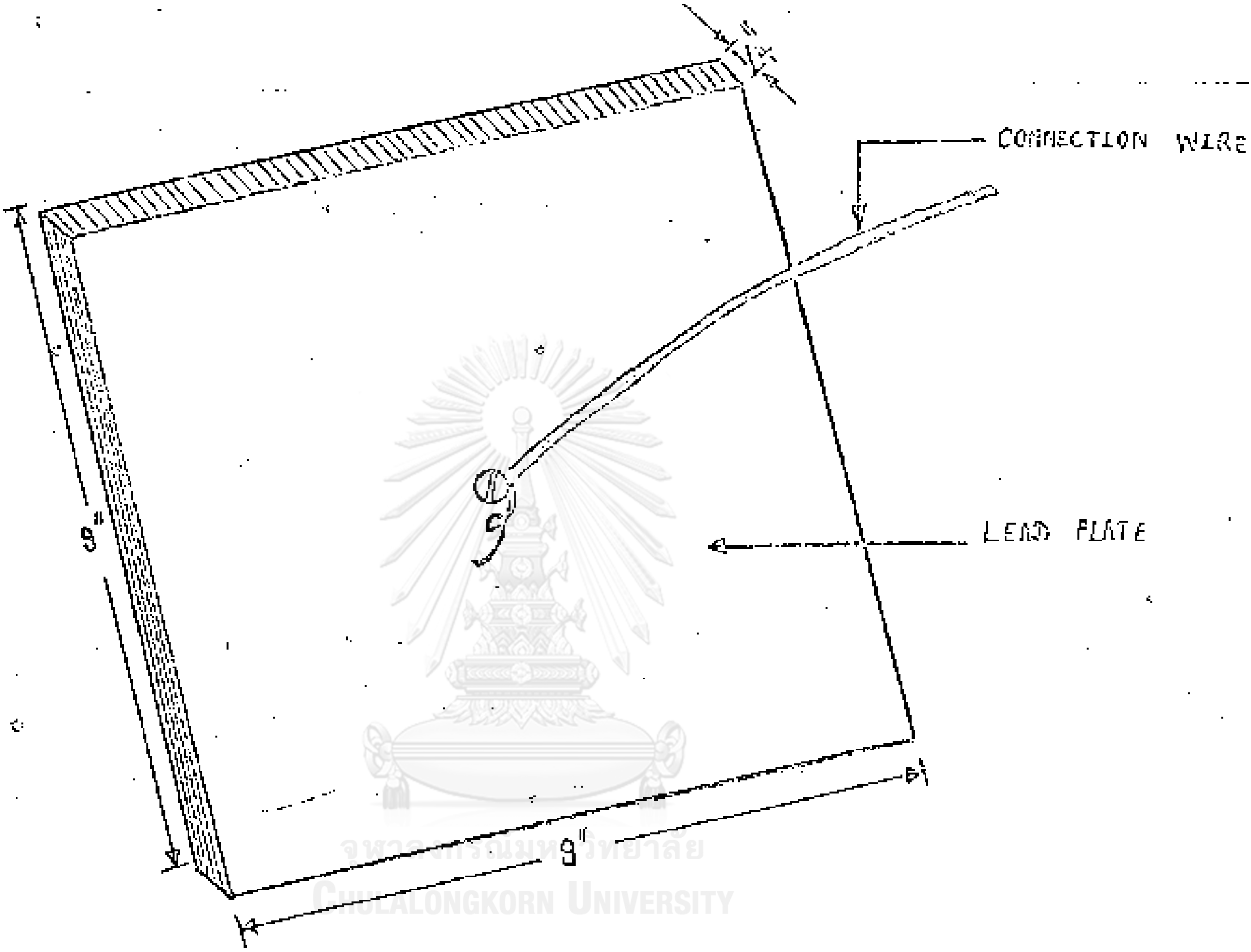


FIG. 18 b. "LEAD PLATES" ELECTRODE.

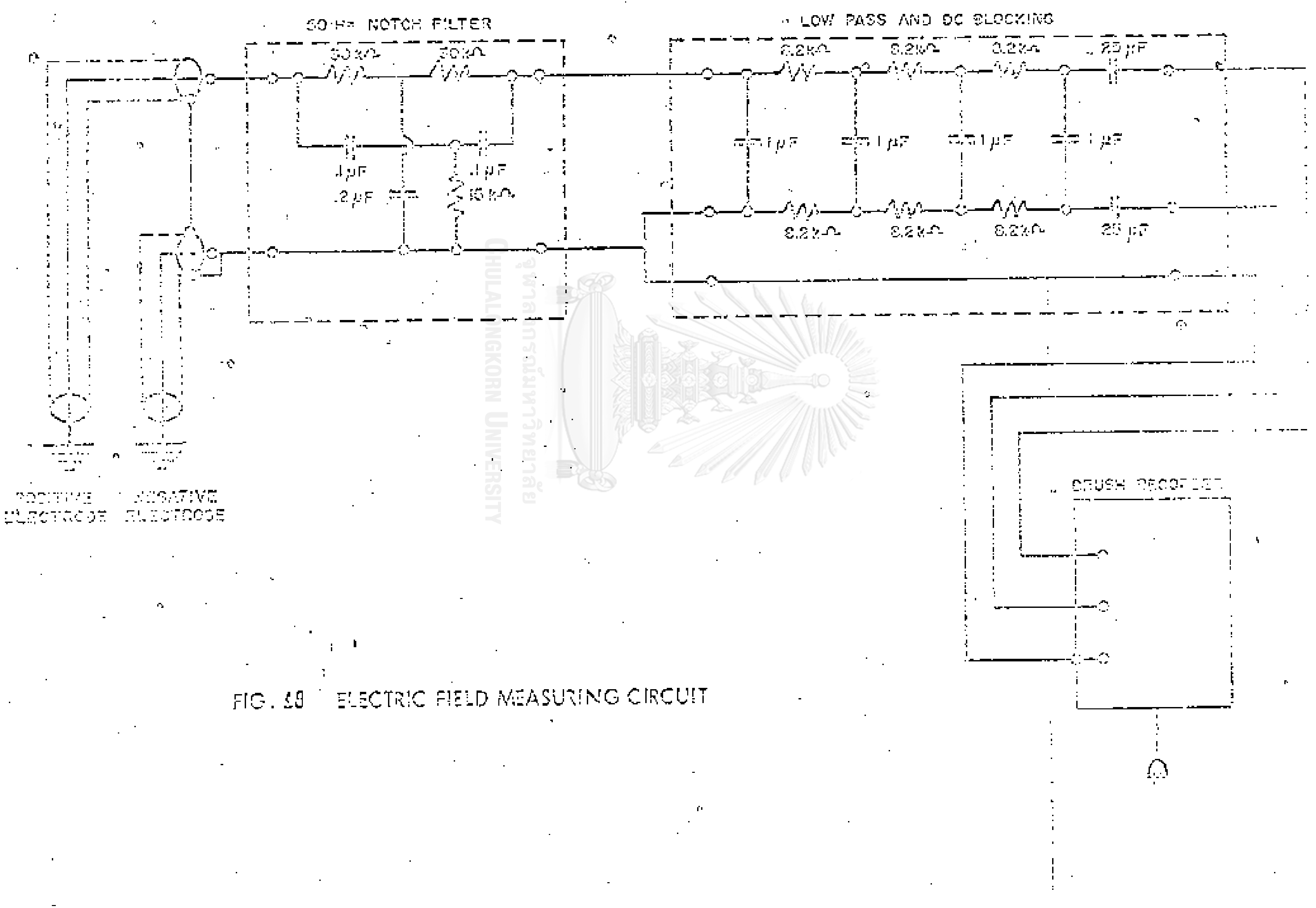


FIG. 49 ELECTRIC FIELD MEASURING CIRCUIT

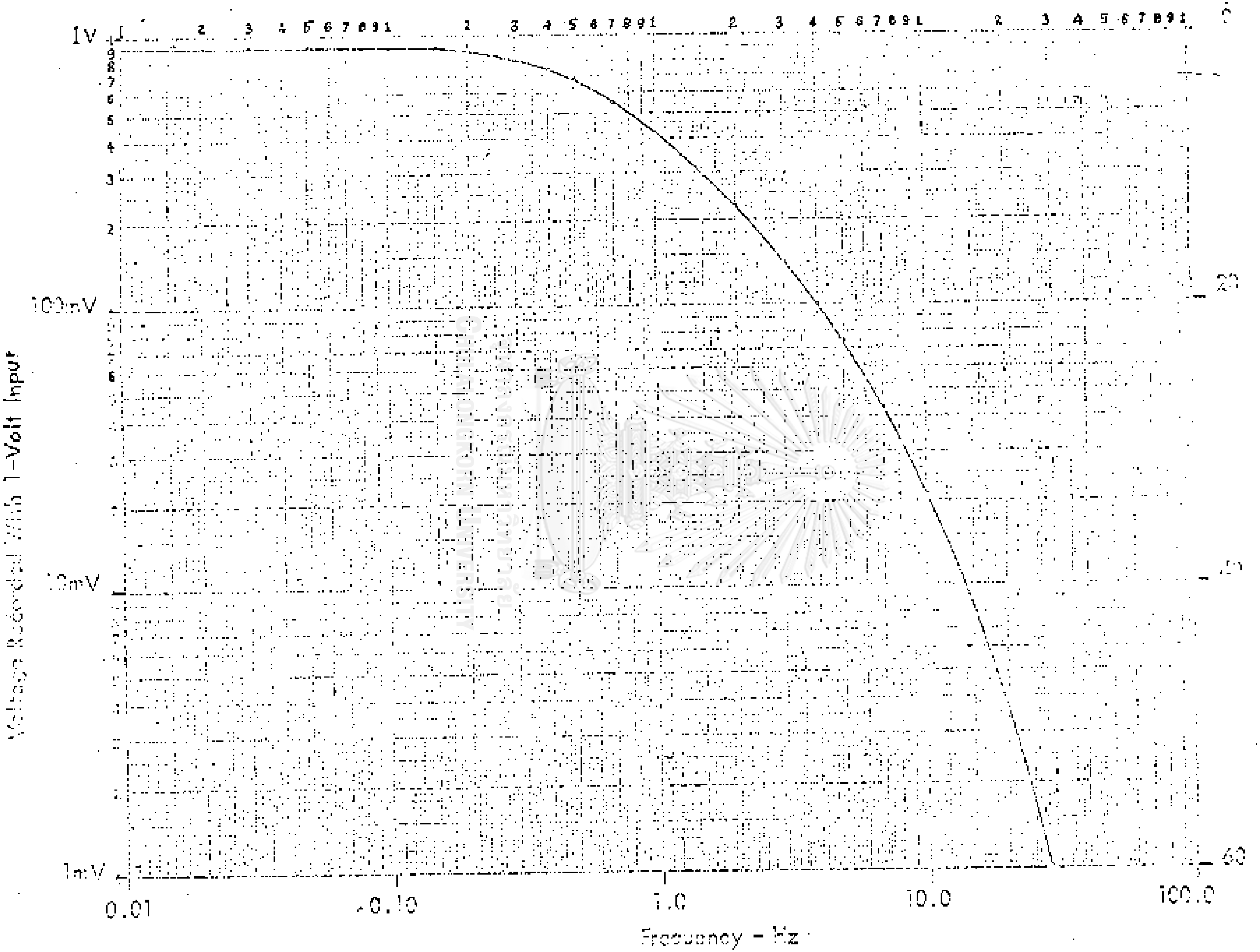
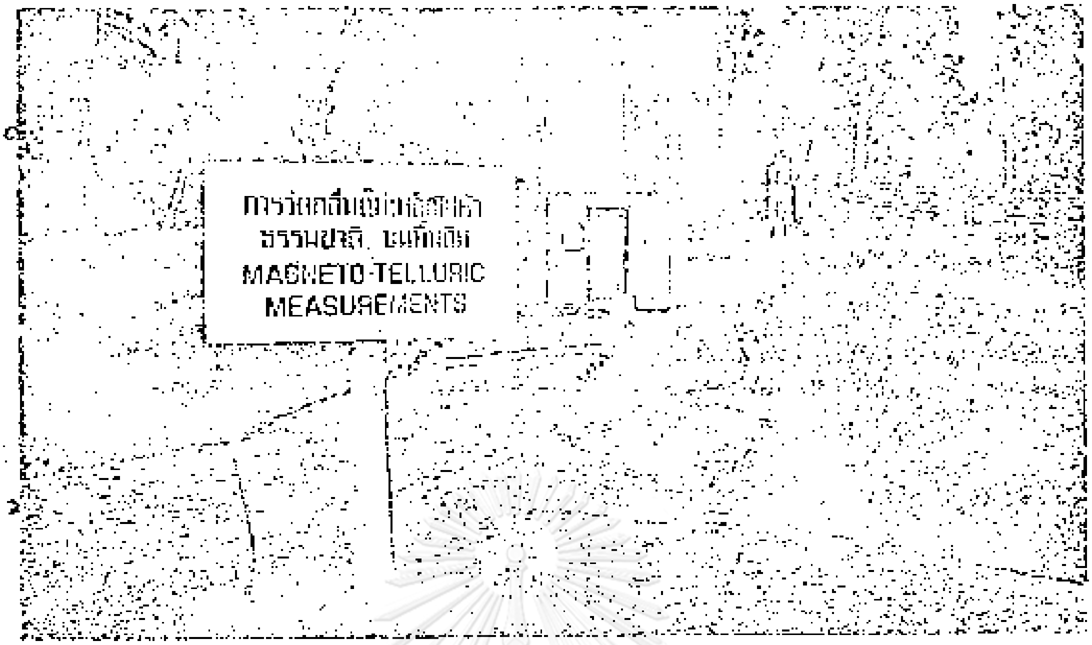
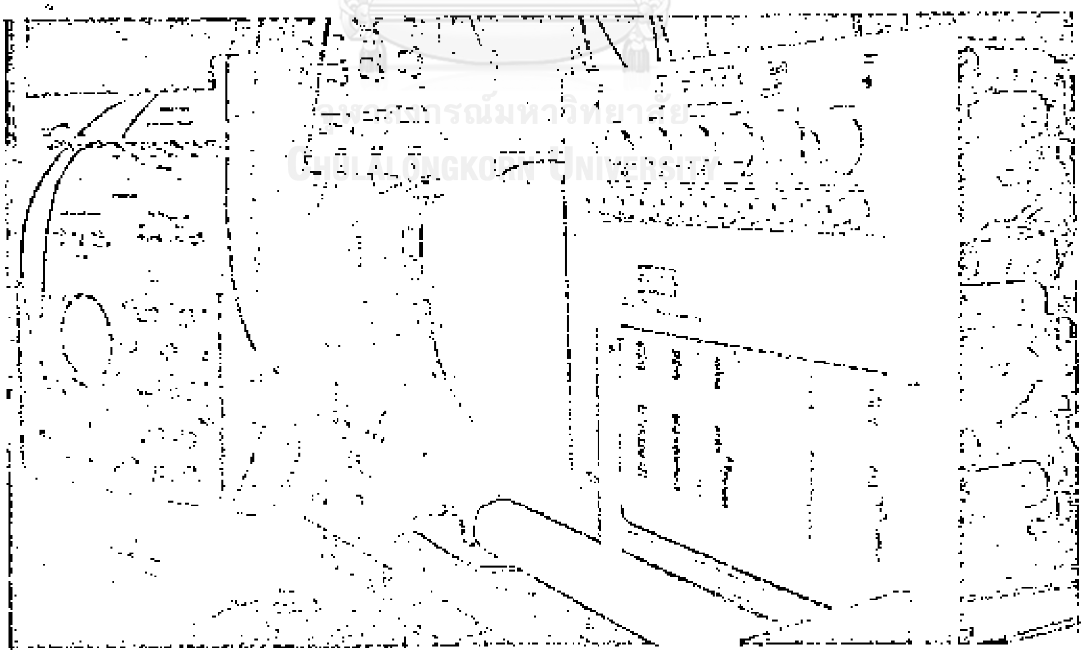


FIG. 20 OVERALL RESPONSE OF ELECTRIC FIELD MEASURING SYSTEM



Van and Surroundings



Interior with Instrumentation

FIG. 21 INSTRUMENT VAN AT TREND SITE

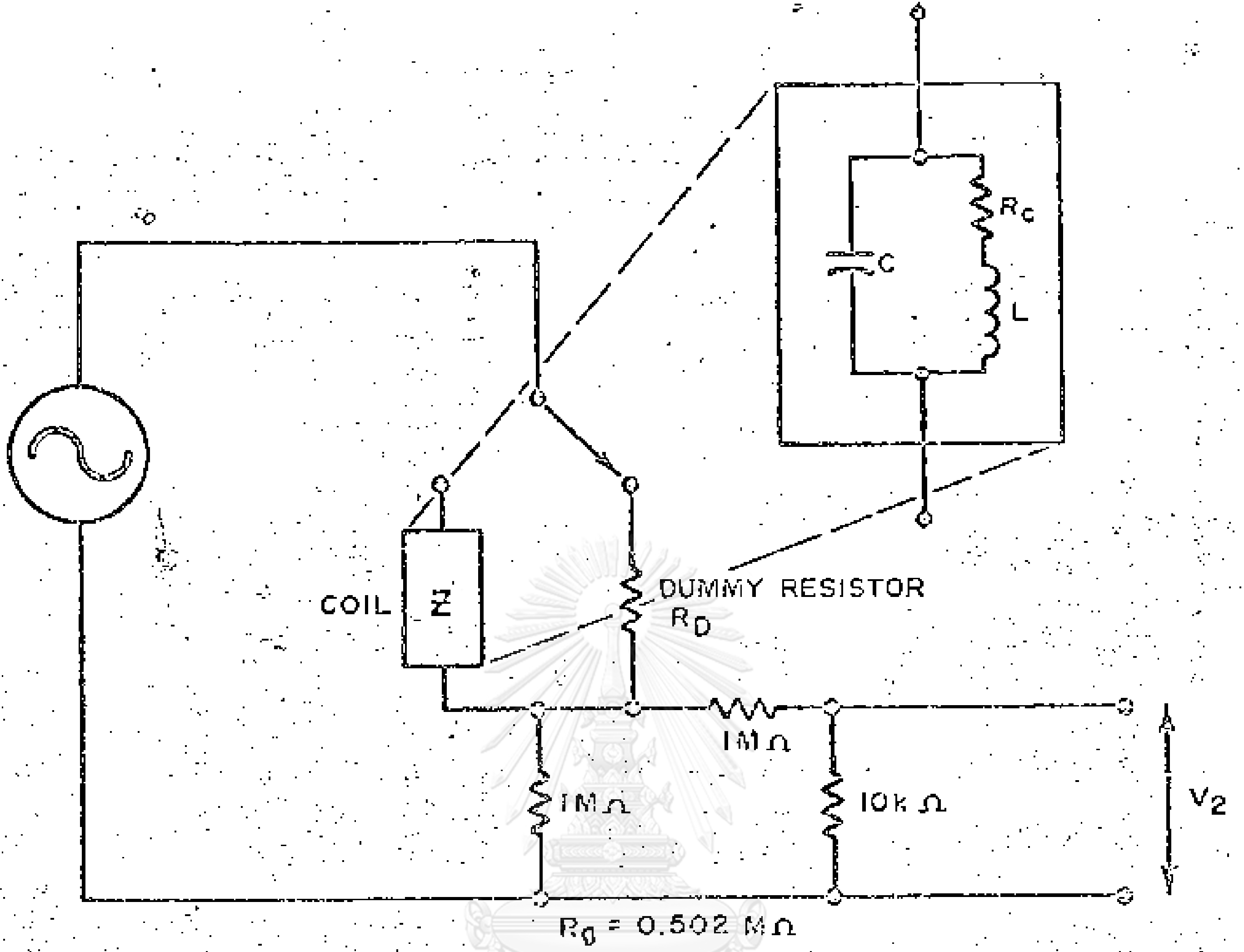


FIG. 22. COIL CALIBRATION CIRCUIT AFTER CAMPBELL (1959)

✓

VITA

Name	Ampai Phongsatha
Birthplace	Potharam, Rajburi
Degrees	B.Sc. (Hons.) in Physics, April, 1968 Chulalongkorn University Bangkok, Thailand
Graduate Scholaship	Applied Scientific Research Cooperation of Thailand Bangkok, Thailand 1968-1970.