1955

Mechanical vibration of vacuum tubes

Jerry Dale Swearingen

MECHANICAL VIBRATION

OF

VACUUM TUBES

BY

JERRY DALE SWEARINGEN

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THESIS

submitted to the faculty of the

SCHOOL OF MINES AND METALLURGY OF THE UNIVERSITY OF MISSOURI

in partial fulfillment of the work required for the

Degree of

MASTER OF SCIENCE, ELECTRICAL ENGINEERING

Rolla, Missouri

1955

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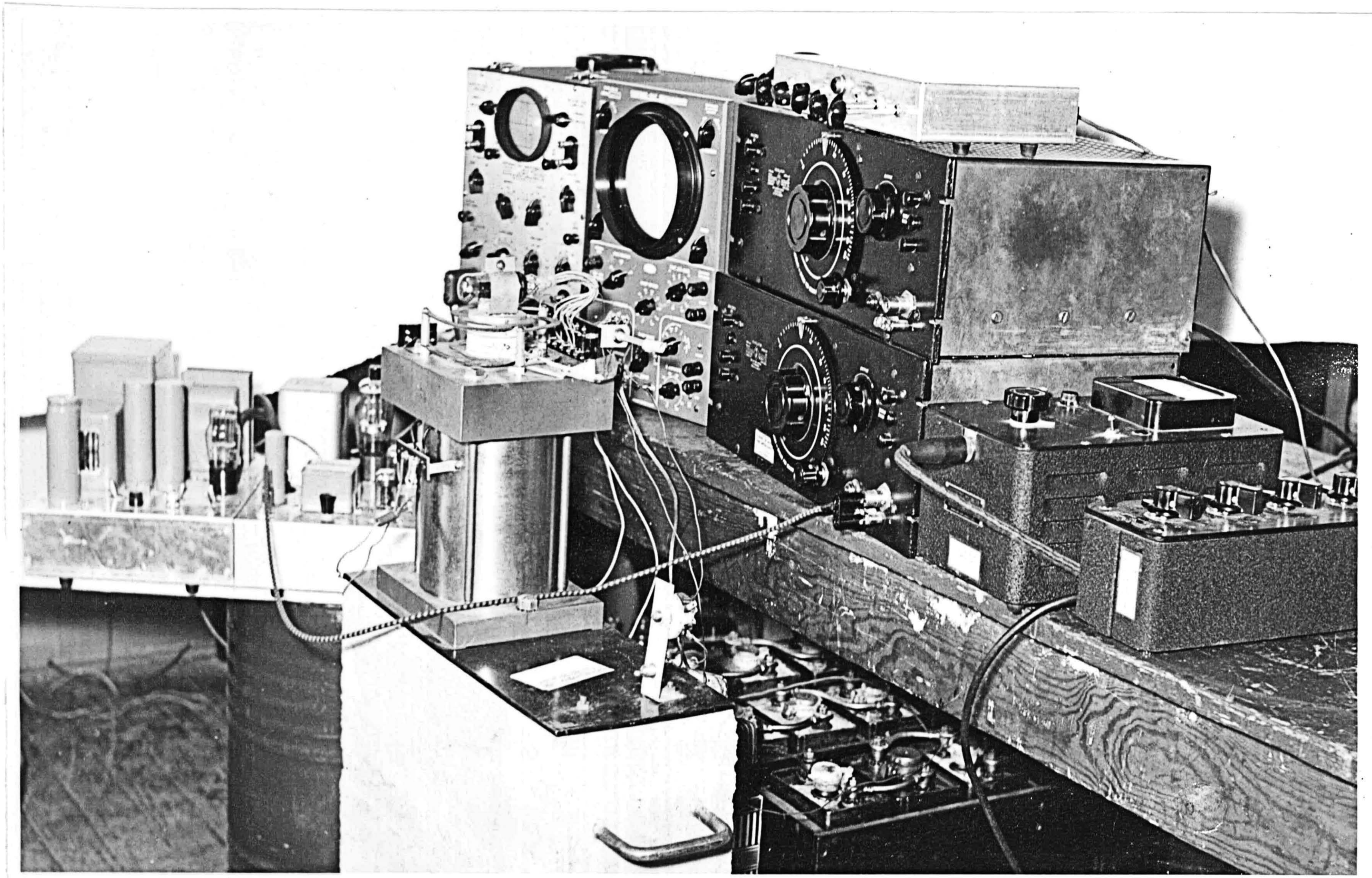
Approved by Gabriel G. Skitek

Associate Professor of Electrical Engineering



Photograph of vibration platform showing tube in test position and all of associated apparatus for vibration testing of vacuum tubes.

ACKNOWLEDGEMENT

The author wishes to express his appreciation to Professor I. H. Lovett, Chairman of the Electrical Engineering Department, whose efforts made this work possible, and also to Professor G. G. Skitek who directed the entire study and contributed many helpful suggestions throughout the course of the investigation and preparation of the manuscript.

Appreciation is also expressed to Mr. Bob Stebbins who did the machine work and construction of the experimental apparatus.

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INTRODUCTION:

Since the beginning of the art of vacuum tube building, vacuum tube engineers have been faced with many mechanical problems as well as electrical problems.

Early mechanical problems were comparatively small because most of the tubes were used in stationary apparatus where little or no vibration was envolved.

As time went on, vacuum tubes were placed in portable equipment and this useage established the need for a tube that was mechanically strong enough to give reliable electrical behavior where the tube was subjected to considerable vibration.

Until World War II the vacuum tube was considered a fragile component, and care was exercised to prevent it's being damaged by excessive shock and mistreatment. During the war a large number of vacuum tubes were placed in field equipment and aircraft and it became necessary for the tube to be able to withstand severe impact and vibration conditions and still remain operative after such abuse.

Many tube manufacturers entered into military contracts to redesign numerous commercial tube types into a "ruggedized" tube which would meet these military requirements. Out of this work came such constructions as RCA's famous "A" frame which, when used in their 6AC7W, was able to support the tube elements from damage when the entire assembly was impact tested at 900 g. acceleration. The specifications for tests such as these being set up by a Joint-Army-Navy specification laboratory. In all cases a tube that would remain operative "after" such tests was considered acceptable and little concern was paid to the tube and it's characteristics "during" the time that such testing was in process.

Recently it has been shown that vacuum tubes operating in the instrument cabins of jet-powered aircraft have shown malfunction in flight because of the very high levels of sound vibration which the tube is subjected to.[1]

Since this vibration condition caused by jet turbines and other moving apparatus of aircraft causes problems in tube failure and circuit misbehavior, the author became interested in the measurement of unwanted internally generated voltages in these vacuum tubes that were caused by the vibration of the tube elements when the tube operates under mechanical vibration.

To be able to utilize the findings of such an investigation it was felt desirable to establish a term in the equivalent circuit of the vacuum tube which would represent the internally generated voltages when the tube is operated under a given range of mechanical vibration frequencies. When this equivalent circuit is established for a given tube type, allowances for these voltages can be made in designing the circuitry that goes with the tube. Also it is of particular interest to observe the effect on the normal output voltages that this new term has and establish a means of finding out the components of the output voltage which can be attributed to the mechanical vibration.

Knowing these things, circuit designers who are designing circuits for airborne and other equipment that is known to operate under vibration will be able to calculate more workable designs with fewer malfunctions.

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(1) Editorial, Electronics at Work, Electronics V.28, No. 2, p. 185 (1955)

REVIEW OF LITERATURE:

The generation of internal voltages by vacuum tubes under mechanical vibration, sometimes called "microphonism", is a subject which has been treated by only a few authors in the form of publications and published articles.

Doutbtless there has been much more work done in this field than the literature indicates because recent years have given great advancements in airborne electronics and electronic-controlled missiles which would be inoperative without the utilization of reliable vacuum tubes. Reliable in this sense includes both phases of circuit failures caused by destruction of the tube under adverse conditions and also malfunction of it's associated circuitry because of the generation of unwanted voltages among the tube elements during vibration.

Work here is primarily concerned with the latter phase, and in regard to the pertinent literature, the sources of information become even smaller.

Several companies are known to have received government contracts in recent years to study this type of problem, but many of these have been with the stipulation that the information obtained was to be used by the particular company envolved and it's production of a product to be supplied to the government. This of course means that the findings become "company confidential" and receive little outside distribution.

The literature does offer the works of a few people in work which is closely associated with the general problem. Particularly the work of people who are striving to eliminate the generated voltage source rather than include the voltage into the equivalent circuits. In most cases the problem is approached from the life-test standpoint and determination is made as to the time a tube will operate under adverse conditions before failing.[2] In reference (2) the writer maintains that an impact contains all of the frequency spectrum and thus considers several designs of impact machines and methods of controlling the duration of impact and the effect of a small number of large impacts compared to a large number of smaller ones. Also the article deals with the design and construction of an accelerometer which, when substituted into the impact machine in the stead of the vacuum tube, will indicate the amplitude and duration of the accelerations the impact machine can supply. These accelerometers are constructed of quartz and ferroelectric crystals which will themselves generate a voltage wave form that can be observed and analyzed.

The fact is also pointed out in the article that present factory tests are over too small a frequency spectrum to be of significant importance in extremely critical applications.

Excitation of random microphony in tubes is treated by Eaglesfield[3] but only from the standpoint of studying the decay rate of generated pulses of voltage that are generated on the impact tests of tubes. No consideration is made of the effects these pulses will have on the external circuits.

Alpert[4] constructed a tester for vacuum tubes by actually attaching the tube under consideration to the cone of a loudspeaker. To

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(2) Stubner, F. W. Acceleration Effects on Electron Tubes Bell System Tech. Jour. V. 32, No. 5, pp 1203 - 29 (1953)

(3) Eaglesfield, C. C. Vibration Tests for Valves, Wireless Engineer, V. 30, No. 3, pp 57 - 60 (1953)

(4) Alpert, N. Microphonics Tester for Vacuum Tubes Electronics, V. 23, No. 3, pp 78 - 9 (1950)

indicate amplitude of displacement, he used an optical lever but admits that it's use above 200 cps was very questionable, so his investigation was made at frequencies below this. This very low limit of frequency spectrum of operation makes the findings too limited for modern-day applications where appreciable amplitudes of vibration are found as high as 6400 cps in some jet-powered aircraft.(5)

To find the amount of generated voltage in a tube, Alpert notes an oscilloscope amplitude of deflection caused by the tube output as the tube is vibrated at a known frequency with zero a-c applied to the grid. He then stops the vibration and applies an a-c voltage to the grid of the same frequency and adjusts it's magnitude until an equal amount of deflection is observed on the scope which is monitoring the tube output. By measuring the input voltage to the grid circuit with a V.T.V.M. the value of the generated voltage is determined by comparison.

Rothstein(6) has received a patent on a vacuum tube which has a grid that can be mechanically moved closer and farther away from the cathode by a mechanical linkage that passes through a vacuum seal to the outside of the tube. By variations of the grid spacing, of course the tube's characteristics change and thus a tube with variable characteristics is provided. This has the advantage of allowing all the tube voltages to be supplied at some constant value.

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(5) Mintz, F. and Levine, M. B. Testing of Airborne Electronic Components Electronics, V. 28, No. 3, pp 181 - 184 (1955)

(6) Rothstein, J. Microphonic Electron Tube U. S. Pat. 2,389,935 Nov. 27, 1945

Since the patent had not been reduced to practice at the time, an effort was made by Waynick[7] to determine the feasibility of doing so. To analyze the resulting variations in plate current, Rothstein proposed the use of a parameter called "motional transconductance". Certain values of this parameter were shown theoretically to provide a location of the grid where little or no microphonism would exist. On this assumption an experiment was set up to attempt to locate these optimum spacings for the grid in given tube types. To obtain vibration, the tube was placed on a table top and a three-inch loudspeaker was inverted over the tube with the cone in physical contact with the tube envelope. The entire assembly of apparatus was held together with gummed paper tape stuck to the table top. The experimenter presumed he was holding the amplitude of vibration constant over the frequency spectrum used because the input to the speaker was held constant at 1 volt. The results of this work are published in tabular form and the complete inconsistancy of result might be traced to acoustic loading and the resonance of the table top and also the non-linear displacement of the speaker cone with one volt input over the frequency spectrum which was apparently not taken into consideration.

One important observation in this work is that the experimenter observed a variation in output magnitude of internally generated voltage with varying values of grid bias, but no shift in frequency with the same grid voltage variations.

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(7) Waynick, A. H. Reduction of Microphonics in Triodes
Jour. of Appl. Phys. V. 8, No. 2, pp 239 - 45 (1947)

Later with an associate Wenzel[8], Waynick constructed a dual triode and observed the mutual effect of the two plate currents as the tube was operated under vibratory conditions. By this method, an analysis was possible whereby the mathmatical expression for the net current from the two plates could be shown to have components which resulted from the sum and difference of the two sections resonant frequencies. This method provides the possibility of being adapted to the analysis of the waveform of the current from a tube that is driven electrically at one frequency and generating an internal voltage as a result of some other frequency of mechanical vibration.

The most recent information available from the literature was published during the period of time that the author's experimental work was being conducted and has to do with the study of vacuum tubes operating under very high levels of sound pressures such as those associated with jet-powered aircraft. Sound levels as high as 140 db. at frequencies between 50 and 6400 cps were recorded in instrument bays of an Air Force jet plane, and failures were observed in the vacuum tubes when operating in this condition of intense sound. To determine the cause of these failures the experimenters have designed a sound chamber into which tubes may be placed for observation and hope to determine their behavior at various frequencies of sound spectrum.

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(8) Wenzel, J. A. and Waynick, A. H. Microphonism in the Dynamically Operated Planar Triode, I. R. E., V. 38, No. 5, pp 524 - 32 (1950)

(9) Mintz F. and Levine, M. B., Testing of Airborne Electronic Components. Electronics V. 28, No. 3, pp 181 - 84 (1955)

In addition to periodic sound waves, the tubes are being subjected to random noise and also to more nearly simulated actual operating conditions, tape recordings were made from jet engines and used to drive the experimental sound chamber. The final result of this work is as yet not available.

VIBRATOR DESIGN

The first consideration to be made in this work was to provide a mechanical vibration platform which could be varied in frequency and amplitude of vibration.

Commercial machines which could be used for this were not available in the laboratory and it was not economically possible to obtain them for this particular study. This left the only alternative, that is, design and build a vibration platform which could be used.

After consideration of several design possibilities it was decided to approach the problem from the "loudspeaker" point of view and simply replace the moveable loudspeaker cone with a platform to which the tube under consideration could be secured. This would provide the versatility of supplying d-c excitation to the fields and driving the moving coil with a-c voltages of any desired frequency and amplitude. Practical limits are present for both frequency and amplitude of vibration depending on the available sources of variable frequency voltages and the power of the driving amplifier and the response of the platform itself.

To present the design of the magnet and the associated platform for the vibration platform, it is first desirable to view the entire assembly in its finished form as in Fig. 1 and by use of the sectional views of Fig. 2 and Fig. 3 discuss the design of each of the vibrator components individually. Figure 1 shows the tube under test secured into position at the top of the vibrating platform. To insure a good solid base for the machine which would allow allof the tube vibration to be with respect to the frame of the vibrating platform as a reference, the entire

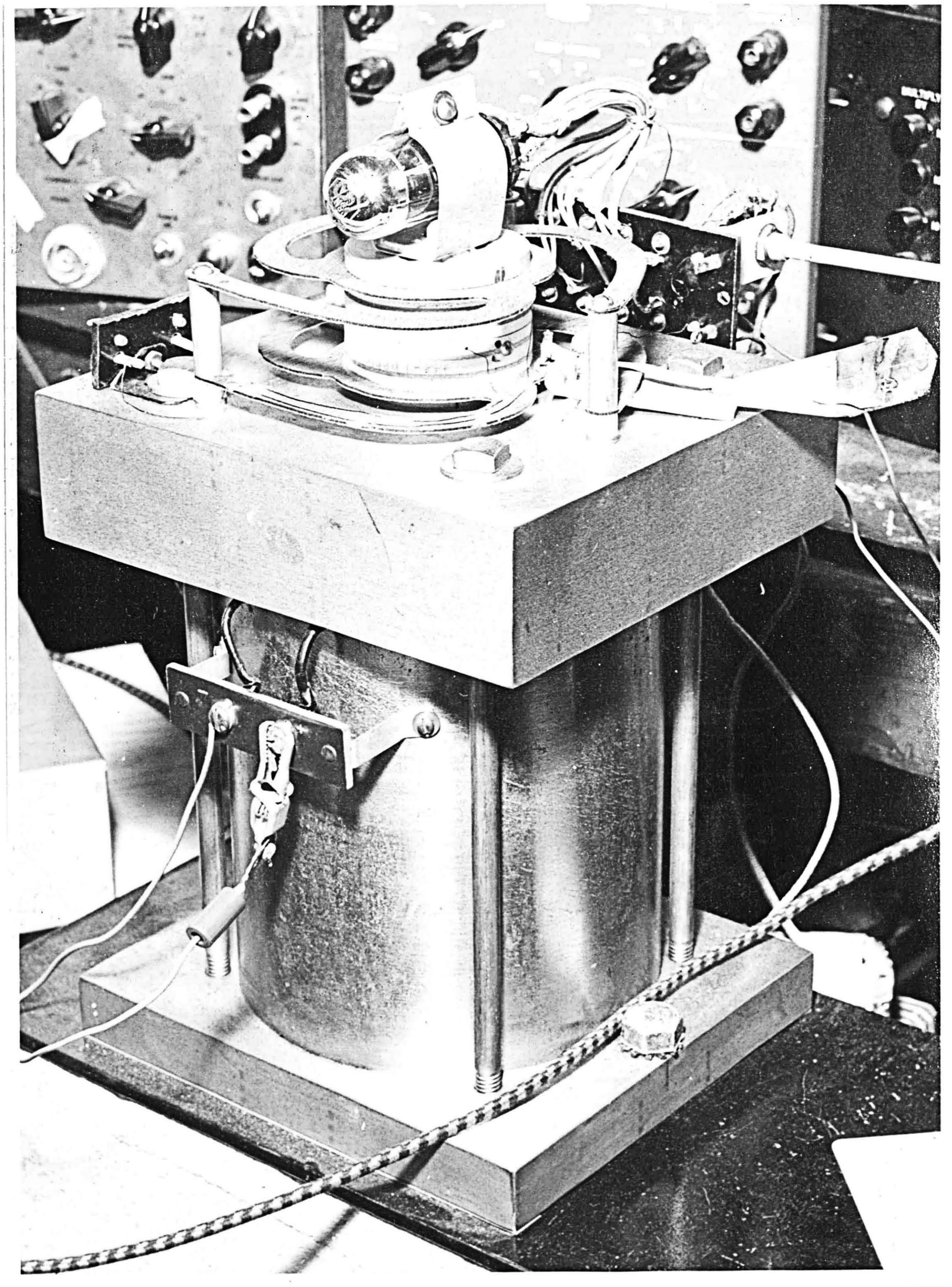

Fig. 1. Complete vibration platform
with 6SN7-GTA tube in test position.

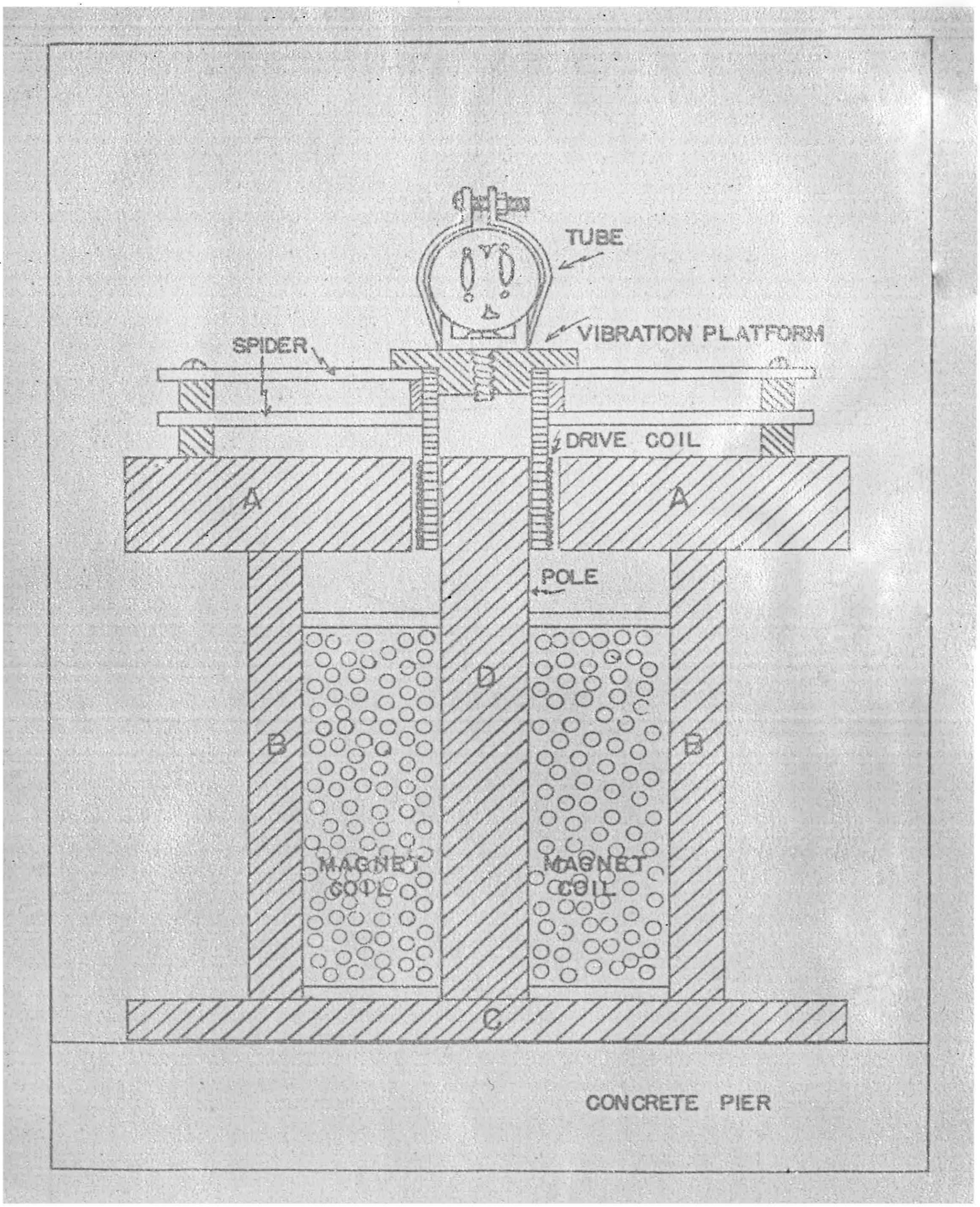

Fig. 2. Sketch of entire vibration platform showing magnet windings and platform suspension.

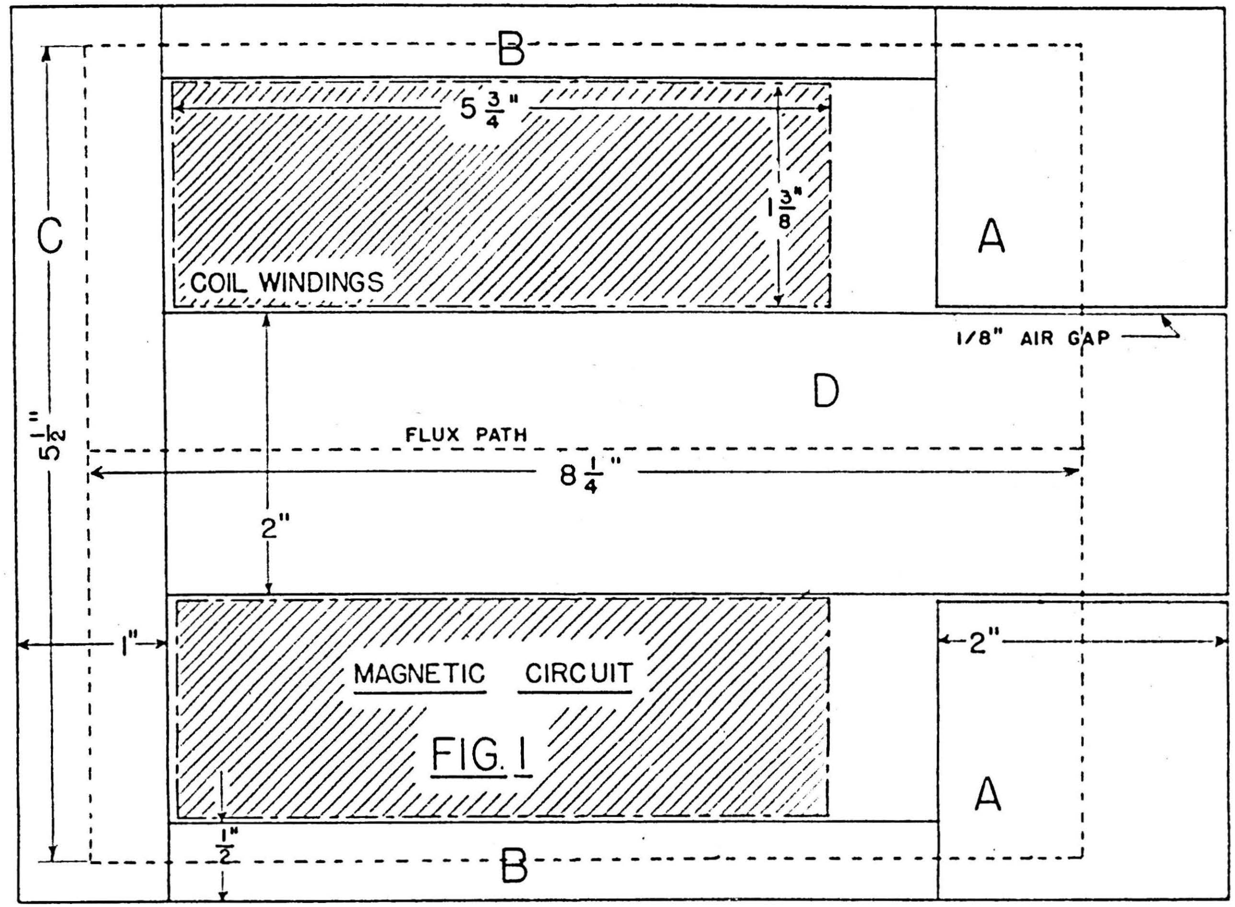

Fig. 3. Sketch showing magnetic circuit of vibration platform magnet.

assembly was securely bolted to a concrete pier which weighed 250 pounds.

In order to provide a starting point on the design of the magnetic field pole system, it was decided to make the diameter of the pole piece D in Fig. 3 equal to 2 inches. It is desirable to have the circumference of the pole large so a large number of flux lines can pass through it without saturating the material from which it is made. Soft steel was chosen because of its availability and also because it has a magnetization curve which shows the knee of saturation to appear at high values of flux density compared to other materials. The magnetization curves for several materials are shown in Fig. 4. Once the pole piece dimension was selected the rest of the members of the magnetic circuit followed and each were selected with a larger cross-sectional area than part D. Considering the cross-sectional area the mechanical rigidity and the dimensions of available soft iron stock, the following areas were chosen referred to Fig. 3.

$A_A = 23.6$ square inches

$A_A = 8.64$ square inches

$A_A = 11.8$ square inches

$A_A = 3.14$ square inches

$A_{(air\ gap)} = 12.6$ square inches

Since a flux density B = 100,000 lines per inch squared is seen to appear at the knee of the magnetization curve of Fig. 4, that value is chosen for the flux density of part D. This corresponds to a flux H = 100 ampere-turns (NI) per inch, from Fig. 4 and thus the total flux ϕ_D = 314,000 lines in part D. This means that 825 ampere-turns would

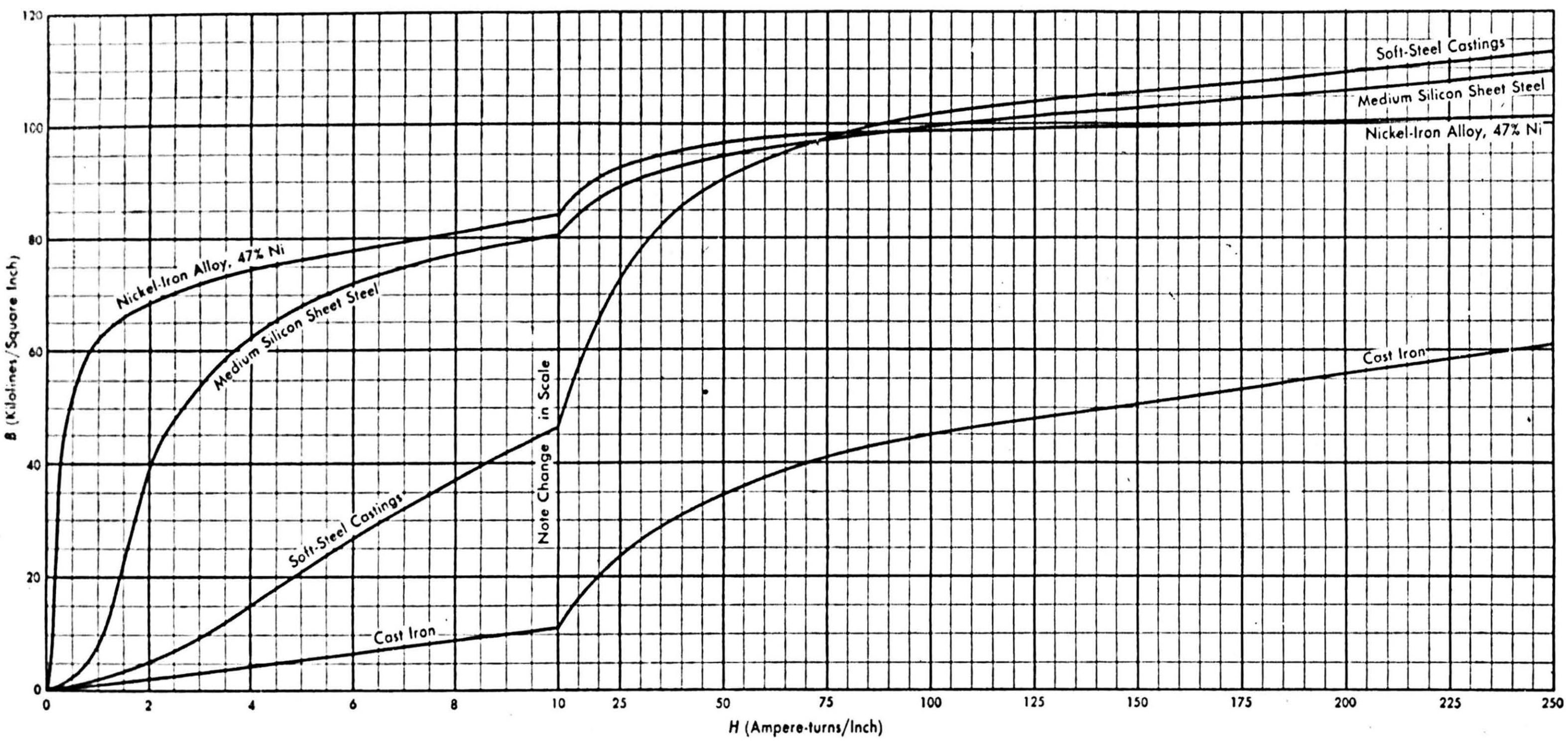

Fig. 11.03. Normal magnetization curves for several magnetic materials with B and H expressed in English units.

Fig. 4. Magnetization curves for several materials including soft steel.

saturate part D as can be seen from Fig. 4. Using this 825 ampere-turns the flux density B_B = 36,400 lines per square inch, this is not saturation for that part and from the saturation curves is seen to correspond to a value of H_B = 63.3 NI. In part A, B_A = 13,300 lines per square inch which is also below the saturation value and therefore the corresponding H_A = 9.61 NI. In part C, B_C = 26,600 lines per square inch which is saturated and the corresponding H_C = 16 NI. In the air gap, $B_{air\ gap}$ = 25,000 lines per square inch and the corresponding value of $H_{air\ gap}$ is 8,333 NI per inch. (Using the approximation that $H_{air\ gap} = B/3$) This provides a total of 1,041 NI in the air gap. If the sum of all the values for H is made, the total number of ampere-turns in the magnetic circuit is 1,955 NI.

Since air gap flux is one of the most significance in this design, a plot of air-gap flux density ($B_{air\ gap}$) versus total ampere-turns (H_{total}) to determine the optimum operating point (p) for the excitation was made. Fig. 5 shows this magnetization curve.

Various values of B are assumed and from them points on this curve are obtained by the following method:

Assume: $B \simeq$ 80,000 lines/square inch

then : H_D= 32 x 8.25 = 264 ampere-turns

and : ϕ = 80,000 x 3.14 = 251,000 lines

therefore: $B_{air\ gap} = \frac{251.000}{4\pi}$ =20,000 lines/sq. in.

and : $H_{air\ gap} = \frac{20,000}{24}$ = 833 ampere turns

The values of $B_{air\ gap}$ and $H_{air\ gap}$ then constitute a point on the curve of Fig. 4. From this curve the value of H = 1250 ampere-turns is chosen as a design point because it can be seen that further increases

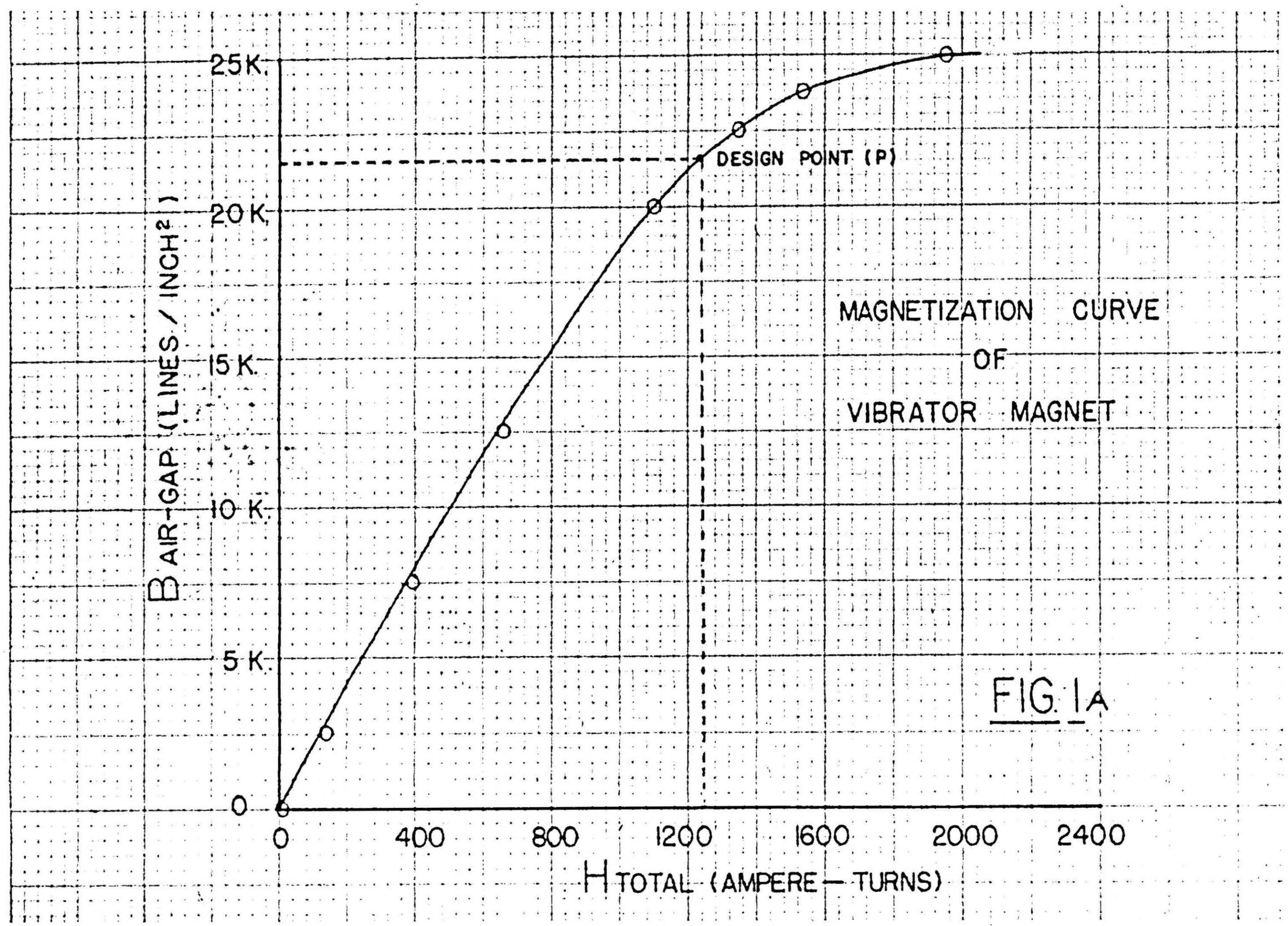

Fig. 5. Magnetization curve of vibration platform magnet showing design point at knee of curve.

in ampere-turns results in only a slight increase in flux density.

From Fig. 3 the available area for winding turns of magnet wire is 7.8 inches square. To have 1250 ampere-turns wound into this space, a total of 160 ampere-turns per square inch must be used. If a current of .5 amperes is assumed to flow in this winding, there will need to be 320 turns per square inch. Consulting the wire tables(10), A.W.G. No. 16 enameled wire will wind 348 turns per inch square (with no allowance for space factor). The mean circumference of the coil is seen to be 10.6 inches and from that, the coil will require 2,170 feet of wire. From the wire tables(11) the d-c resistance of this length of wire is 8.71 ohms. With the assumed .5 amperes of current flowing in this coil, there will be 2.17 watts of energy dissipated as heat due to ohmic loss and thus no special precaution need be provided for cooling.

With the d-c field magnetic circuit complete, the next problem was to design a moving coil of wire which is attached to the vibration platform. Since the moving coil was to be driven by an audio amplifier which has an output impedance of 8 ohms, the coil must be matched impedance-wise to the amplifier to provide maximum power transfer. Obviously this impedance is a function of the frequency of the driving current as well as the mechanical impedance of the coil suspension system. In loudspeaker design the impedance that is considered the characteristic impedance of the speaker is the impedance of the device measured at 400 cps. In this case the coil was designed to match the impedance of 8 ohms at d-c. This seemed the logical approach since the spring

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(10) Langford and Smith, Radiotron Designer's Handbook
N. Y., Radio Corporation of America, 1953, Section 19, pp 1408 - 17

(11) Ibid.

constants of the coil support system was not easily obtainable with the equipment at hand. Since the only effect of this assumption would be to possibly decrease the power which might be delivered to the vibration platform, the assumption is justifiable. It is well to keep in mind that the input impedance of the moving coil will increase with increases in frequency of driving voltage and thus the current will decrease with an increase in frequency.

The diameter of this moving coil is 2 inches and if A.W.G. No. 30 enameled copper wire is used, 77.5 feet of wire will wind a close-wound single-layer coil two inches long and have a d-c resistance of 8 ohms. This matches the 8 ohm tap on the output transformer of the driving power amplifier when d-c operation is assumed.

To visualize the order of magnitude of the force exerted on a tube under vibration, a power of 10 watts will be assumed to be delivered to the moving coil by the power amplifier. Assuming this to be d-c power, the force is calculated as follows:

$$F = B\ L\ I\ N\ \text{Sin}\ \theta$$

where: $B = .302$ webers/meter^2

$L = .160$ meters

$I = 1.11$ amperes

$N = 149$ turns

$\text{Sin}\ \theta = 1$ since $\theta = 90^\circ$

$F = 8$ newtons

or $F = 8 \times .225 = 1.78$ pounds

Here again it should be noted that this current will decrease with increase in frequency as discussed above, but calculation of the decrease becomes unnecessary for the use in this investigation.

Since the amplifier used was capable of 40 watts of output power, the force exceeded this value at high frequencies where the response of the vibration table was very poor.

The physical dimensions of the moving coil suspension system can be be illustrated by the photograph of Fig. 1 which shows the spider-type suspension system made from 1/16 inch formica sheet.

CALIBRATION OF THE VIBRATION PLATFORM

The problem of monitoring the motion of the vibrating platform was solved by placing a piezo-electric phonograph pickup cartridge along the plane of motion of the platform and letting the platform displace the phonograph needle as it vibrated. The output of the cartridge feeding the vertical deflection plates of a cathode ray oscilloscope (c.r.o.) presented a waveform of the platform motion. The amplitude of the waveform, when corrected by the manufacturer's statement of the cartridge response showed the amplitude of the vibration of the platform. Figure 6 shows a close-up view of this monitoring cartridge mounted on the side of the vibration platform.

To calibrate the c.r.o. in inches of platform displacement, a mechanical lever system was used which works as follows: An electrical contact was fastened to the vibration platform and another contact was fastened to a pointer which was pivoted at a point 10 units from one end and one unit from the other end. With the vibration platform at rest, the pointer was displaced until the two contacts just caused continuity in a vertical deflection circuit of a c.r.o. and the long arm of the pointer was used to indicate a point on a reference scale. The point of contact was indicated at the instant the trace of the c.r.o. became a

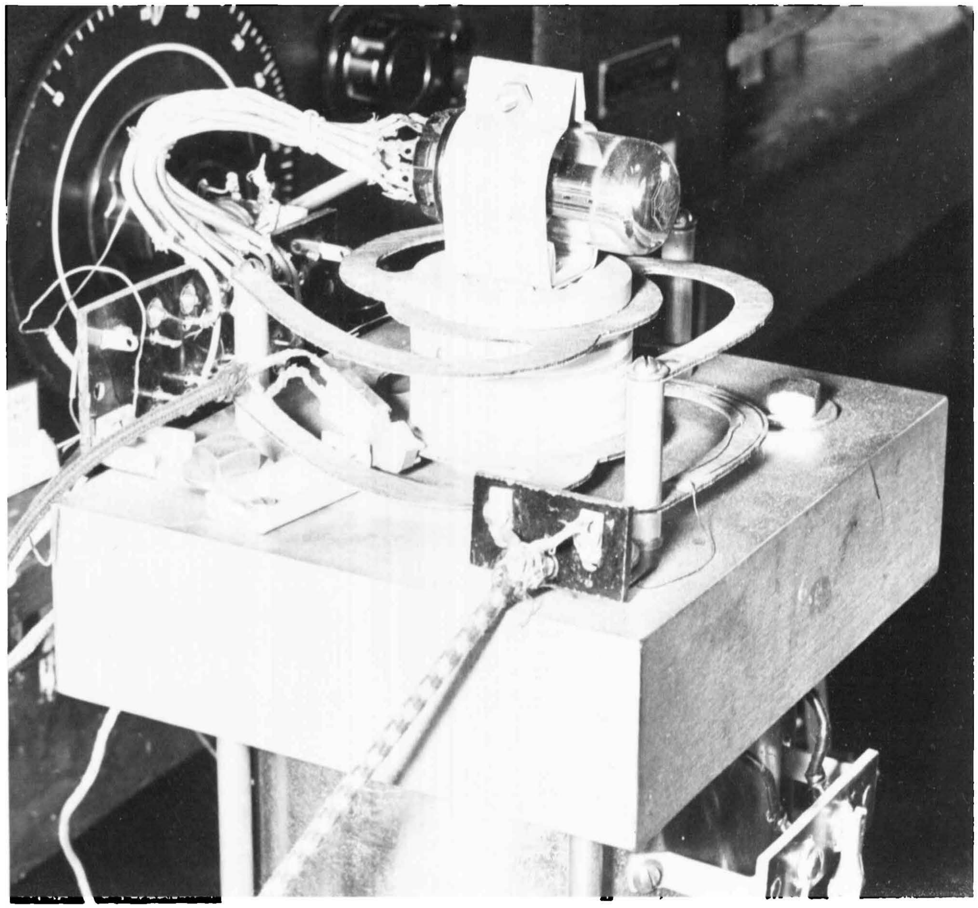

Fig. 6. Vibration platfo n showing amplitude
monitor attached to platform (center left).

straight line. Having observed a reading under this condition, the platform was set in motion and the same procedure repeated. The new point of contact was observed and when it's corresponding reading was taken, the information was sufficient to determine the amplitude of vibration of the platform. The difference between the first and second pointer readings when multiplied by the lever ratio of 1 : 10, gave half of the displacement of the platform since it was being displaced by a sinusodial driving voltage. The measured amplitude now corresponds to an amplitude of the waveform presented on the monitoring c.r.o. This method yielded a deflection of 1 inch on the scope for a vibration amplitude of .0094 inches which was constant over the frequency spectrum available on the vibration platform. This mechanical lever is shown in Fig. 8.

It became of interest to find the frequency response of the vibration platform with a constant input voltage to the moving coil. A voltage of 1.5 v. rms was used as a driving source from a General Radio Audio Oscillator and monitored with a Ballantine Model 304 vacuum-tube volt meter. This voltage was passed into the power amplifier which powered the vibrator and data was observed to obtain the response-curve of the amplifier and the vibrator combined. This curve is shown in Fig. 7 and since the power amplifier used was a linear amplifier the curve becomes the response of the vibration platform only. The amplifier used was a 40 watt Williamson modification using two 807 output tubes operating ultra-linear. The author built this amplifier for another purpose and it's design will not be discussed here. The power response of the amplifier shows a curve that is down only .2 db. from 20 to 100,000 cps with less than .01% intermodulation distortion and less than .001% harmonic content as observed by use of a General Radio Wave Analyzer.

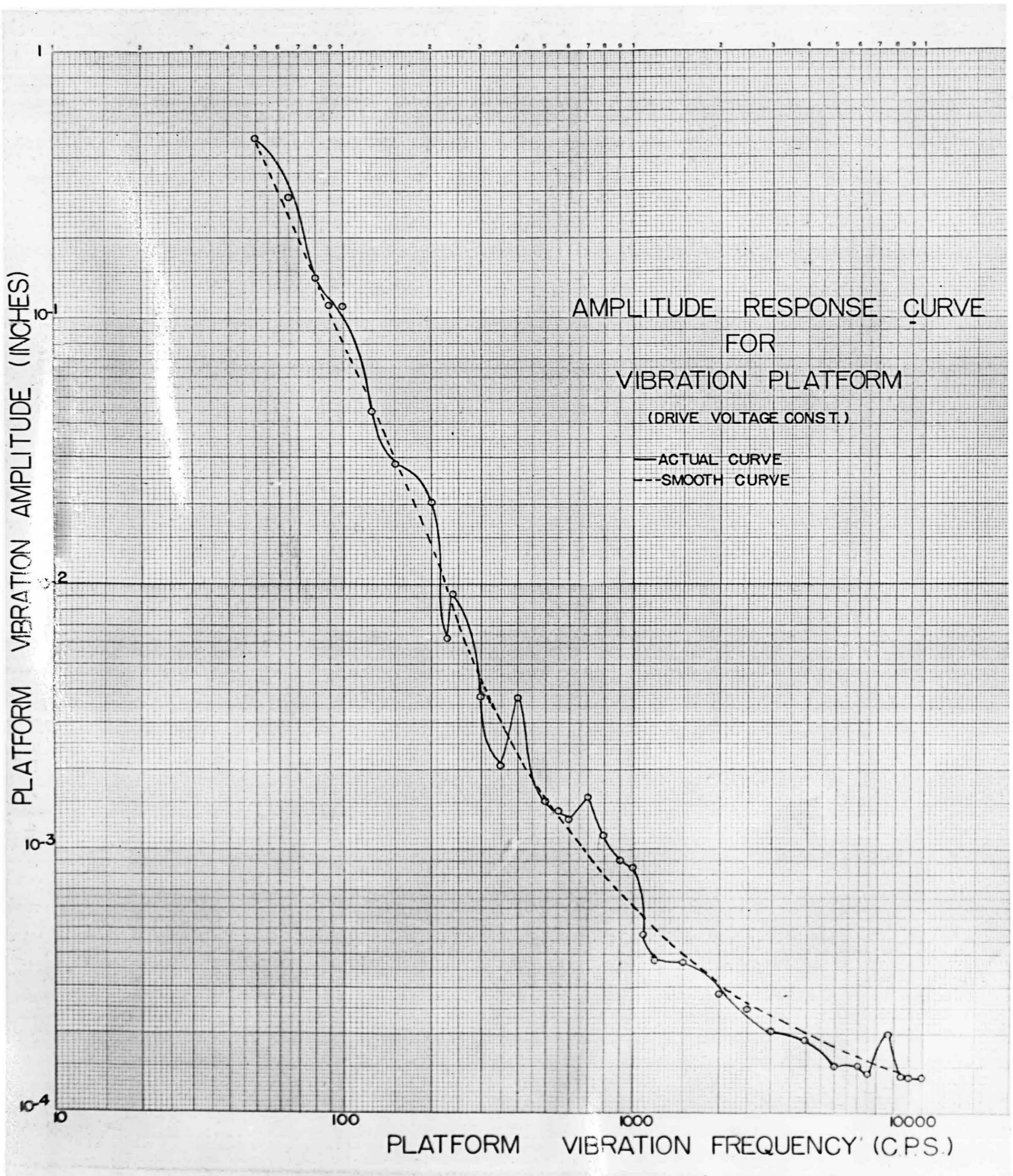

Fig. 7. Amplitude versus frequency response curve for the vibration platform being driven with a constant voltage.

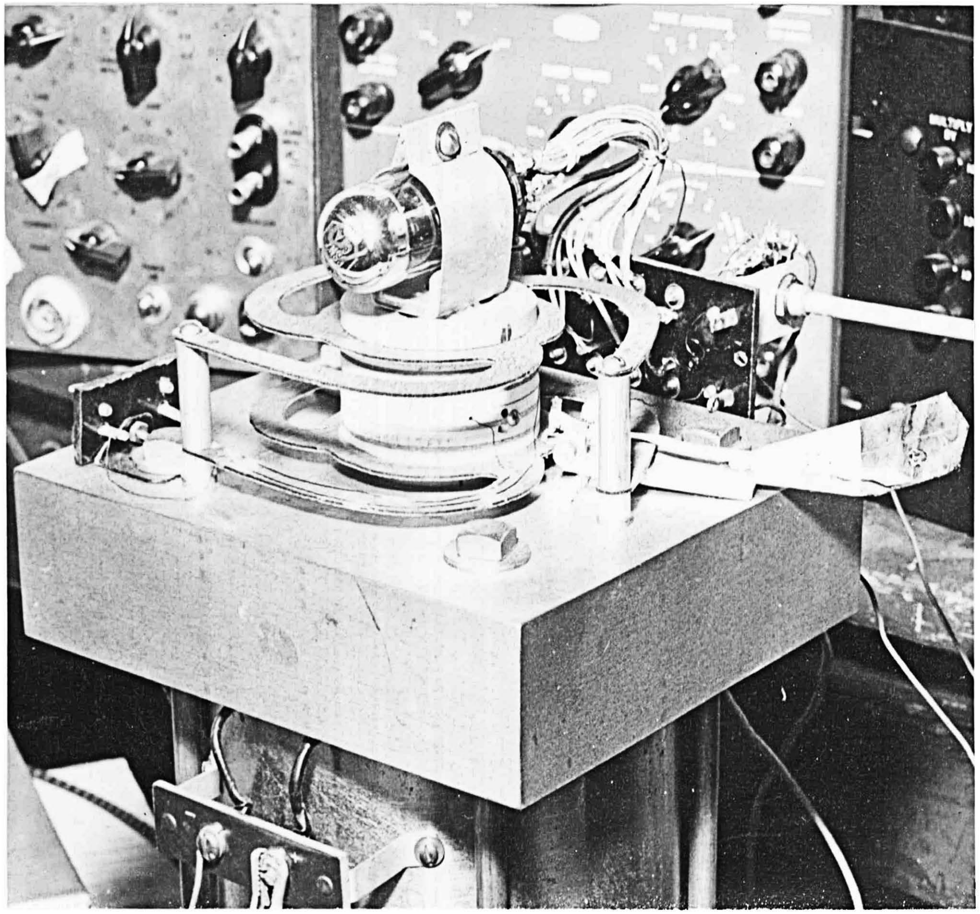

Fig. 8. Photograph of vibration platform showing mechanical lever arm (center right) for amplitude of vibration calibration.

These ratings were observed at a power output of 40 watts which were being dissipated into an Audio-Frequency load.

When the d-c field circuit of the vibration machine was powered by a 6.0 volt d-c Edison cell, it drew .6 amperes of current.

THEORY OF INTERNALLY GENERATED VOLTAGE DETECTION

Every known mechanical structure has some resonant frequency at which the structure will mechanically vibrate with resonance. Since the elements which go to make up a vacuum tube are a mechanical structure, they too have frequencies of mechanical resonance and when this frequency is found there will be physical motion of the elements and thus physical displacement. This physical displacement will vary the spacing between the elements and thus vary the capacitance observed between the two elements. When a d-c voltage is placed across these elements that are changing in capacitance, a charging current will flow in the circuit and it's waveform will be dictated by the motion of moving elements. When this current is caused to flow through a linear resistor the voltage drop across it then possesses the same waveform. This voltage can then be impressed on the vertical axis of a c.r.o. and when swept with a saw-tooth sweep voltage, will present the waveform of the induced charging current generated by the vacuum tube under vibration.

The fundamentals of the method used here to detect the generation of internally generated voltages is not new, but to the author's knowledge, it has never been applied to the detection of internally generated voltages in vacuum tubes.

The principle is simple and was first used by Lord Kelvin in his famous electrometer[12]. If the plates of a parallel-plate capacitor are separated by an amount s and have a d-c potential of V across them, the capacitance of the system is: $C = \frac{\epsilon_o KA}{s}$ where K is the dielectric constant of the medium between the plates, ϵ_o is 8.85×10^{-12} (mks units), A is the effective area of the plates and s is their separation. The charge Q is then equal to C V. Since the current that flows in the capacitor is by definition dQ/dt, where t is time, the expression for current becomes: $I = dQ/dt = V(dC/dt)$. If the capacitance of the plates should be changing at a uniform rate with respect to time, the current that flows is directly proportional to the voltage V since the dC/dt term is constant.

Since $C = \frac{\epsilon_o KA}{s}$ for the static case, dC/ds becomes equal to

$$dC/ds = \epsilon_o KA \left(\frac{-1}{s^2}\right)$$

$$\frac{dC}{ds} = \lim_{\Delta s \to o} \frac{\Delta C}{\Delta s}$$

$$\therefore \Delta C = \epsilon_o KA \left(\frac{-1}{s^2}\right) \Delta s$$

$$C_{inst.} = C + \Delta C$$

$$\therefore C_{inst.} = \frac{\epsilon_o KA}{s} - \frac{\Delta s \text{ Sin } \omega t}{s^2} (\epsilon_o KA)$$

now since $i_{inst.} = V\left(\frac{dc}{dt}\right)$

$$i_{inst.} = V\left(- \frac{\epsilon_o KA \, \Delta s \, \omega \cos \omega t}{s^2}\right)$$

Where Δs is a change in spacing between plates much smaller than s where $s = (s_o + \Delta s \sin \omega t)$. This is an expression for the

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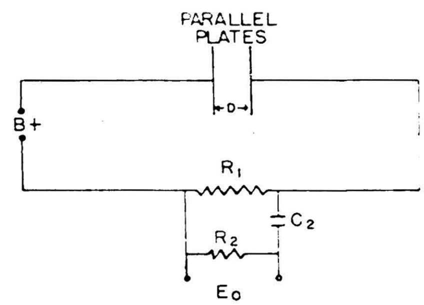
(12) Boast, W. B., Principles of Electric and Magnetic Fields N. Y. Harper and Brothers, 1948, pp 109 - 113

current that flows in the circuit of Fig. 9 shown below. C_2 and R_2 represent a coupling network to isolate d-c from E_o.



KELVIN ELECTROMETER CIRCUIT

(PARALELL PLATES HAVE VARIABLE SEPARATION D.)

Fig. 9

In cases where an r.m.s. current meter might be used to detect the charging current that flows in the circuit, the current becomes:

$$I_{rms.} = \left(\text{average value of} \left(i_{inst.}\right)^2\right)^{\frac{1}{2}}$$

$$= \frac{\omega}{2\pi} \int_{t=o}^{t=\frac{2\pi}{\omega}} \frac{V^2 \epsilon_o{}^2 K^2 A^2 \Delta s^2 \omega^2 \cos^2 \omega t}{s^4} \, dt$$

$$= \frac{\omega}{2\pi} \frac{V^2 \epsilon_o{}^2 K^2 A^2 \Delta s^2 \omega^2}{} \int_o^{\frac{2\pi}{\omega}} (1 - \text{Sin}^2 \omega t) \, dt$$

$$I_{rms.} = \left(\frac{V \epsilon_o KA \Delta S \omega}{s^2}\right)^2$$

This method has also been used by the author while working at The General Electric Research Laboratory on the determination of static potentials of television picture tube screens. (13) (14) The process was applied in reverse however; since the frequency of vibration was known and also the amplitude of vibration and from the measurement of the charging current flowing the d-c static potential was determined.

In the present case, the d-c voltage is known and also the frequency of vibration and with these two parameters, the observation of the charging current can be used to determine a generated voltage. This voltage is observed on the c.r.o. and amplitude, frequency and waveform can be determined.

PRELIMINARY VERIFICATION OF THEORY

To further study this method prior to it's use with vacuum tubes and vibrating tube elements, a pilot model was constructed from a four-inch P.M. loudspeaker to which had been attached a metal disc onto the moving cone. Another disc parallel to the first was placed stationary a short distance away and a d-c potential was applied between them. The speaker was driven with an audio oscillator and the resulting charging current that flowed through a resistor caused a voltage which was observed on the c.r.o. Fig. 10 shows this pilot model. The purpose of this preliminary run was to become familiar with the technique and also to determine the adequacy of the gain of the vertical amplifiers of the c.r.o. The gain was found insufficient in this case and as a result a

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(13) Young, J. R. A Method of Measuring the Screen Potential of Cathode Ray Tubes Memo Report No. EC-18, Electron Physics Research Laboratory, The Knolls, New York (1952)

(14) Young, J. R. A Versatile Electrostatic Voltmeter R. L. Report No. 898, Electron Physics Research Laboratory, The Knolls, New York (1953)

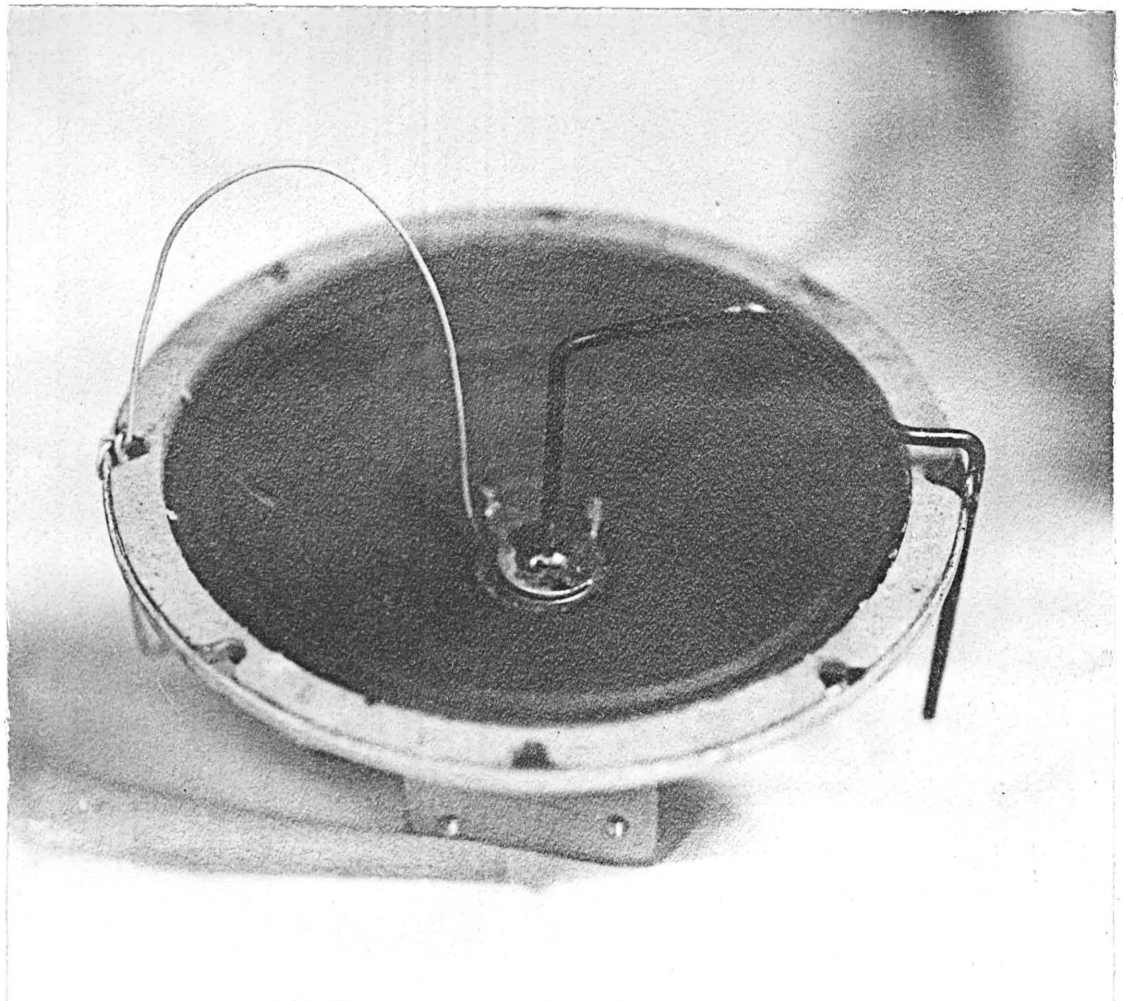

Fig. 10. Photograph of experimental apparatus for verification of Kelvin method showing metal discs.

special preamplifier was incorporated into the circuit to amplify the induced voltage to sufficient amplitude for accurate detection. These high gain stages made electrostatic shielding absolutely necessary to prevent stray a-c pickup in the connecting wires. As a result of this finding a shield was constructed for the supply batteries and other circuitry which was used in tube testing.

The Dumont Model 304-H c.r.o. and preamplifier were calibrated as a unit so the observed trace amplitudes could be converted to rms volts of internally generated voltage observed across a load resistor. A constant voltage of .025 rms volts was supplied to the preamplifier and as the frequency was varied from 30 to 10,000 cps the amplitude of the trace was recorded. From this data a calibration curve was obtained and from it the actual values of internally generated voltage could be determined. This curve appears in Fig. 11.

GENERAL TUBE TYPE SURVEY

To determine the behavior of various types of mechanical structures and vacuum tube constructions, a survey-type run was made on several different tube types. The first tube to be considered in this survey was the 5R4-GY, a dual-diode rectifier tube. The tube was vibrated with its plates in both a vertical and horizontal plane for both sections of the tube. To determine relative values of the generated voltages, it was necessary to hold the amplitude of vibration constant as the frequency was varied from 30 to 10,000 cps. These limits on frequency were chosen because of the amount of amplitude available at the high frequency end of the spectrum and because of the frequency response of the c.r.o. on the low frequency end. The amplitude of vibration was chosen as .008

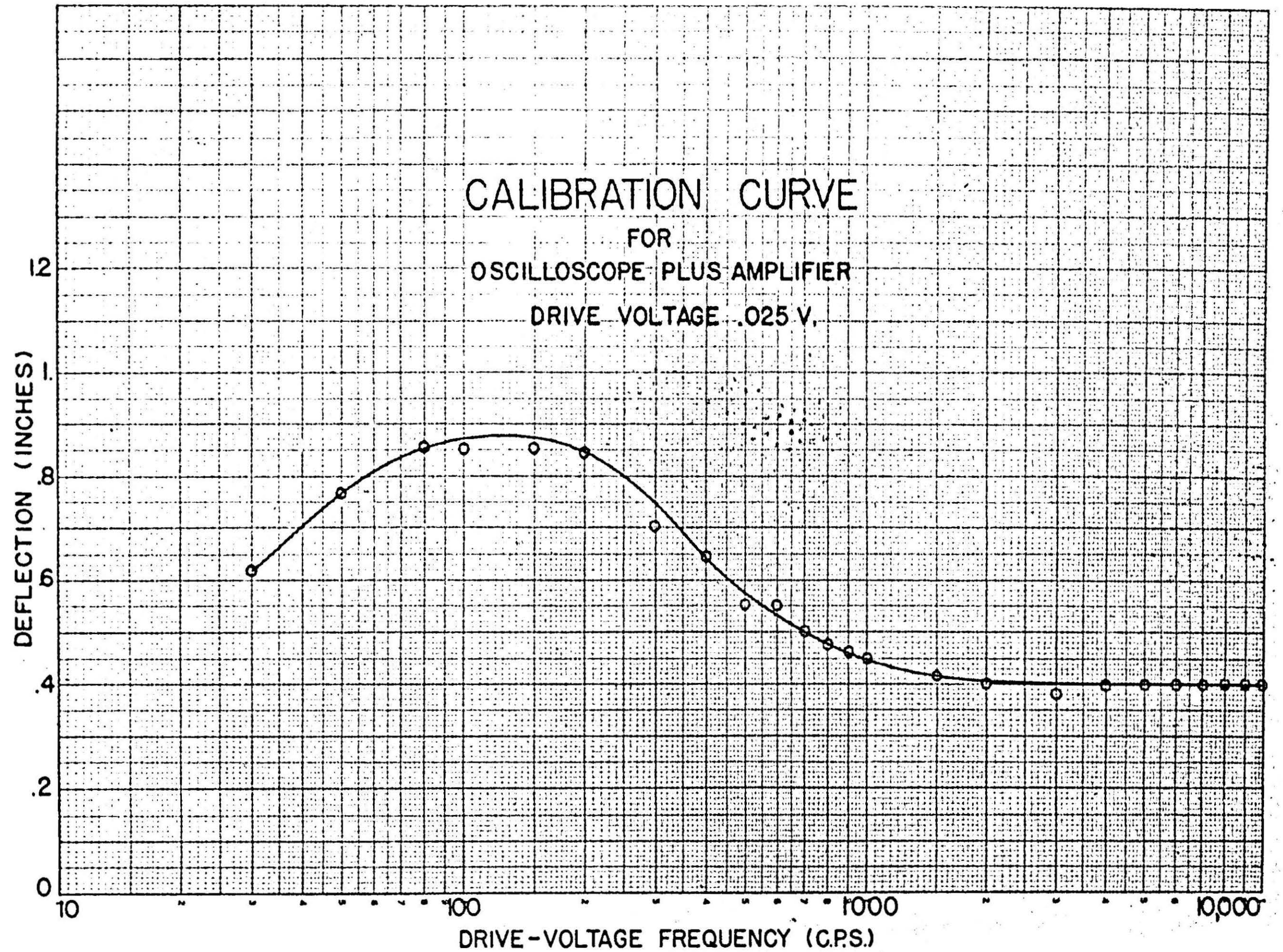

Fig. 11. Calibration curve showing voltage response of cathode ray oscilloscope and preamplifier.

inches peak to peak and was held constant by variation of the gain of the amplifier. This value of amplitude was chosen because it was the maximum value obtainable from the vibration platform when operating at 10,000 cps.

The generated voltage versus frequency characteristics of this and other survey-type runs on various tube types and constructions appear in the following pages. The curves are self explanatory. Figure 12 shows the electrical circuit used for the determination of the resonant frequencies of the grids of the various constructions.

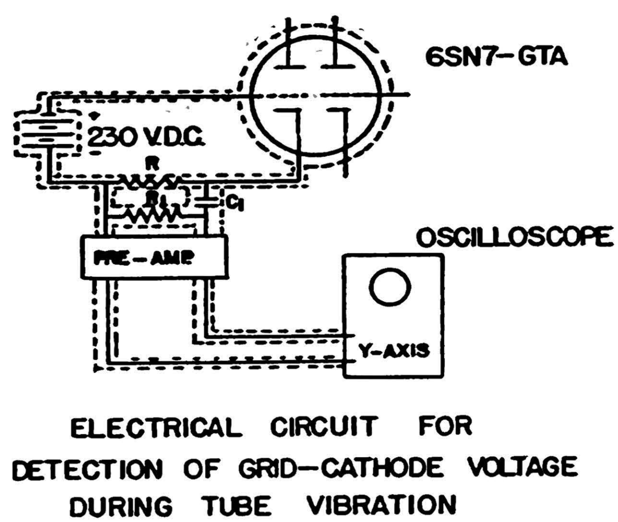

Fig. 12. Grid-Cathode voltage detection circuit.

With the completion of the preliminary survey runs, the 6SN7-GTA was chosen as the tube type to study in detail and an exhaustive set of tests were run to determine the average characteristics of the type and give basis for formulation of the general-behavior theory of tubes under mechanical vibration.

THE 6SN7-GTA DUAL TRIODE

JAN specifications[15] are available which gives the allowable magnitudes of internally generated voltage for vacuum tubes operating under specific conditions of vibration if used in certain pieces of military equipment. Since no specific application is in mind here, no maximum allowable voltage will be established.

The Sylvania version of the 6SN7-GTA is a twin triode which uses two separate constructions for each of the triode sections. The cathode is an indirectly heated, oxide-coated, cylindrical construction, supported at the ends only by insertion through the mica wafers. The grid is elliptic and uses two grid-support rods which are parallel to the cathode. The plate is rectangular and is provided with a very large crimped-seam side support which acts as both a radiating surface for heat dissipation and also provides additional mechanical rigidity. The envelope is glass and the base is conventional octal. The method of support for the entire cage structure is by allowing the top mica to contact the glass envelope and the bottom is spot welded to the button header. The mica at the bottom of the cage does not contact the glass envelope. The tube is shown in test position in Fig. 8.

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(15) Evaluation of Mechanical Design Level of Electronic Equipment Leading to Vibration and Shock Design Criteria. Wright Air Development Center Contract No. AF 33(616) - 223, ARF Project Number K044-1.

Fig. 13 provides the electrical characteristics of the tube as published by the General Electric Company in their "Electronic Tubes" manual.

The 6SN7-GTA was chosen for the detailed study because of its common appearance in many pieces of electronic apparatus and also because the dual triode is a particularly versatile tube and will doubtless receive much useage by designers in the future. The conventional simplicity of this triode construction provides a somewhat less complicated routine for testing and at the same time illustrates theory and method which can easily be expanded to accommodate tubes with a larger number of elements incases where it becomes necessary. The GTA version of the 6SN7 has identical characteristics electrically with the 6SN7 but some attempt has been made to ruggedize its construction to meet the needs of even less strenuous demands of such equipment as mobile two-way communications equipment commonly used by taxicabs and utility service cars. Testing of this type further revealed the limitations of a comparatively new design to the market.

The fly-leaf photograph shows the complete laboratory set-up of apparatus for the 6SN7-GTA study and Fig. 23 presents the same apparatus in block-diagram form.

Two of the tubes were first tested by the circuit of Fig. 12 to determine the resonant frequencies of the structure of the grids and to measure the relative voltages generated between the grid and the cathode. The values of voltage generated were relative because the grid was operated at plus 230 volts d-c above the cathode and allowed to draw zero d-c current. Figures 19 through 22 show the results of this run as the tube was vibrated with the plates in both a horizontal and vertical

GE Electronic TUBE

PAGE 1

6SN7-GTA
Description and Rating
TWIN TRIODE

The 6SN7-GTA is a medium-mu twin triode suitable for use in a wide variety of general-purpose amplifier and phase-inverter applications. It is also especially useful as a blocking oscillator, multivibrator, or vertical deflection amplifier in television receivers. Each section of the tube has a separate cathode connection. Electrically and physically, the 6SN7-GTA is a replacement for the 6SN7-GT.

GENERAL

Cathode - Coated Unipotential
Heater Voltage, A-C or D-C . . . . . . 6.3 Volts
Heater Current . . . . . . 0.6 Ampere
Envelope - T-9, Glass
Base - B8-6, Intermediate Shell Octal 8-Pin
or B8-58, Short Intermediate Shell Octal 8-Pin
Mounting Position - Any

Direct Interelectrode Capacitances *

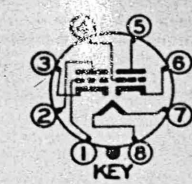
	Section 1	Section 2	
Grid to Plate	4.0	3.8	μμf
Input	2.2	2.6	μμf
Output	0.7	0.7	μμf

MAXIMUM RATINGS

DESIGN-CENTER VALUES UNLESS OTHERWISE INDICATED, EACH SECTION

	Class A_1 Amplifier	Vertical Deflection Service †	
D-C Plate Voltage	450	450	Volts
Peak Positive Pulse Plate Voltage ▽	---	1500	Volts
Peak Negative Grid Voltage	---	250	Volts
Plate Dissipation, Each Plate	5.0	5.0 #	Watts
Total Plate Dissipation, Both Plates	7.5	7.5 #	Watts
D-C Cathode Current	20	20	Milliamperes
Peak Cathode Current	---	70	Milliamperes
Heater-Cathode Voltage			
Heater Positive with Respect to Cathode			
D-C Component	100	100	Volts
Total D-C and Peak	200	200	Volts
Heater Negative with Respect to Cathode			
Total D-C and Peak	200	200	Volts
Grid Circuit Resistance			
With Fixed Bias	1.0	---	Megohm
With Cathode Bias	1.0	2.2	Megohms

BASING DIAGRAM

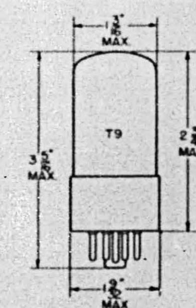


RTMA 8BD
BOTTOM VIEW

TERMINAL CONNECTIONS

Pin 1 - Grid (Section 2)
Pin 2 - Plate (Section 2)
Pin 3 - Cathode (Section 2)
Pin 4 - Grid (Section 1)
Pin 5 - Plate (Section 1)
Pin 6 - Cathode (Section 1)
Pin 7 - Heater
Pin 8 - Heater

PHYSICAL DIMENSIONS



RTMA 9-11 or 9-41

Fig. 13. Published description and ratings of the 6SN7-GTA twin triode.

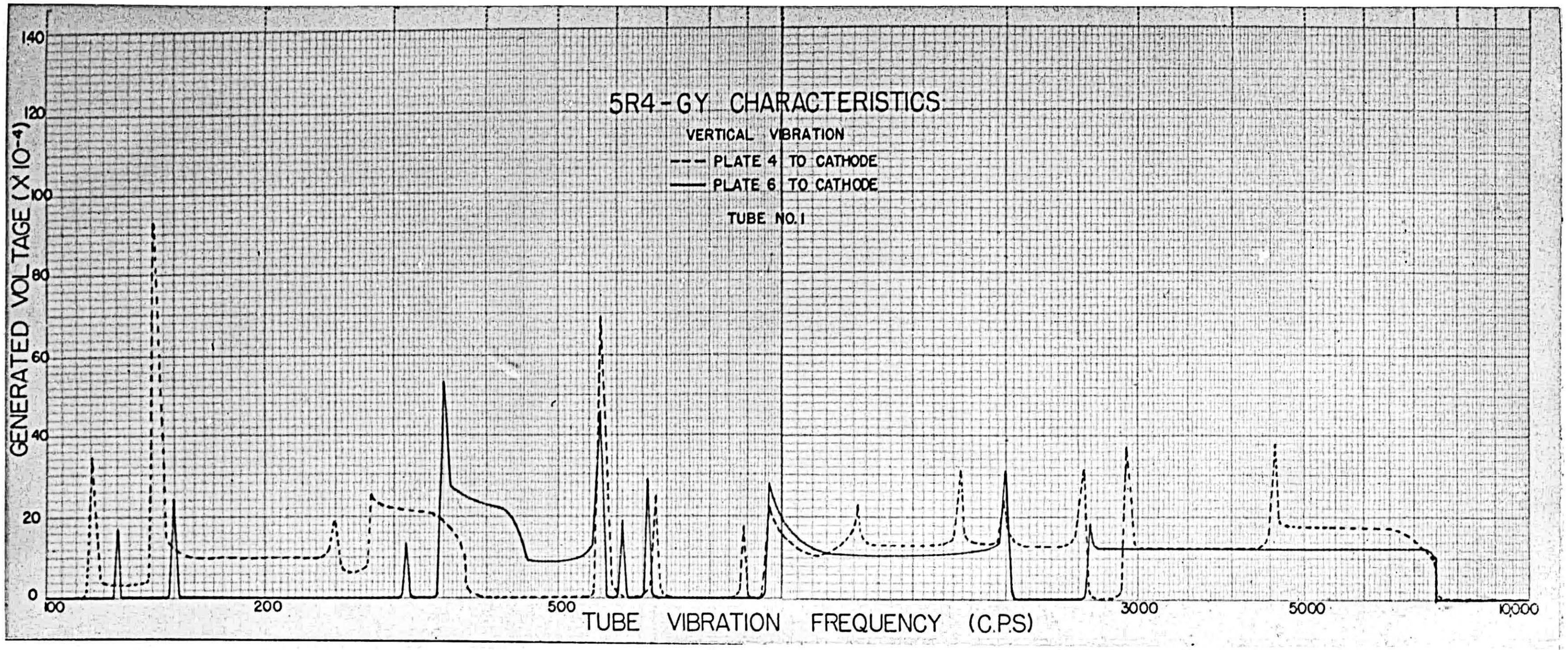


Fig. 14. 5R4-GY Characteristics showing internally generated rms voltages versus frequency. Plate 4 to Cathode and Plate 6 to Cathode voltages are compared for vertical vibration of tube no. 1.

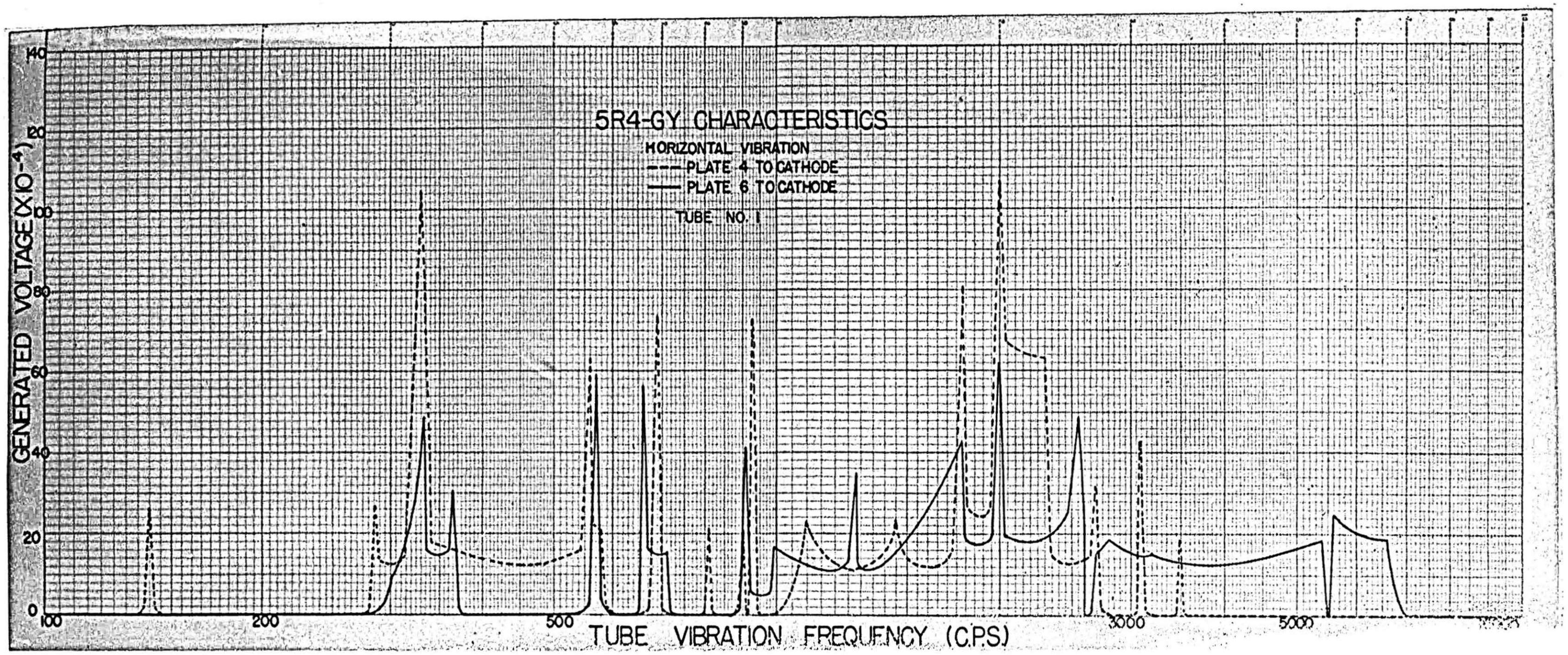


Fig. 14.a. 5R4-GY Characteristics showing internally generated rms voltages versus frequency. Plate 4 to Cathode and Plate 6 to Cathode voltages are compared for horizontal vibration of tube no. 1.

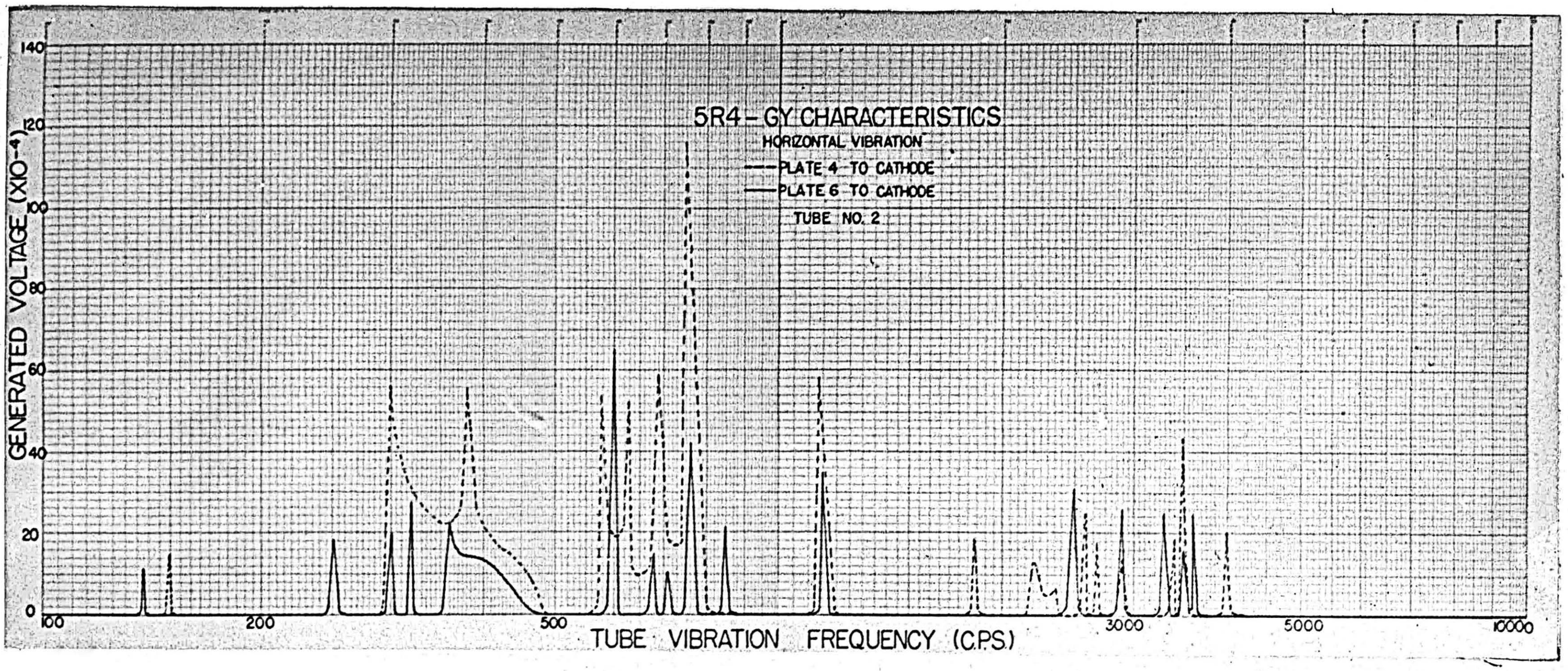


Fig. 15. 5R4-GY Characteristics showing internally generated rms voltages versus frequency. Plate 4 to Cathode and Plate 6 to Cathode voltages are compared for horizontal vibration of tube no. 2.

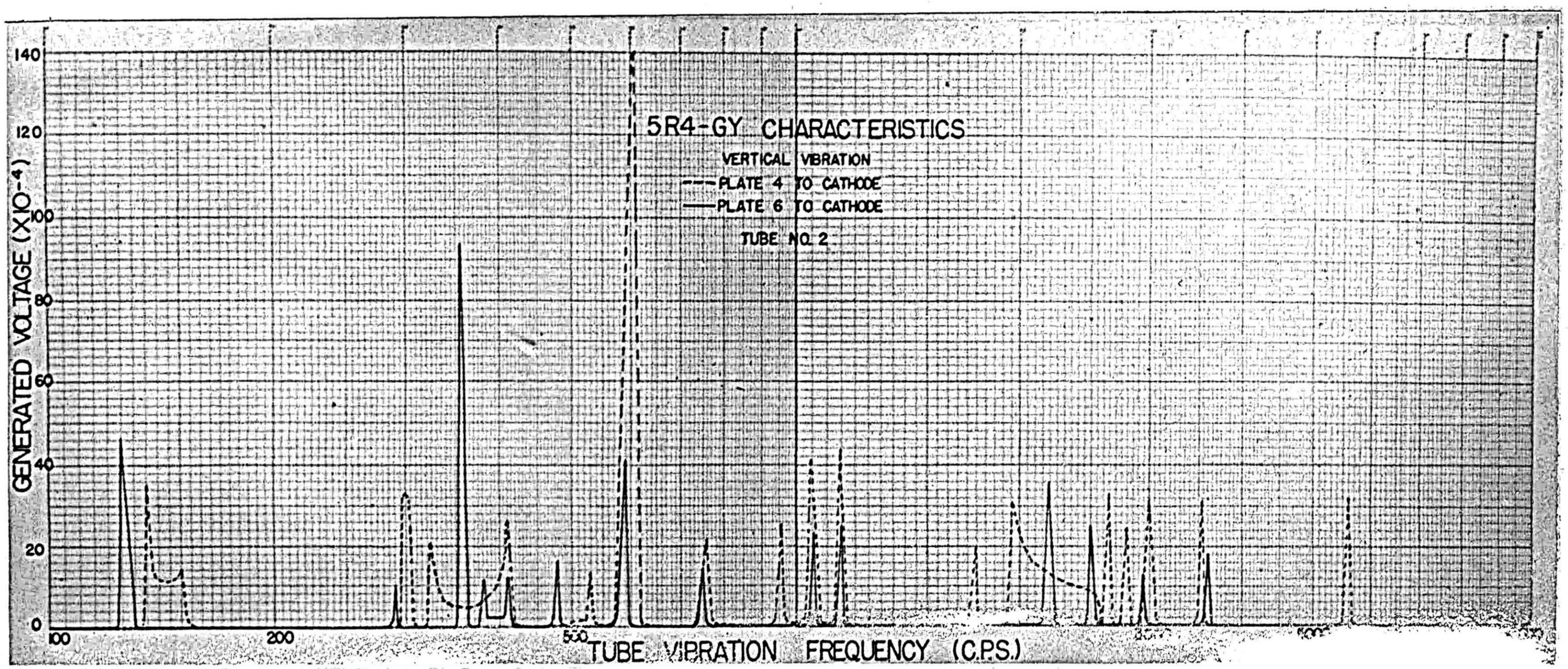


Fig. 16. 5R4-GY Characteristics showing internally generated rms voltages versus frequency. Plate 4 to Cathode and Plate 6 to Cathode voltages are compared for vertical vibration of tube no. 2.

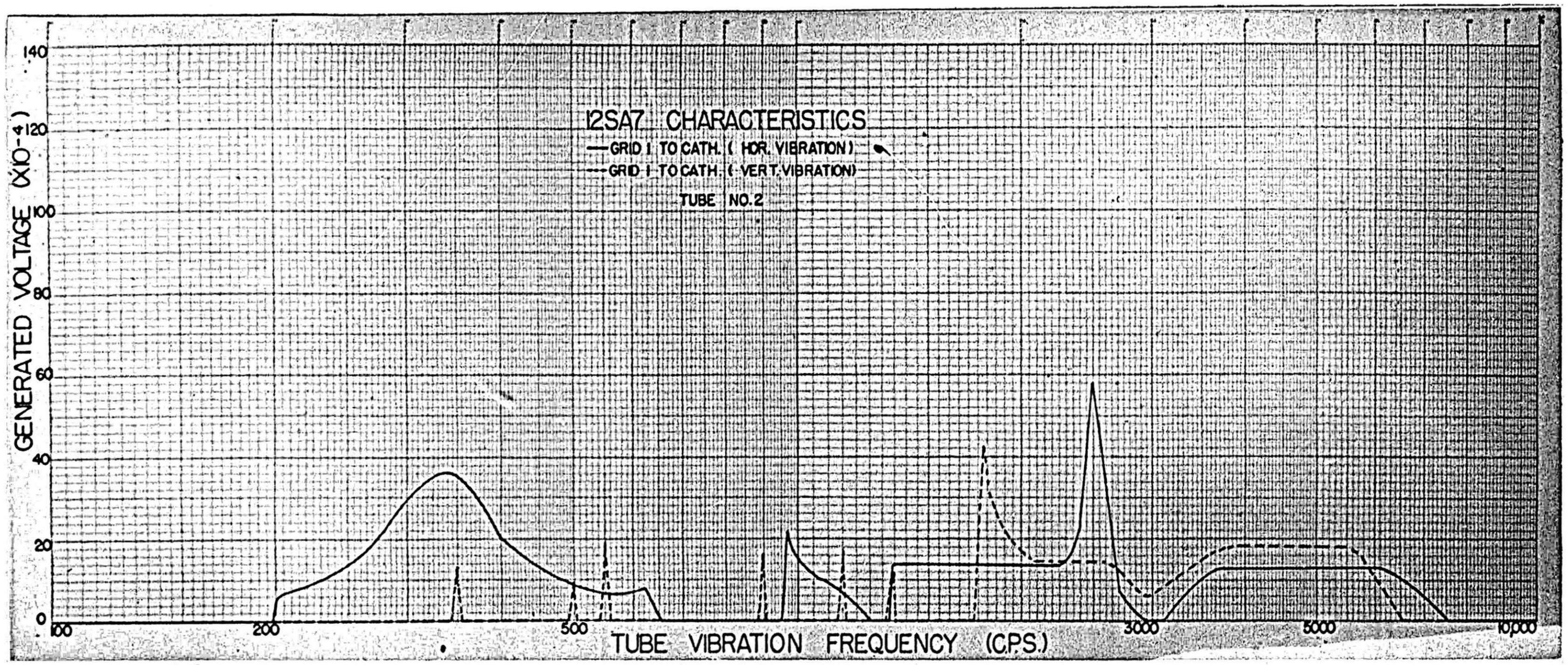


Fig. 17. 12SA7 Characteristics showing internally generated rms voltages between Grid 1 and Cathode versus frequency. Vertical and horizontal vibration are compared for tube no. 2.

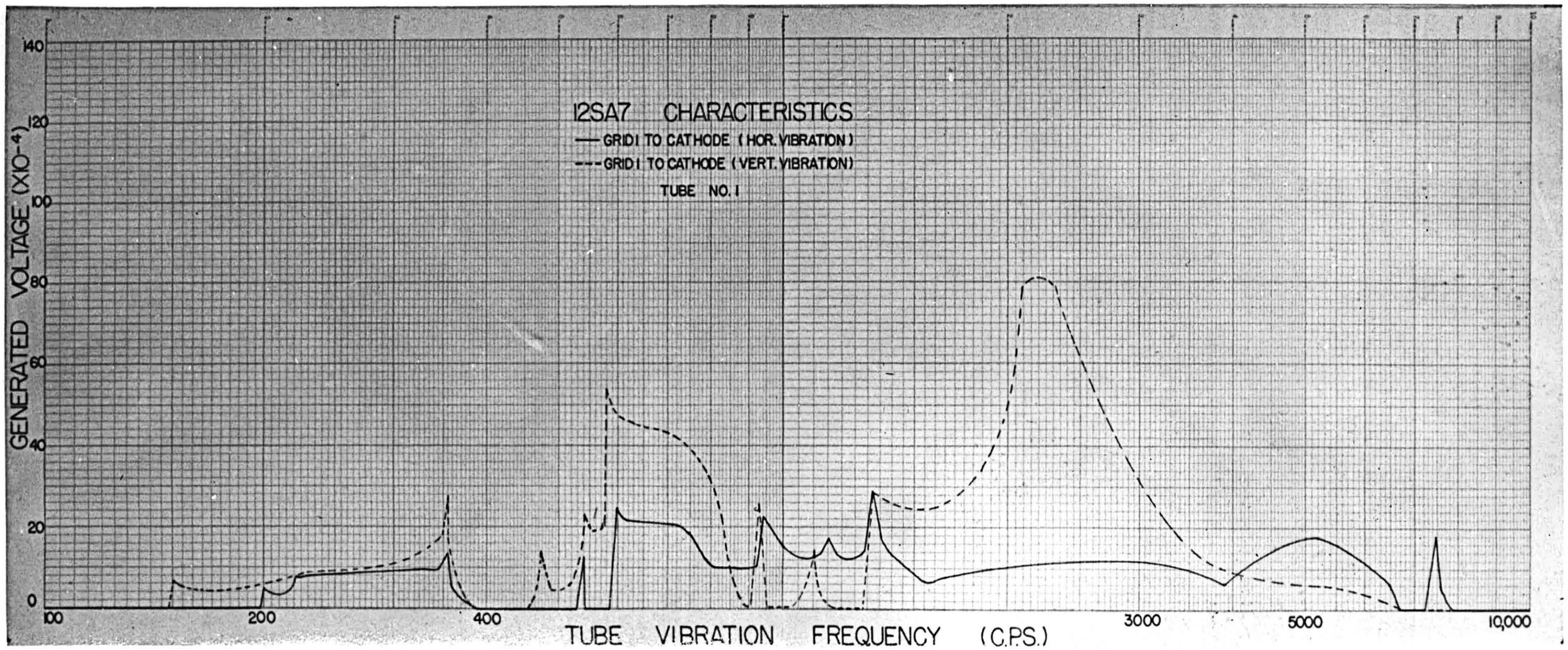


Fig. 18. 12SA7 Characteristics showing internally generated rms voltages between Grid 1 and Cathode versus frequency. Vertical and horizontal vibration are compared for tube no. 1.

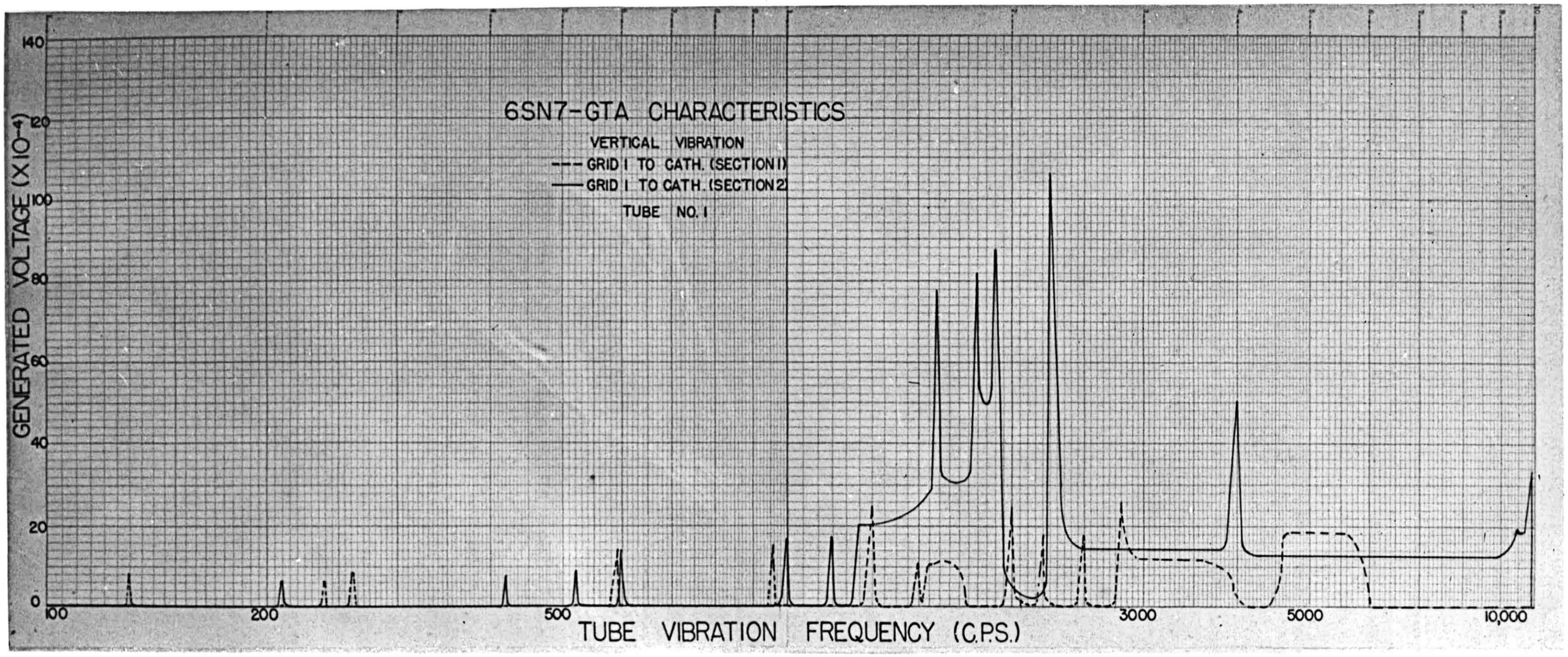


Fig. 19. 6SN7-GTA Characteristics showing internally generated rms voltages between Grid 1 and Cathode versus frequency. Section 1 and 2 are compared for vertical vibration of tube no. 1.

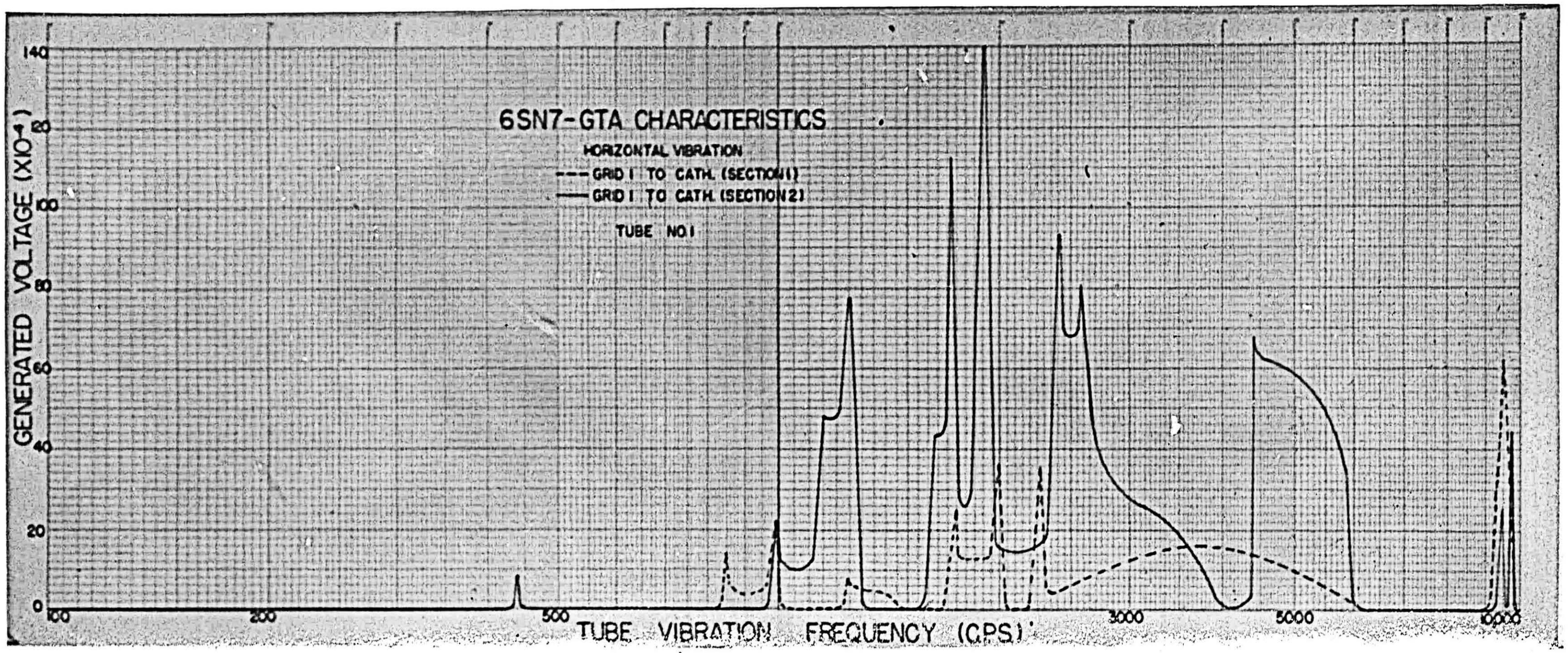


Fig. 20. 6SN7-GTA Characteristics showing internally generated rms voltages between Grid 1 and Cathode versus frequency. Section 1 and 2 are compared for horizontal vibration of tube no. 1.

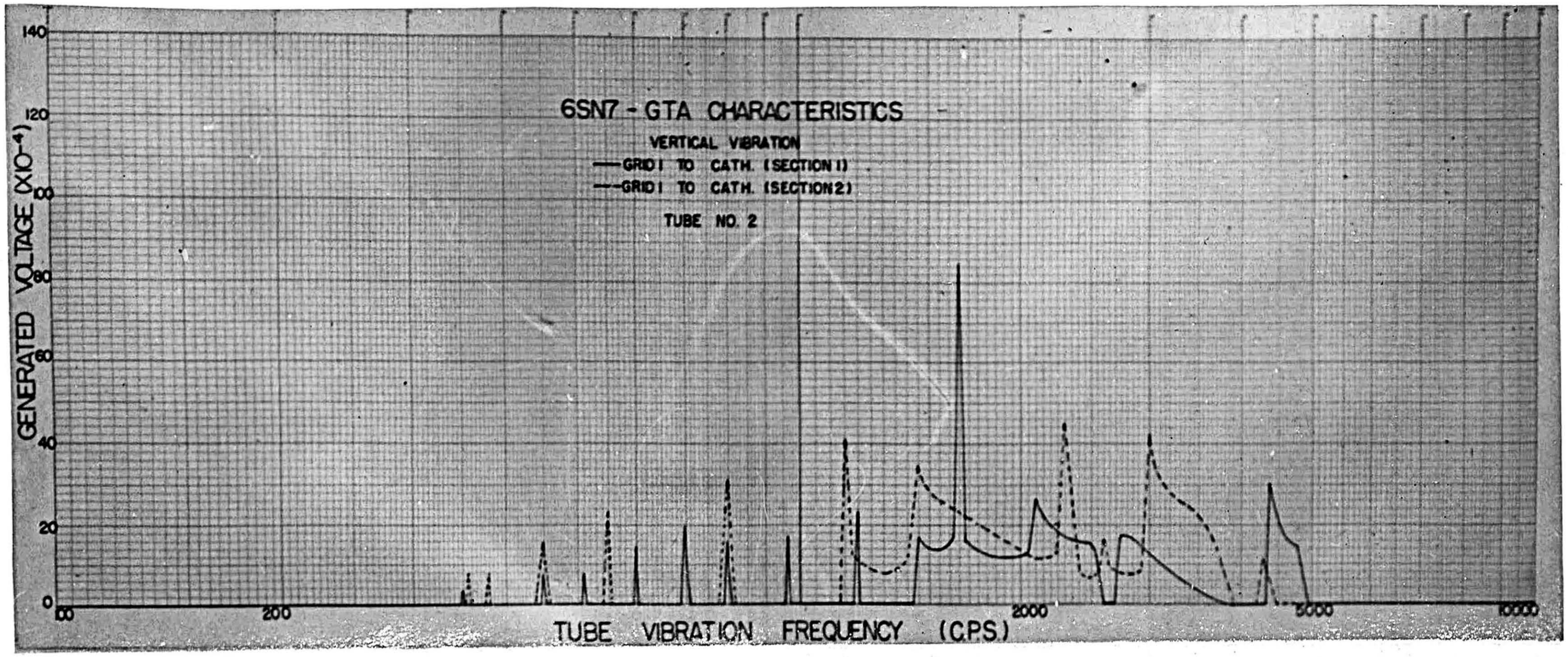


Fig. 21. 6SN7-GTA Characteristics showing internally generated rms voltages between Grid 1 and Cathode versus frequency. Section 1 and 2 are compared for vertical vibration of tube no. 2.

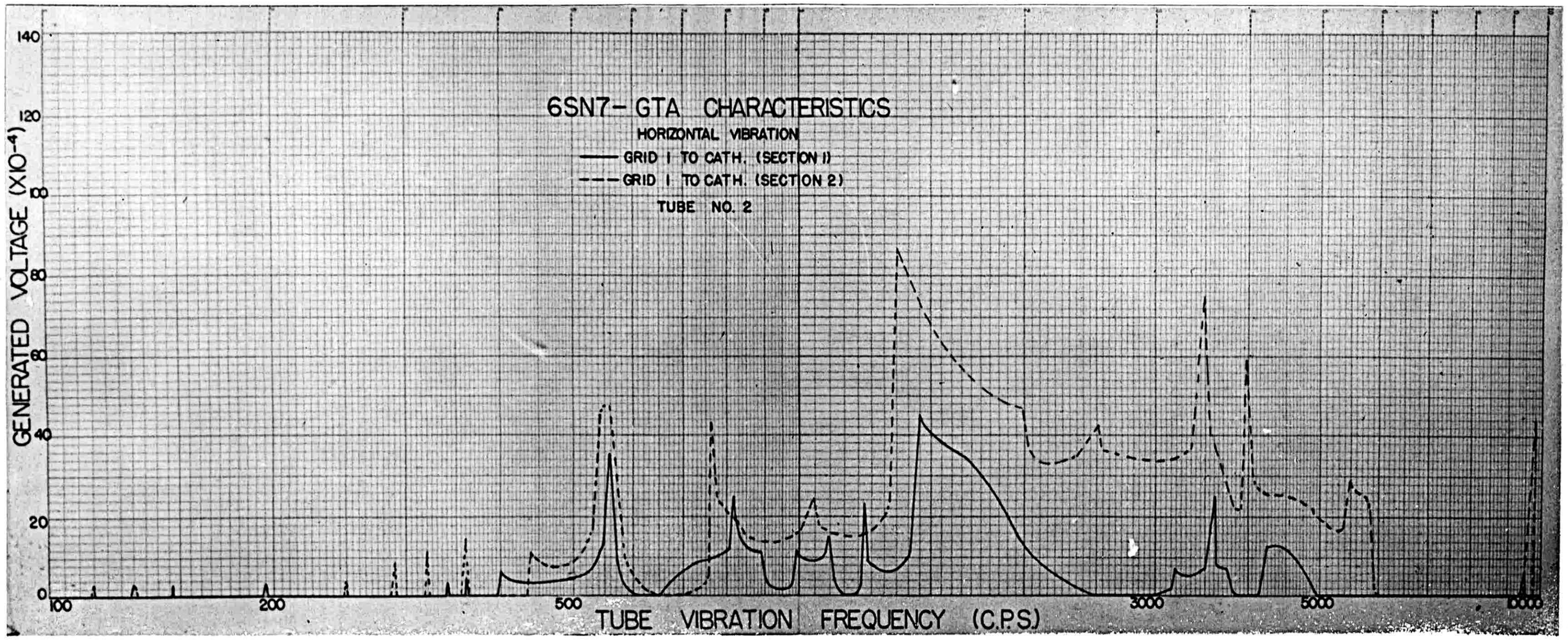


Fig. 22. 6SN7-GTA Characteristics showing internally generated rms voltages between Grid 1 and Cathode versus frequency. Section 1 and 2 are compared for horizontal vibration of tube no. 2.

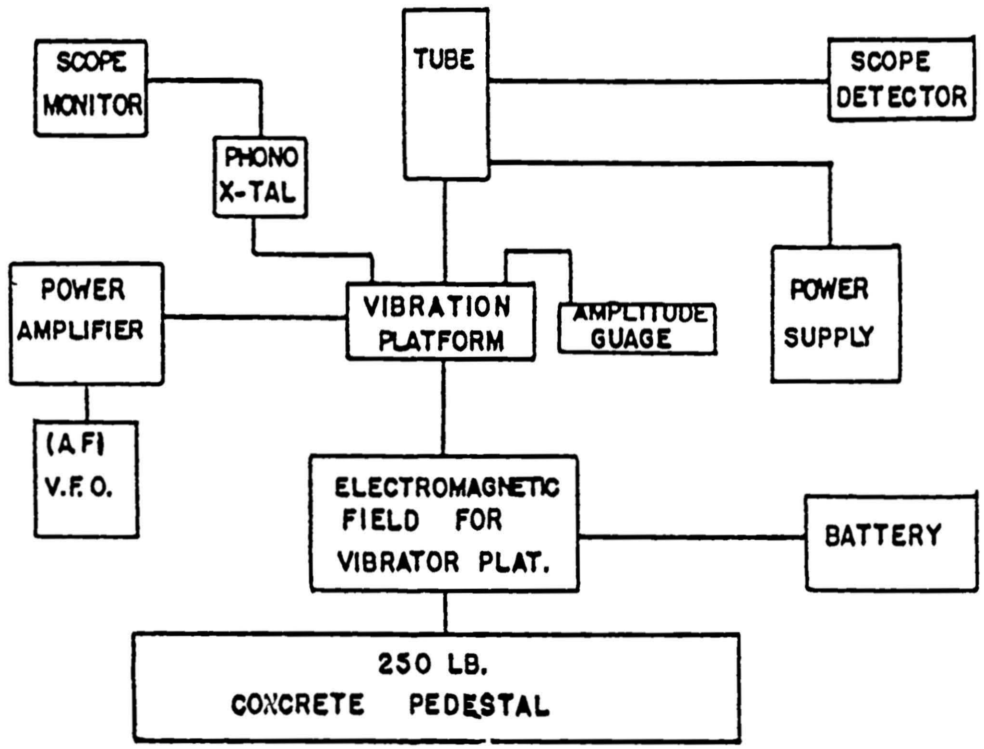


Fig. 23. Block diagram of vibration apparatus showing auxiliary equipment.

plane. The curves present the two sections of the tube on the same sheet for easy comparison. This test was conducted with the heater cold so the cathode assembly would be more nearly rigid and the results would more closely reflect the behavior of the grid structure. Predominant resonant frequencies are observed to appear in the frequency spectrum of 500 to 2500 cps. This indicates that the tube will be expected to experience the most difficulty retaining its normal behavior when subjected to vibrations of these predominant frequencies.

Since the capacitance between the grid and cathode is a function of the separation of the two elements and also the dielectric constant of the medium between them, it became of interest to determine the effects of the grid bias on the internally generated voltage as observed in the plate circuit and also the effect of the electrons being present between the two elements.

In the region between the cathode and grid, very near the cathode, a concentration of electrons causes a potential redistribution that effectively changes the physical location of the cathode. This new location is known as a "virtual cathode"[16] and is a function of the electric field between the grid and cathode, and thus a function of the potential of the grid or amount of grid bias.

If the grid were not present in the tube the energy of the emitted electrons would cause them to be projected into the region between the cathode and plate some finite distance from the cathode. As more electrons gather at this point in space the potential of it becomes more negative until finally the effects of the negative field produced by it

(16) Ryder, J. D. Electronic Fundamentals and Applications. N. Y. Prentice-Hall, 1950, pp 174 - 176

at the cathode allows no more electrons to be emitted. The plate is positive however, and thus electrons are being drawn away from the "space charge" region at some rate dictated by the load resistor of the plate circuit. This allows more electrons to enter the region from the cathode to replace the electrons that went to the plate and thus a condition of dynamic equilibrium is established where electrons are entering and leaving the space charge region at the same rate.

Since the space charge carries a negative potential, the addition of the negative grid would have the effect of forcing it closer to the cathode since the emitted electrons would have insufficient energy to oppose the action of the field set up by the grid. Variations in grid potential provide variations in the separation (s') between the grid and virtual cathode and offer the possibility of varying the capacitance between the two elements since $C = \frac{\epsilon_o KA}{s}$ as has been previously shown.

To determine whether such was the case, a tube was placed in mechanical vibration at one of its resonant frequencies and an output voltage was observed on the c.r.o. The grid bias was then varied from o to cut-off and the amplitude of generated voltage was observed. The results are presented in the curve of Fig. 24.

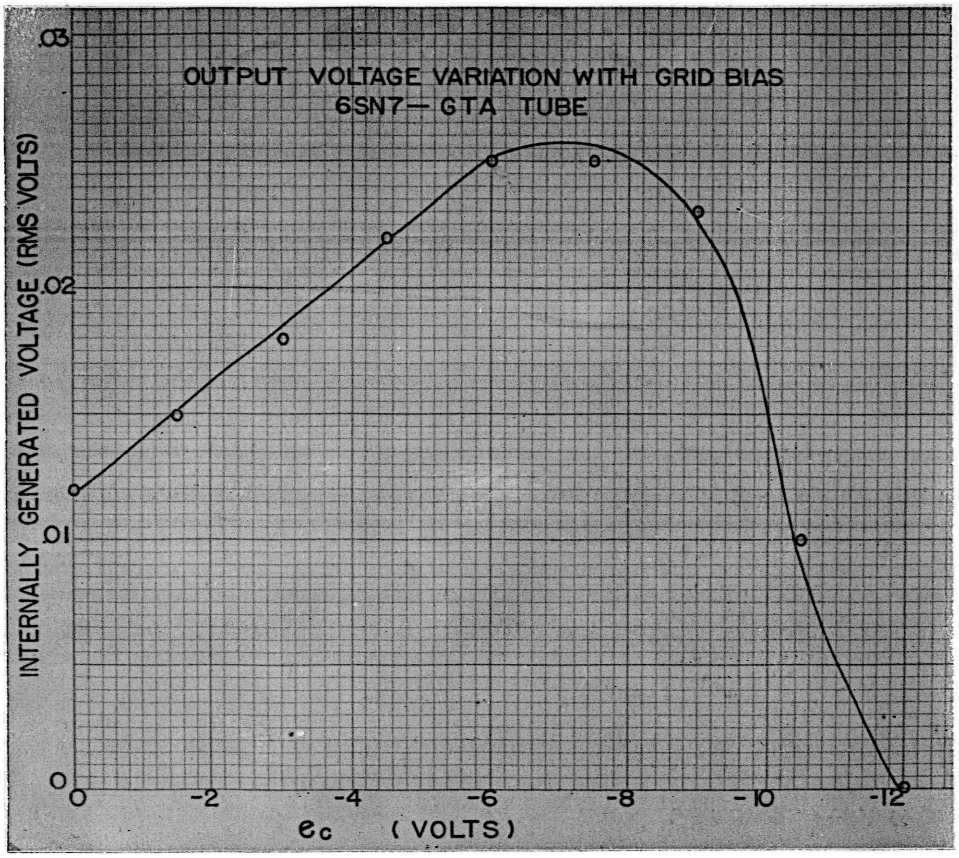


Fig. 24. Effects of grid bias on internally generated output voltage.

To determine the effect of series grid circuit resistance on this curve, the experiment was repeated with a 470,000 ohm resistor in series with the grid bias batteries which were new and possessed practically zero internal impedance. No effect was observed so explanation could not be attributed to variation in grid circuit resistance as the bias was changed. It was noticed however; that no internally generated voltage appeared in the plate circuit when the d-c plate current was cut-off. This was observed for both the case where the plate was driven to cut-off by the grid bias and also when emission was stopped by turning off the heater power.

Since the separation (s') between the virtual cathode and the grid is determined by the grid bias, this separation becomes fixed for a given value of grid bias. When the tube is placed in mechanical vibration, if the grid is assumed to be the only element in motion the virtual cathode will then follow it's motion and the separation remain constant. The special case where this behavior might not be true is when the tube is biased at exactly cut-off and the virtual cathode is assumed to be forced onto the surface of the cathode. When the tube is placed in mechanical vibration on one half of the cycle of vibration the grid will separate farther from the cathode and thus allow the virtual cathode to follow it away from the cathode surface because of the reduced electric field with the increase in separation. The effective capacitance between the grid and virtual cathode would be some constant because the distance s' would remain constant.

Over the other half of the cycle the grid would be getting closer to the cathode and since the virtual cathode cannot go behind the cathode the separation s' then becomes some new value smaller than in the previous half cycle. This variation in separation over the second half cycle causes a variation in capacitance and thus a charging current which should appear as internally generated voltage in the plate circuit. The result of such a behavior would cause a rectified wave-form to appear in the output circuit. Since the above phenomena could never be observed it would appear that the space charge was not contributing to the internally generated voltage and thus does not appear to be the explanation for the shape of the curve of Fig. 24. Numerous tubes were observed experimentally and in every instance, the same relative curve appeared.

To provide one possible explanation, the same tube as was used to plot the curve of Fig. 24 was selected on which to run the dynamic transfer characteristics. This was done for a constant plate voltage E_{bb} and the grid bias was varied between zero and cut-off which was -10.5 volts. This curve is plotted in Fig. 25.

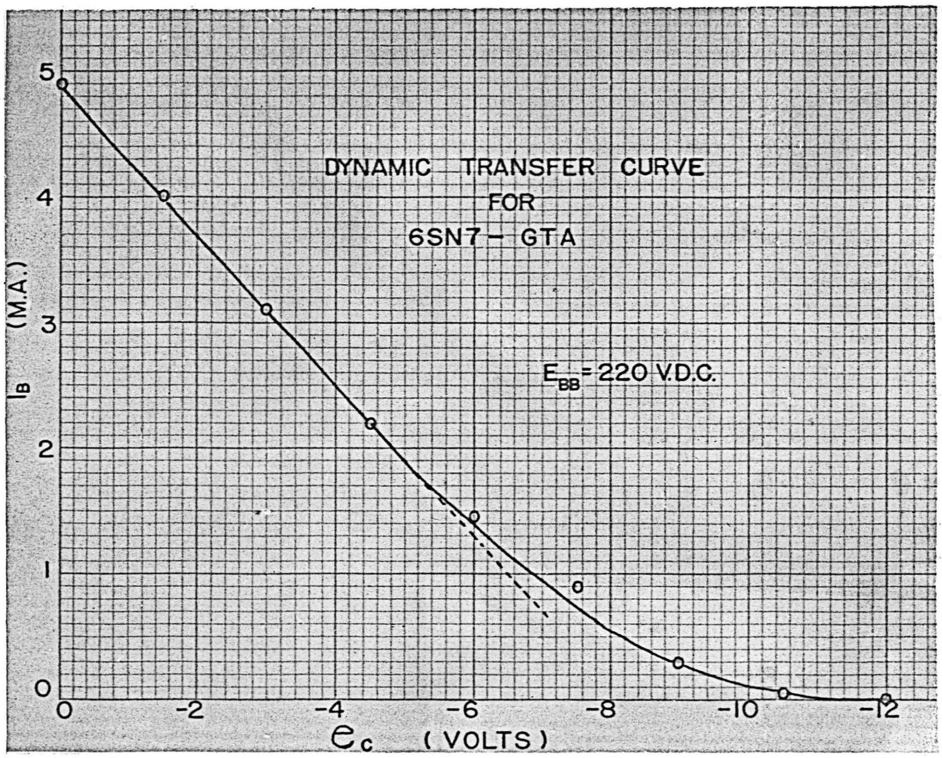


Fig. 25. Dynamic transfer characteristics for 6SN7-GTA.

The slope of the curve at any point is the mutual transconductance of the tube g_m and by definition, $g_m = \partial i_b / \partial e_c$ where i_b is an instantaneous value of total plate current and e_c is an instantaneous total grid to cathode voltage. It should be noted that g_m is constant for values of e_c between o and -6 volts and then changes to zero in a short time in the region of e_c = -6 to e_c = cut-off.

The following is a possible explanation for the shape of the curve of Fig. 24. The point on the curve where e_c = o shows that internally generated voltage is present in the plate circuit. This voltage cannot be generated in the grid-cathode region by charging currents because it has been shown previously that the equation for charging current between two elements is:

$$i_{inst.} = \frac{-V \epsilon_0 K A \Delta S \omega}{S^2} \cos \omega t$$

and since V = 0 this current becomes equal to zero.

Since the tube is drawing electron current at grid bias equal to zero, the motion of the grid could be causing variations in the electric field intensity in the grid-cathode region which would control the number of electrons flowing in the plate circuit and thus cause an a-c output to appear.

The μ of the tube is equal to $g_m r_p$, where r_p is the plate resistance. The current that flows in the plate circuit is some function of $(\mu e_c + e_b)$ where e_b is a plate voltage variation which in this case is a constant and μ is the amplification factor of the tube. Therefore, $i_b = f(\mu e_c)$ and since μ is proportional directly to g_m which is going from some value to zero in the $e_c = -6$ to e_c = cut-off region of the transfer curve, it would seem that the current will also approach zero in the plate circuit.

Figures 26 through 29 show the results of vibrating a 6SN7-GTA in its various planes of vibration as the grid bias is changed over the -3 to -9 volt region. The nearly linear variation can be observed as indicated in Fig. 24. In no case did the variation in grid bias cause a shift in the mechanical frequency of resonance. The circuit used for this measurement was that of Fig. 30 and the values for the a-c and d-c load resistors and the coupling capacitor are those specified by the manufacturer to give maximum gain of the stage when used as a Class A audio amplifier.

To make a general statement about the behavior of any tube type would require a knowledge of the behavior of many samples of the type and from them average characteristics could be noted. Testing various samples showed that the 6SN7-GTA tubes each displayed similar characteristics in regard to generated voltage versus frequency with only slight variation among the individual samples. A slight variation in output voltage was observed among the samples as their plane of vibration was changed from vertical to horizontal.

Ten 6SN7-GTA tubes were selected for a complete observation and both sections of each tube were vibrated through the frequency spectrum from 30 to 10,000 cps as the amplitude of vibration was held constant. This provided forty sets of information for every frequency of vibration used. Sample data sheets are included (see Appendix) and the complete set of laboratory data is on record at the Department of Electrical Engineering, Missouri School of Mines and Metallurgy, Rolla, Missouri.

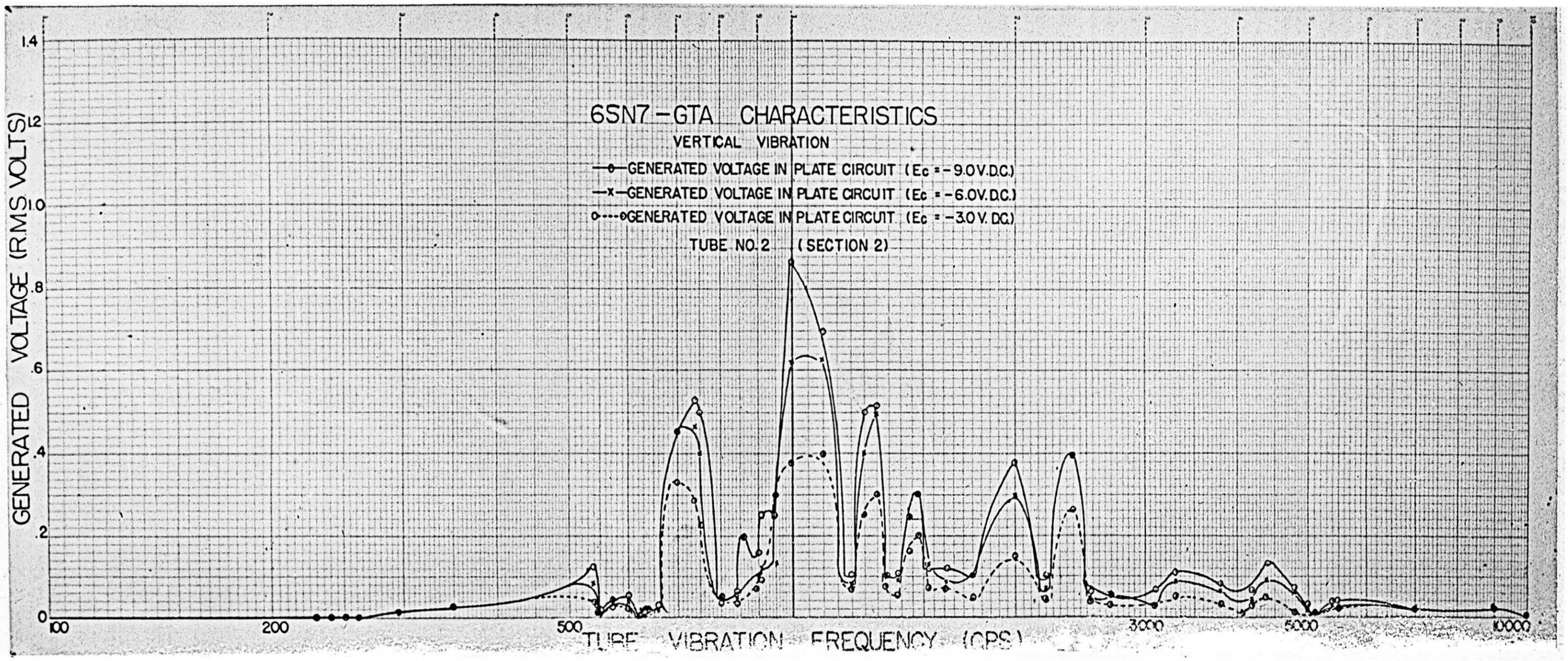


Fig. 26. 6SN7-GTA Characteristics showing amplitude of internally generated rms voltage versus frequency of vibration for various values of grid bias. Curve is for section 2 of sample no. 2 under .008 inches peak-to-peak of vertical vibration.

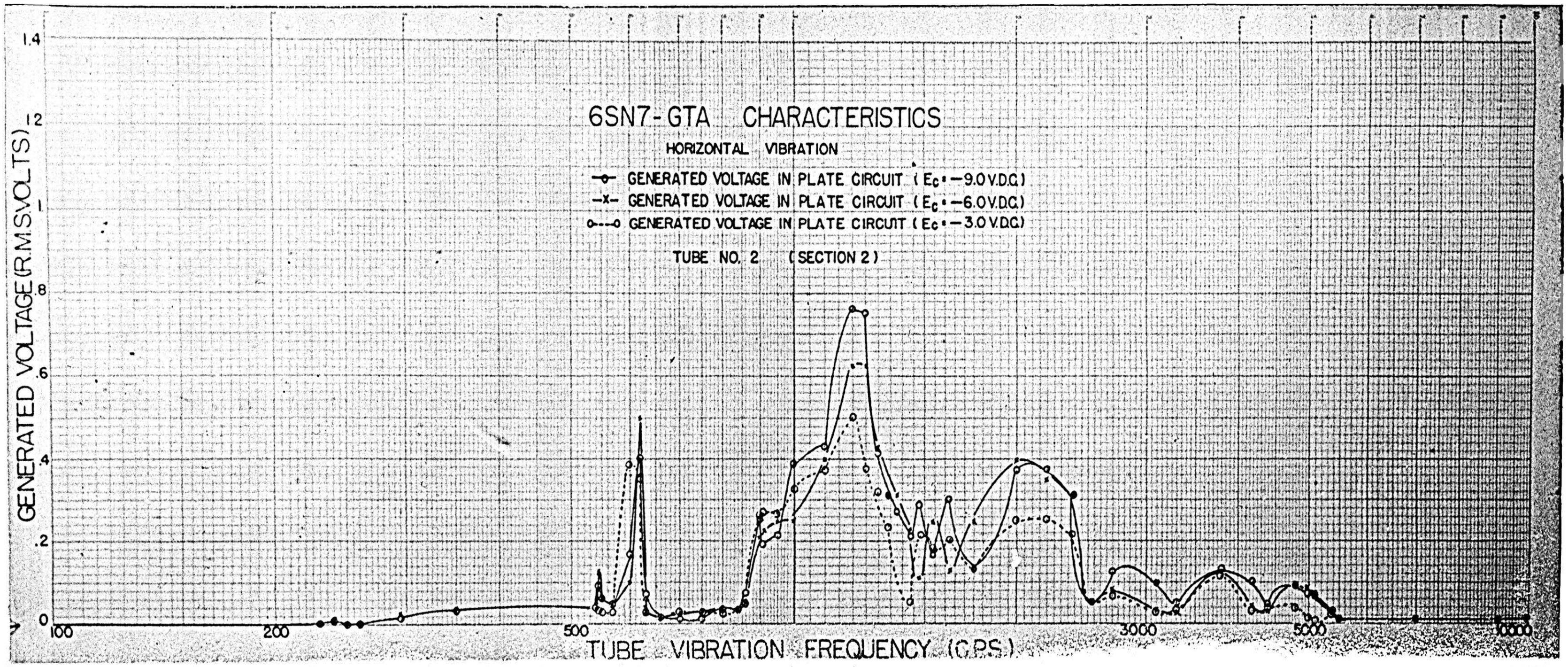


Fig. 27. 6SN7-GTA Characteristics showing amplitude of internally generated rms voltage versus frequency of vibration for various values of grid bias. Curve is for section 2 of sample no. 2 under .008 inches peak-to-peak of horizontal vibration.

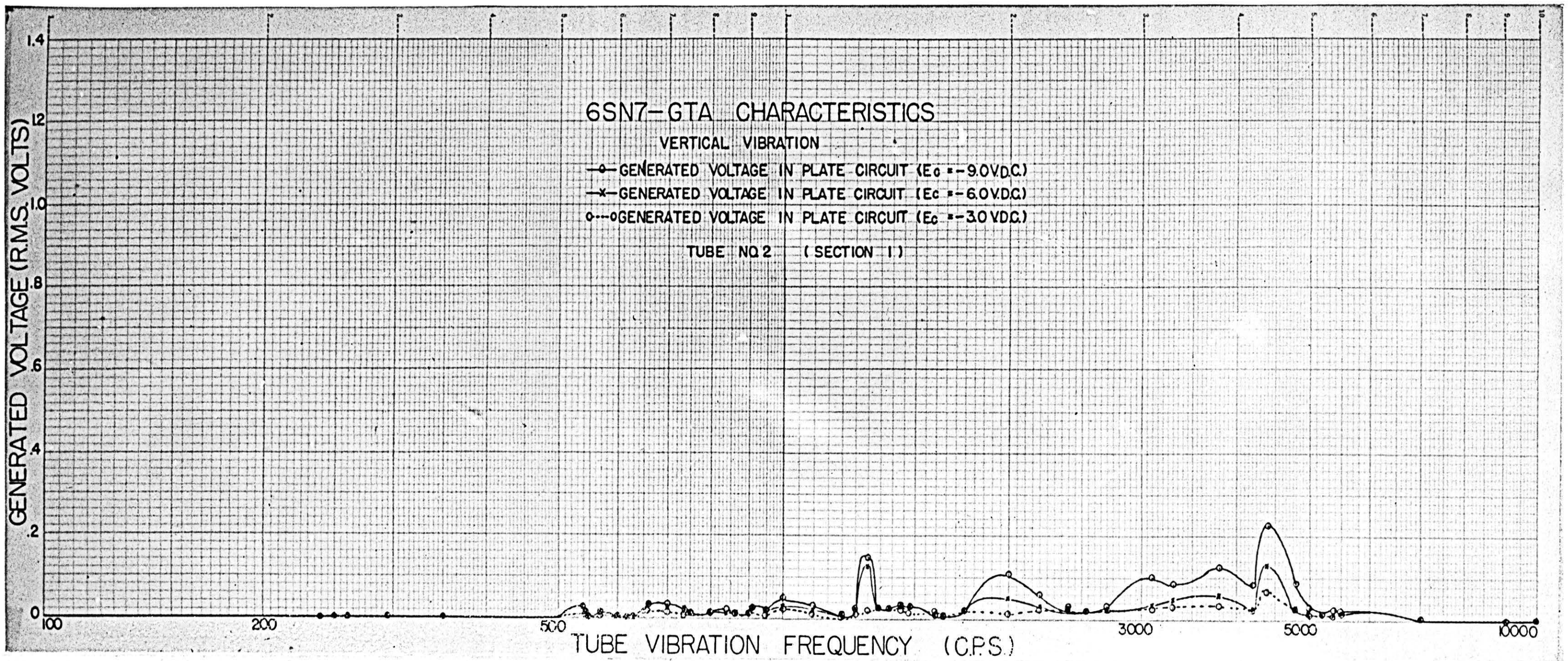


Fig. 28. 6SN7-GTA Characteristics showing amplitude of internally generated rms voltage versus frequency of vibration for various values of grid bias. Curve is for section 1 of sample no. 2 under .008 inches peak-to-peak of vertical vibration.

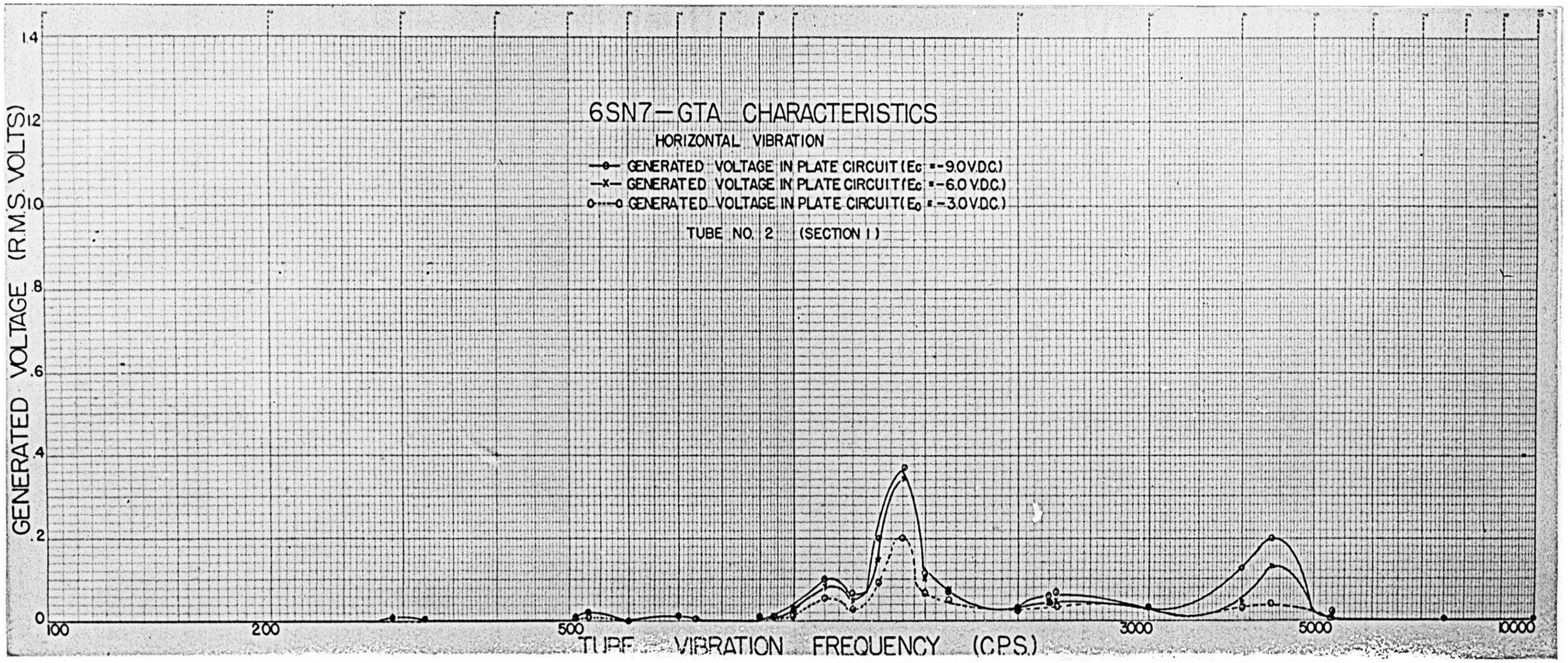


Fig. 29. 6SN7-GTA Characteristics showing amplitude of internally generated rms voltage versus frequency of vibration for various values of grid bias. Curve is for Section 1 of Sample no. 2 under .008 inches peak-to-peak of horizontal vibration.

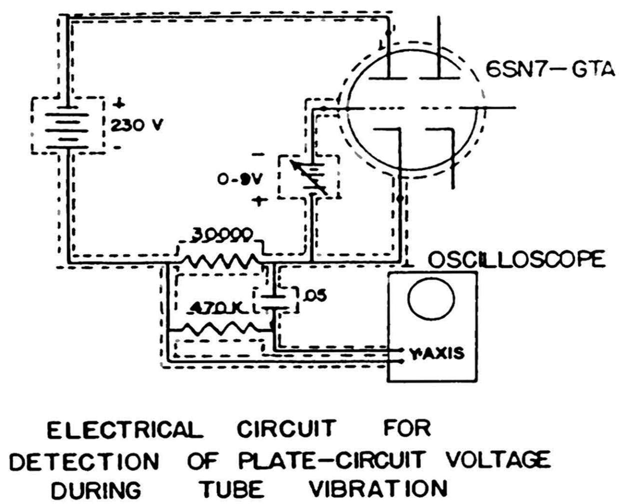


Fig. 30. Electrical circuit for detection of internally generated plate-circuit voltage during tube vibration.

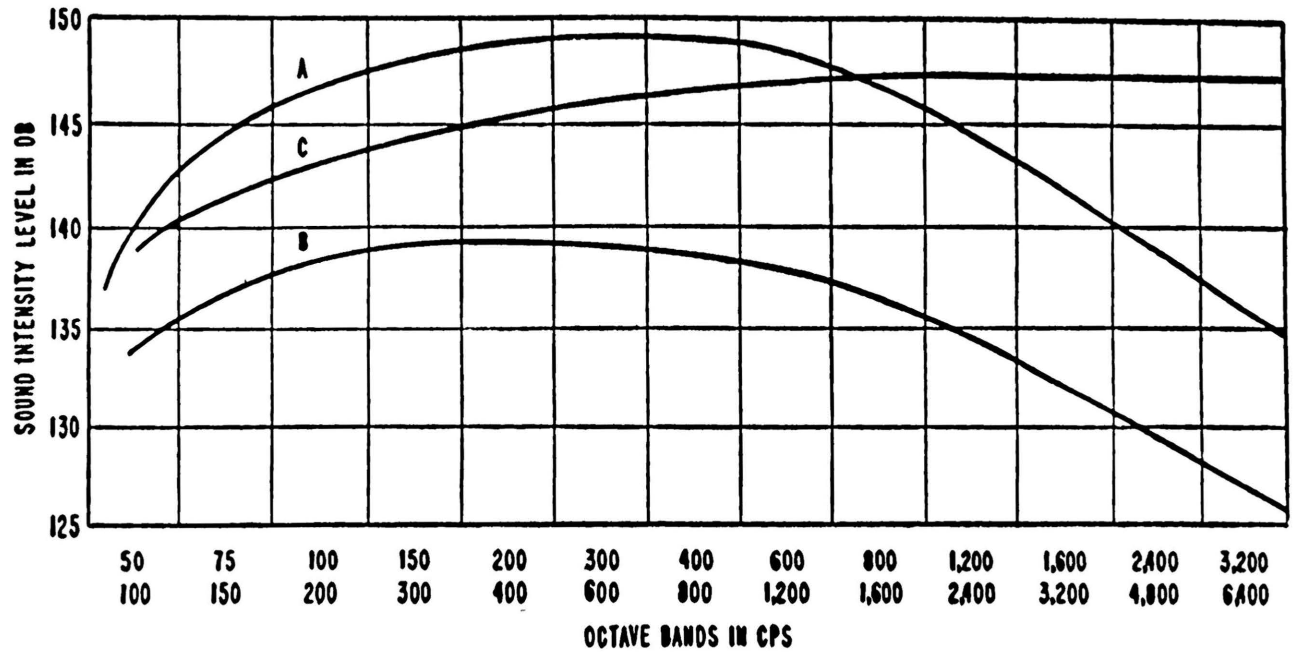


Fig. 31. Typical sound spectra of aircraft jet engine at full thrust measured 10 feet from tailpipe (A), sound level at inboard equipment bay of aircraft (B) and average sound pressure level obtainable in Armour Research test chamber (C). The 0-db reference level for airborne sound intensity is 10^{-16} watts per sq. cm.

Throughout the entire observation the d-c plate voltage was held constant at +230 volts. The grid was operated at -9 volts d-c bias which provided maximum output voltage in the plate circuit. The amplitude of vibration was held constant at .008 inches and the heaters run at 6.3 volts d-c. The frequency spectrum was chosen because it contained all of the frequencies of significant amplitude found in present-day jet driven aircraft as shown by the published curves of Fig. 31.(17)

The circuit of Fig. 30 was used for this observation and it was necessary to completely shield all of the circuitry and apparatus with shielded wire and aluminum foil to prevent stray a-c pickup from getting into the high gain stages. It was found that the gain of the vertical amplifiers was sufficient to detect the internally generated voltage of these tubes so the preamplifier used previously was not necessary. To convert the scope amplitudes to rms voltages the Dumont 304-H Oscilloscope was driven with a constant input voltage supplied from a General Radio 1302-A Audio Frequency Oscillator and monitored with a Ballantine 304 Audio Frequency Vacuum Tube Voltmeter. The scope was found to have a linear response over this frequency range and the calibration curve of Fig.32 shows it.

An average characteristic curve for all the sections operating in the horizontal plane was made and appears in Fig. 33. When compared to the corresponding average curve for vertical vibration in Fig. 34 it can be seen that the two so closely compare an average of the two curves would very closely predict behavior of the tube regardless of its plane

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(17) Mintz, F. and Levine, M. B. Testing of Airborne Electronics Components Electronics V. 28, No. 3, pp 181 - 84 (1955)

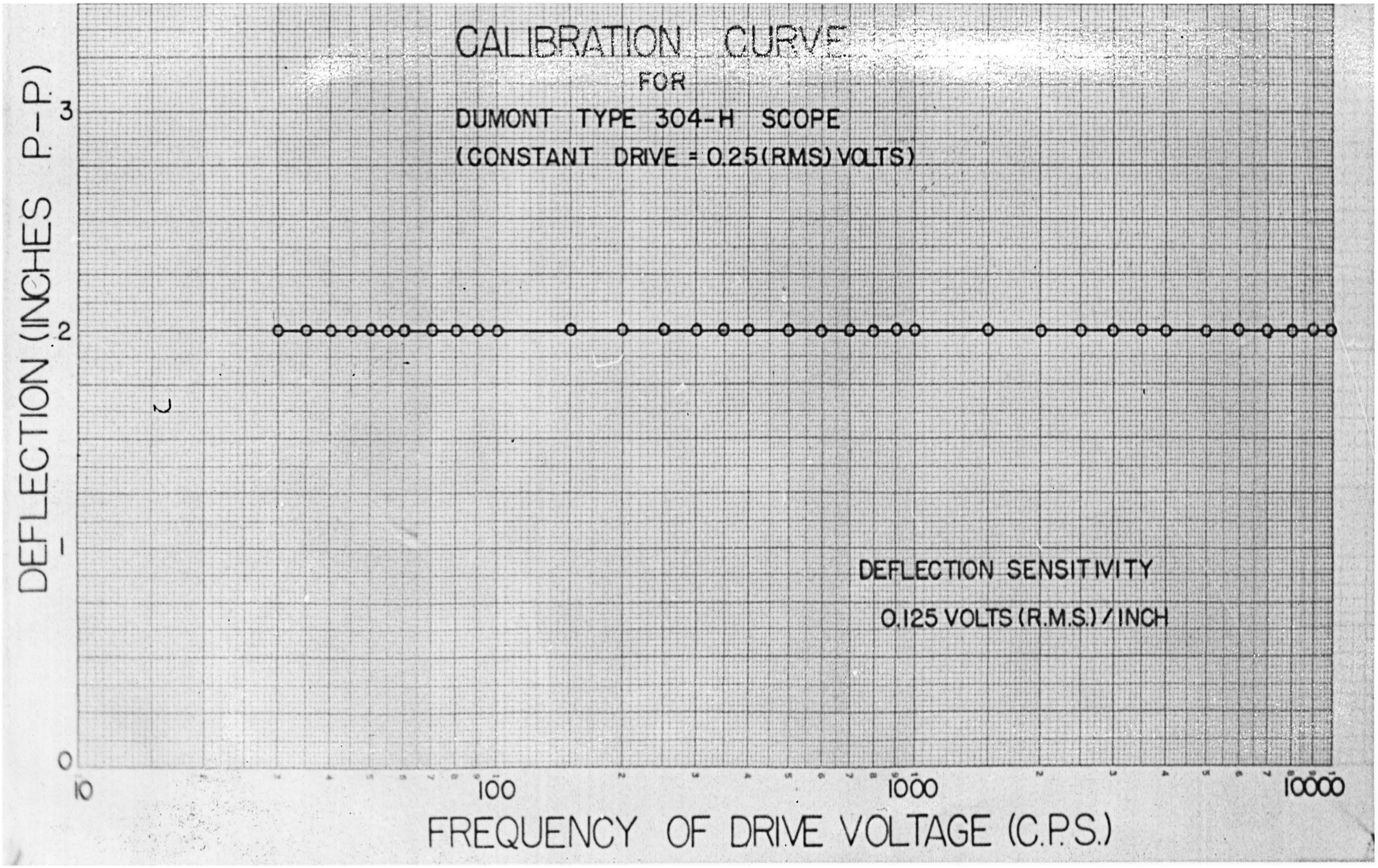
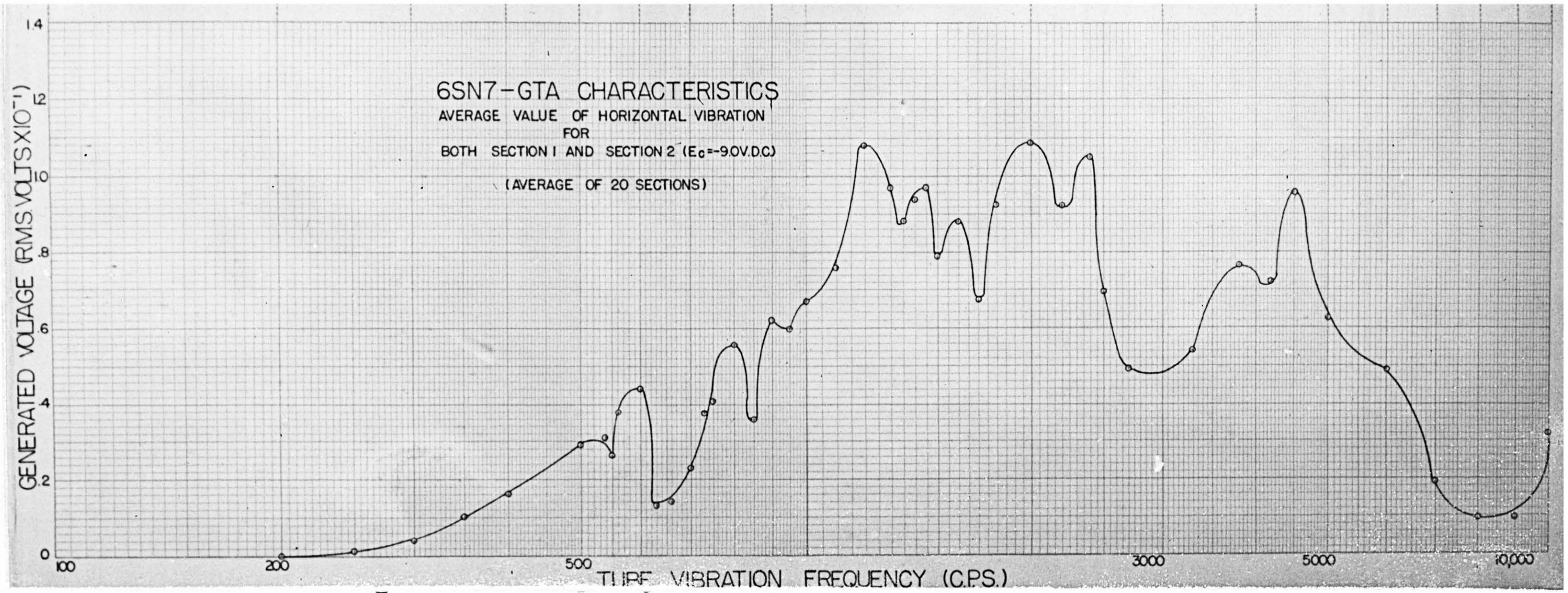


Fig. 32. Calibration curve of Dumont 304-H Oscilloscope showing linearity of response versus frequency characteristics.



under horizontal vibration of .008 inches peak-to-peak.

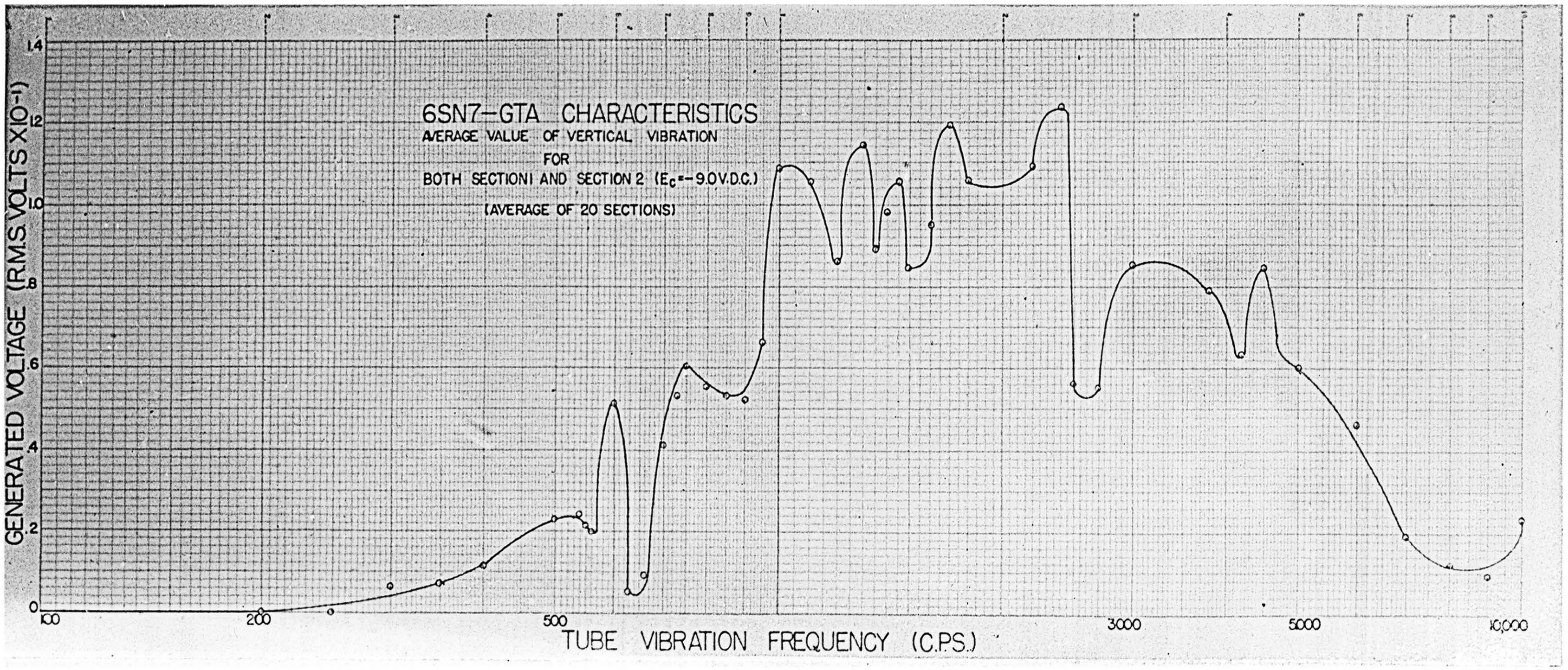


Fig. 34. 6SN7-GTA Characteristics showing amplitude of internally generated rms voltage versus frequency of vibration for average of all tubes operating under vertical vibration of .008 inches peak-to-peak.

of operation. This curve appears in Fig. 35. From it one can observe that the spectrum of frequency between 980 and 2460 cps contains most of the resonant frequencies which cause large internally generated voltages. If the tube is assumed to be operating under vibration at any of the frequencies of this spectrum one could establish the mean amount of internal voltage that would be likely to appear if the amplitude of the vibration is as much as .008 inches. No attempt was made to determine a relationship between amplitude of generated voltage and amplitude of vibration but it seemed to be very nonlinear as the amplitudes were adjusted to the given .008 inches for each frequency observed above.

To determine the mean ordinate of the area above the .075 volt line on Fig. 35 a graphical integration method was used. An overlay of the area was made and appears to scale in Fig. 36 which shows the mean value of generated voltage in the spectrum to be .100 volts.

From this it can be said that for the general 6SN7-GTA operating at +220 volts d-c on the plate, 30,000 ohms plate load resistance, grid bias of -9 volts d-c and the tube under .008 inches of mechanical vibration at a frequency in the spectrum between 980 and 2460 cps the mean internally generated voltage is .100 volts caused by the vibration.

EQUIVALENT CIRCUIT

To be of use, an internally generated voltage that appears in the plate circuit should be reflected back into the grid circuit as some equivalent voltage there. To do this would provide a means whereby circuit designers could include known effects of vibration into the circuit design. Since it has been shown here that the amount of internally generated voltage in the tube plate circuit is a function of the grid bias

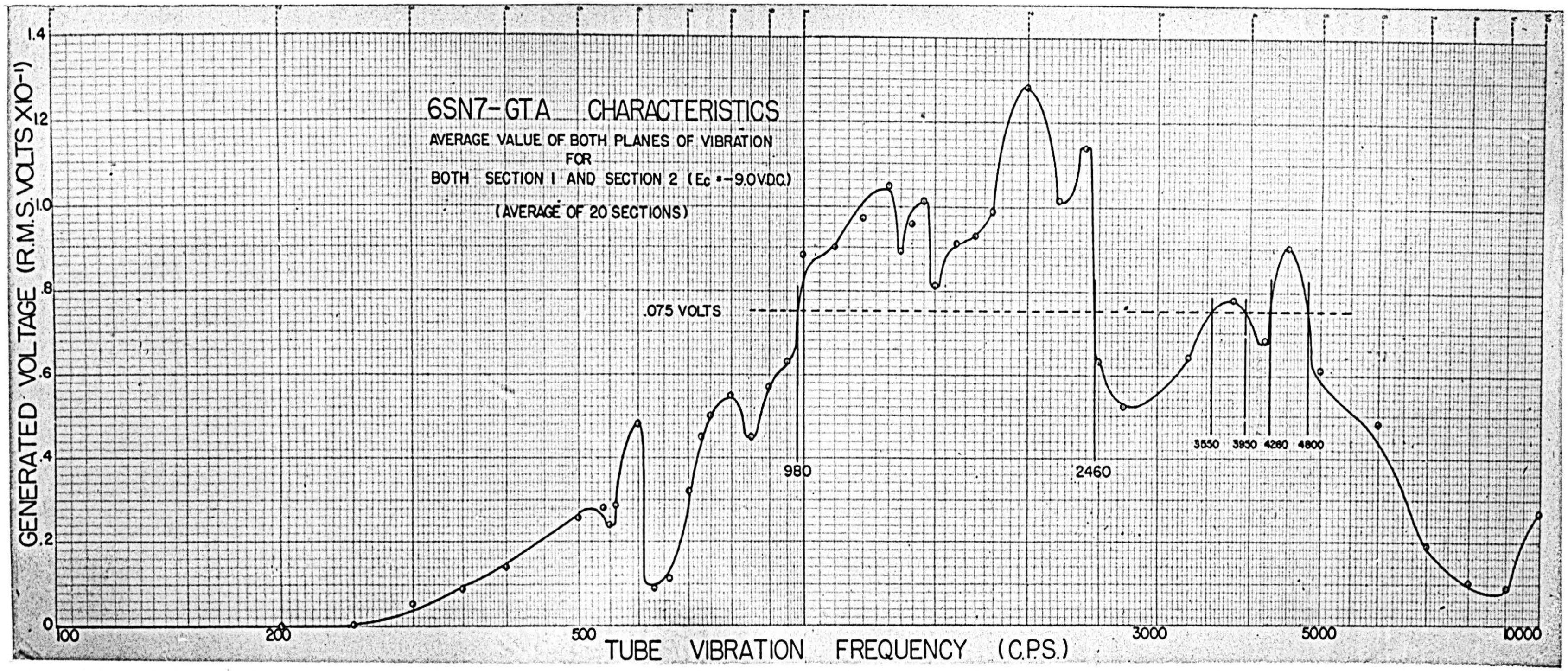


Fig. 35. 6SN7-GTA Characteristics showing internally generated rms voltage versus frequency for the over all average of all 6SN7-GTA tubes vibrated in both the vertical and horizontal planes with .008 inches of vibration peak to peak.

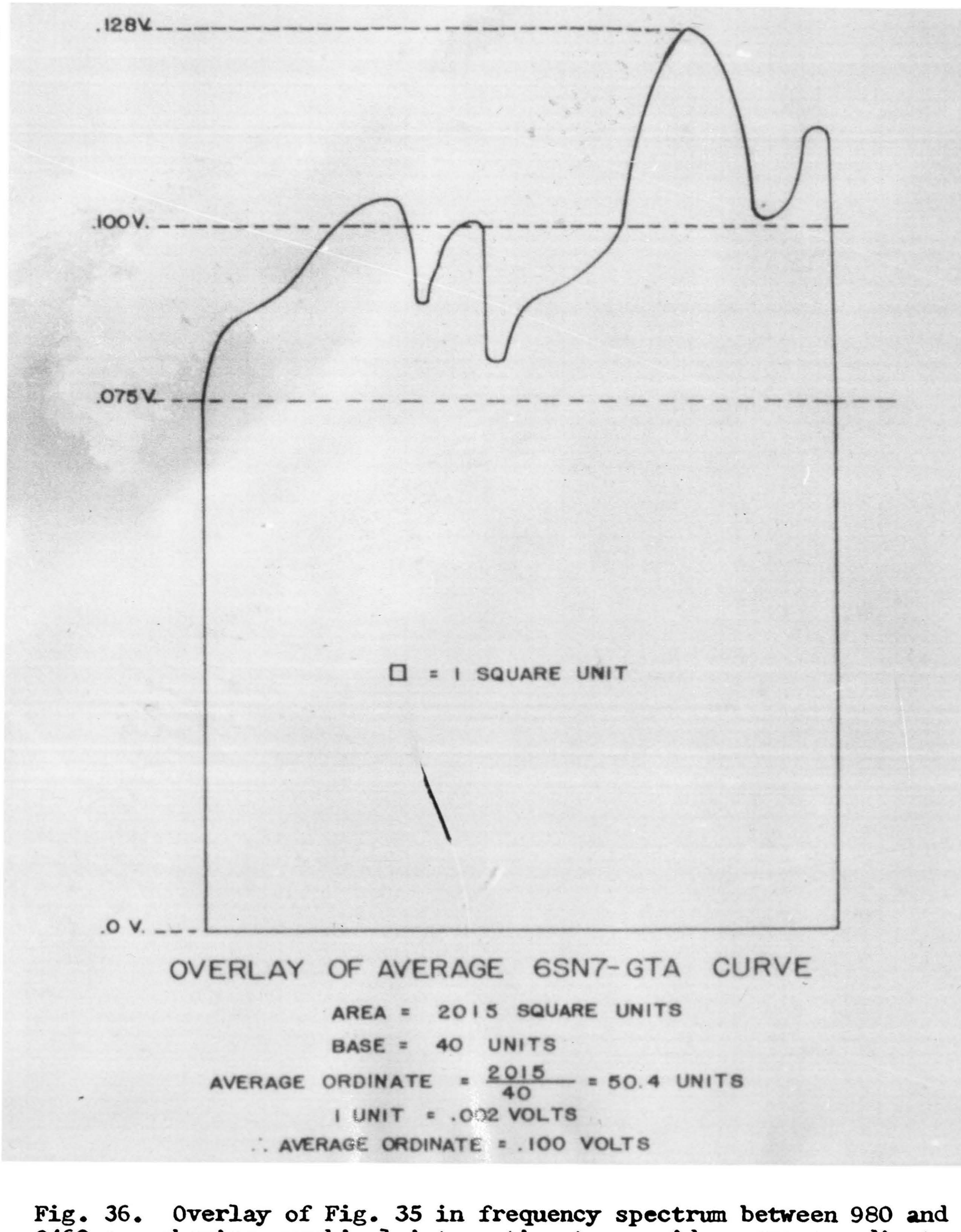


Fig. 36. Overlay of Fig. 35 in frequency spectrum between 980 and 2460 cps showing graphical integration to provide average ordinate of generated voltage in the region.

and also dependent on the flow of plate current to provide sufficient amplitudes for detection, the placing of this voltage into an equivalent circuit seems valid.

The development of equivalent circuits for vacuum tubes is common knowledge[18] and will only be stated here.

From Thevinin's Theorem the tube may be considered as a generator of a constant voltage equal to $-\mu e_g$ in the plate circuit, the negative sign indicating the change of phase in the tube. The internal resistance of the tube r_p is the equivalent series generator impedance. A conventional amplifier stage is shown in Fig. 37.

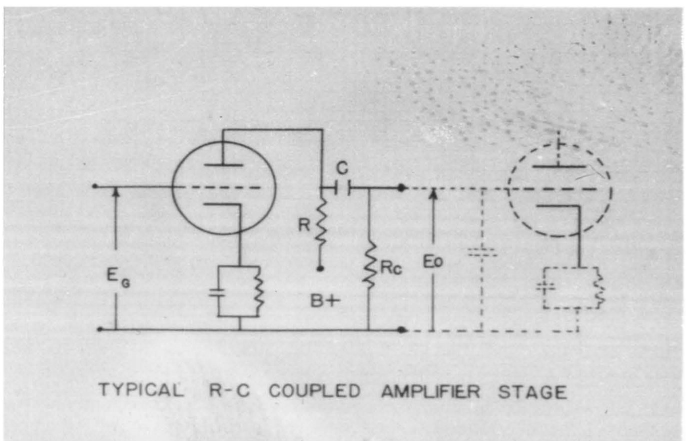


Fig. 37

(18) Smith, L. F. Radiotron Designers Handbook, Sydney, Australia, The Wireless Press, 1942.

The constant-voltage equivalent circuit at mid frequency then becomes that of Fig. 38.

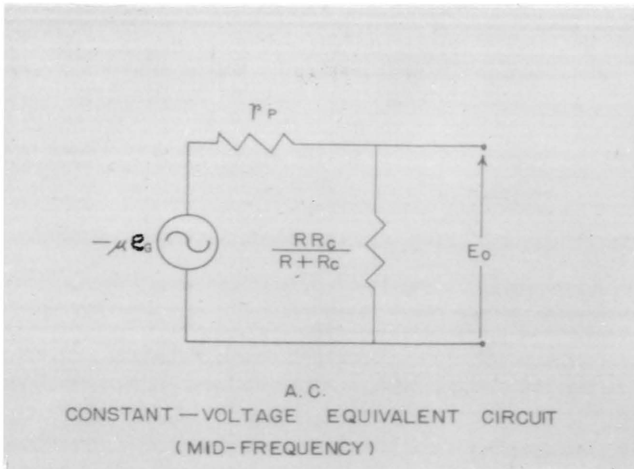


Fig. 38

It should be pointed out that this circuit pays no regard to d-c and thus says nothing about the d-c current that flows with zero a-c grid signal. Also the coupling capacitor c is assumed to present zero impedance to any a-c in mid-frequency operation.

By previous analysis the vibration was assumed to be associated with the grid only, moving with respect to the cathode and plate. Since any vibration of voltage in the plate circuit can be treated as if it originated as a voltage appearing across the grid by the above equivalent circuit, the internally generated voltage can be treated as some e'_g appearing at the grid. Also since the voltages at the grid are amplified by the amplification factor μ of the tube in the equivalent circuit, the following rearrangement of the equivalent circuit in Fig. 39 should also account for internal voltages due to vibration.

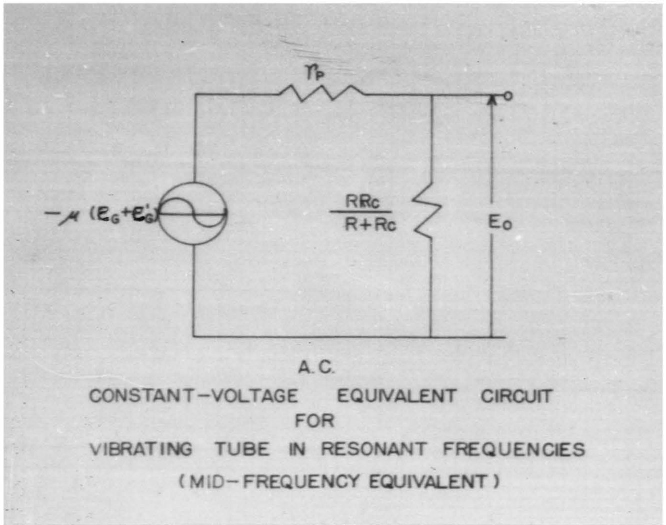


Fig. 39

The total equivalent generator becomes $-\mu(e_g \pm e'_g)$ where the sign of e'_g is determined by the phase shift of the vibration motion with respect to the already present signal voltage e_g. In the present case, the value of e_g is some d-c constant and thus would not be considered in this a-c equivalent circuit. Since no a-c driving voltage was present as such from external sources, the equivalent generator then becomes $-\mu(\pm e'_g)$ for the zero-signal case. Under this condition some output voltage E_o is observed when the tube is vibrated at resonance.

The value for the gain of the stage A can be expressed in terms of the known circuit parameters as: $A = \frac{-\mu R}{r_p + R}$. Also since $A = \frac{E_o}{E_g}$, E_g can be solved for and found to be:

$$E_g = \frac{E_o}{A} = -\frac{E_o(r_p + R)}{\mu R}$$

Since E_o is caused by vibration-generated voltages only, E_g becomes e'_g and the above equivalent circuit is then shown to be correct.

From the expression for $e'_g = - \frac{E_o(r_p + R)}{\mu R}$:

$$e'_g = - \frac{.100 \quad (7{,}000 + 30{,}000)}{20\ (30{,}000)}$$

$$e'_g = -.0061 \text{ volts}$$

for the special case where $\mu = 20$, $E_o = .100$ volts rms, $r_p = 7{,}000$ ohms, $R = 30{,}000$ ohms, $e_c = -9.0$ volts d-c and $E_{bb} = +230$ volts. The tube is assumed to be vibrating in the frequency spectrum between 980 and 2460 cps with an amplitude of .008 inches.

This provides an equivalent generator in the equivalent circuit equal to $-20\ (e_g - .0061)$.

To determine the waveform and amplitude of a total output voltage across the load resistor in an actual case where e_g is some known a-c voltage applied to the grid, it becomes necessary to make an analysis of the complex wave which will have many terms depending on the difference in frequency and phase shift between the mechanical vibration frequency and the frequency of e_g. Also of significance is the ratio of the portion of the output wave form which is from the vibration action compared to the voltage which is applied signal.

To investigate wave form and amplitude of the resulting output voltage when the tube is vibrating at one frequency and generating voltage at that frequency and being driven electrically at another frequency, Chaffee[19] presents a method of analysis.

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(19) Chaffee, E. L. A Simple Harmonic Analysis Rev. Sci. Inst., V. 7, p. 384, October 1936

After Chaffee[20] the space-charge-limited plate current of a triode section is given by

$$I_p = \frac{2.336 \times 10^{-6}\, A}{d^2} \left(\frac{E_g + DE_p}{1 + D} \right)^{3/2}$$

where: $D = \frac{1}{\mu}$

and: $\mu = \dfrac{2\pi nb}{\log_e \frac{1}{2\pi NR}} = \frac{b}{K}$

E_g = grid-cathode voltage

E_p = plate-cathode voltage

b = grid-plate distance

d = grid-cathode distance

R = radius of grid wires

n = number of grid wires per unit length

A = area of effective cathode surface

which in the practical case becomes:

$$I_p = \frac{C}{d^2} \quad E_g + \frac{KE_p}{b} \quad {}^{3/2} \qquad \text{where } C = 2.336 \times 10^{-6}\, A$$

This equation states that the plate current is some function of E_g, d and b if E_p, n, R and A are constants for a given triode. To account for small variations in E_g, d and b when the tube is in vibration, let $E_g = E_g + \Delta E_g$, $d = d + \Delta d$ and $b = b + \Delta b$ at some instant of time, where E_g, d and b are quiescent values and ΔE_g, Δd and Δb are instantaneous magnitudes of variation from these quiescent values. The plate

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(20) Chaffee, E. L., Theory of Thermionic Vacuum Tubes N. Y., McGraw-Hill 1933 pp. 147 eq. 114

current then becomes a function of the following form:

$$I_p = F\,(E_g + \Delta E_g,\ d + \Delta d,\ b + \Delta b)$$

A second order Taylor's series expansion can be made of this function and has the form:

$$I_p = f(E_g,d,b) + \Delta E_g \frac{\partial f}{\partial E_g} + \Delta d \frac{\partial f}{\partial d} + \Delta b \frac{\partial f}{\partial b}$$

$$+ \frac{1}{2!}\Bigg[(\Delta E_g)^2 \frac{\partial^2 f}{\partial E_g^2} + (\Delta d)^2 \frac{\partial^2 f}{\partial d^2} + (\Delta b)^2 \frac{\partial^2 f}{\partial b^2}$$

$$+ 2\,\Delta E_g \Delta d \frac{\partial^2 f}{\partial E_g \partial d} + 2\,\Delta E_g \Delta b \frac{\partial^2 f}{\partial E_g \partial b}$$

$$+ 2\,\Delta b \Delta d \frac{\partial^2 f}{\partial d \partial b}\Bigg]$$

Solving this expression for plate current after Wenzel and Waynick(21) where an incremental amount of plate current variation ΔI_p caused by the tube being mechanically vibrated at one frequency f_m and being electrically driven by another f_g is present, The variation in plate current ΔI_p can be expressed for the voltage generated in the grid-cathode circuit as:

$$\Delta I_p = K_m C_m \sin \omega_m t - K_{mm} C_m^2 \cos 2\,\omega_m t$$

$$+ K_g C_g \sin \omega_g t - K_{gg} C_g^2 \cos 2\,\omega_g t$$

$$+ K_{mg} C_m C_g \cos (\omega_m - \omega_g)t$$

$$- K_{mg} C_m C_g \cos (\omega_m + \omega_g)t$$

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(21) Wenzel, J. A. and Waynick, A. H., Microphonism in the Dynamically Operated Planar Triode, Proc. I.R.E., V. 38, p. 527 (1950)

This is assuming both mechanical motion and electrical voltages on the grid are sinusoidal and the variations of the grid-cathode spacing is $\Delta d = C_g \sin \omega_g t$. K_m, C_m, K_{mm}, K_{gg}, C_{mg}, and K_{mg} are constants.

The above expression indicates the presence of sums and differences of two frequency components which are called the intermodulation frequencies.

To experimentally observe the behavior predicted above, a phase shift circuit of a conventional kind was constructed, using the mechanical driving voltage as a reference, and the output from it was used to drive the grid of the tube electrically. By changing the phase of the grid voltage the amplitude of the output waveform could be adjusted as would be expected. Another oscillator was then used to drive the grid at frequencies independent of the vibration frequency and this produced distorted waveforms which could have been analyzed by a wave-analyzer for harmonic components of the fundamental wave taken as reference. The above tests were performed at approximately 1500 cps because the particular tube selected had a high resonant output at that frequency. The output of the internally generated voltage was adjusted to be a perfect sine wave so it could readily be compared by inspection to the sine wave voltage which was feeding the grid.

Occasionally during the course of the work the elements inside the tube were noted to vibrate audibly and without exception this would present a distorted waveform of internally generated voltage indicating the element was being moved within the mica supports rather than the element itself supplying all the motion. This type of operation would doubtless present much more wear to the mica supports and would result in physical failure of the tube as well as an electrical failure.

Another interesting observation can be made by noting the curve of Fig. 22 which compares the internally generated voltages in the two sections of the tube. It can be seen that the two curves are similar in form but are slightly shifted apart with one having smaller amplitude. One possible explanation is that one of the elements is resonant at the particular frequency and through sympathetic vibration is causing the other section to vibrate but at a reduced amplitude.

CONCLUSIONS

The application of the Kelvin method of detecting the flow of charging currents proved to be successful and by use of this method the generated voltage characteristics of given vacuum tubes were determined as they were subjected to various frequencies of mechanical vibration.

This method of testing for internally generated voltage in vacuum tubes under mechanical vibration gave results for the 6SN7-GTA which show that a region of frequencies between 980 and 2460 cps possess the major resonant frequencies of the tube structure. At these frequencies the tube provides its largest output of internally generated voltage.

The shape of the internally generated voltage versus frequency curves for the tubes when operated with horizontal vibration and vertical vibration appeared so nearly the same that they were combined into a single mean curve. In the region of highest output the tube type in general produces .100 rms volts of output voltage when vibrated at .008 inches of vibration amplitude.

The effect of various values of grid voltage bias on the amplitude of the internally generated voltage was observed and it was found that for values of zero bias there was a definite amount of internally generated voltage and it is suggested that this voltage was contributed to the variation in spacing between the grid and plate. Charging currents were assumed not to flow in the grid-cathode region because the voltage between them is zero. The region between the $e_c = 0$ and $e_c = -6$ values show that for the particular tube under test there was a linear increase in output of internal voltage. It was noted that no output of internal voltage could be observed in the absence of d-c current flowing in the plate circuit. For the particular tube under test, the linear increase in output voltage with bias increase negatively, stopped being linear at exactly the same e_c voltage as where the g_m of the tube changed from a constant to a decreasing value toward zero. At the instant the g_m became zero the tube cut off and no internally generated voltage appeared in the plate circuit.

The magnitude of the internally generated voltage of the tube was observed to be a function of the grid bias, frequency of mechanical vibration, amplitude of mechanical vibration and value of plate supply and load circuit.

For given conditions of tube operation mechanically and electrically the internally generated voltage was shown placed into a constant voltage a-c equivalent circuit and the equivalent circuit then has use to circuit designers who would choose to include the generated voltage in a circuit design. The magnitude of the equivalent voltage caused by vibration is controlled by the circuit parameters above.

Mathmatical analysis of the effects of the tube vibrating at one frequency and being driven electrically at another, were shown by the method of Chaffee that sum and difference frequency terms should appear in the total output circuit of the tube. Distorted wave forms were observed but without wave analysis it can only be resumed that the distortion is that of intermodulation.

SUMMARY

It was definitely shown that vacuum tube structures have resonant mechanical frequencies and if the tube is operated within them, a voltage will be produced internally that appears in the output waveform of the circuit in which the tube is used.

To detect these wave-forms of voltage generated in the tube, apparatus was built to excite the vibration and by use of the Kelvin charging current method, the waveforms were detected and observed on the screen of the cathode ray oscilloscope. The waveform observed was compared to the waveform of the vibration platform motion and coincidence was seen to exist at all times except when audible vibration occurred inside the tube indicating the elements were moving within the mica supports.

The effects of variation of grid voltage were observed and it was found that increases in negative grid voltage caused increases in the amplitude of the output voltage up to the negative value of e_c where g_m became a variable approaching zero at tube cut-off.

For values of e_c more negative beyond this point the output voltage rapidly decayed to zero at cut-off much the same as did the value for g_m of the tube as taken from the dynamic transfer characteristic curve.

In no case did variation in grid bias cause a shift in resonance frequency of the mechanical structure of the tube and series resistance in the grid circuit were shown to have no effect on the output of internally generated voltage.

Finally the output voltage was calculated in terms of the amplification factor of the tube and the load resistance and placed into the a-c constant-voltage equivalent circuit. The output waveform was observed to possess a form of distortion, and by the mathematics of the spacing variations that cause the internally generated voltage and the input waveform of the grid driving voltage, this distortion is presumed to be of the intermodulation form caused by driving the grid at different frequencies while vibration frequency was held constant. The distorted output waveform was observed on the oscilloscope.

While the 6SN7-GTA was the tube selected on which to conduct this work because of its frequency of application, the method is perfectly general and can be extended to any desired tube type provided the circuit parameters of the associated circuitry are known so they may be duplicated under test. Since the internally generated voltages are a function of the mechanical vibration as well as the electrical constants, they too must be established for a specific tube test.

APPENDIX

The sample calculations and laboratory observed data to substantiate the presented curves in this manuscript appear in tabular form in this appendix.

TABULATED DATA FOR CALIBRATION CURVE OF FIG. 7

Input to power amplifier = 1.50 volts rms
Deflection sensitivity of scope = deflection/.0094" (p-p) platform motion

Frequency of Vibration (cycles per second)	Deflection of Platform (inches)
50	4.7×10^{-1}
65	2.8×10^{-1}
80	1.4×10^{-1}
90	1.1×10^{-1}
100	1.1×10^{-1}
125	4.4×10^{-2}
150	2.8×10^{-2}
200	1.0×10^{-2}
230	6.1×10^{-3}
240	9.4×10^{-3}
300	3.8×10^{-3}
350	2.1×10^{-3}
400	3.8×10^{-3}
500	1.6×10^{-3}
550	1.4×10^{-3}
600	1.3×10^{-3}
700	1.7×10^{-3}
800	1.2×10^{-3}
900	9.0×10^{-4}
1000	8.6×10^{-4}
1100	4.8×10^{-4}
1200	3.8×10^{-4}
1500	3.7×10^{-4}
2000	2.8×10^{-4}
2500	2.5×10^{-4}
3000	2.0×10^{-4}
4000	1.9×10^{-4}
5000	1.5×10^{-4}
6000	1.5×10^{-4}
6500	1.4×10^{-4}
7500	2.0×10^{-4}
8560	1.3×10^{-4}
9000	1.3×10^{-4}
10000	1.3×10^{-4}

TABULATED DATA FOR CALIBRATION CURVE OF FIG. 11

Input to preamp = .025 volts rms
Scope y-axis amplifier gain = maximum
Scope y-axis attenuation ratio = 1000:1

Scope amplitude of deflection (peak-peak measured in inches)	Frequency of rms driving voltage (cycles per second)
.62	30
.85	80
.75	50
.85	100
.85	150
.85	200
.70	300
.65	400
.55	500
.55	600
.50	700
.47	800
.46	900
.45	1000
.42	1.5K
.40	2K
.38	3K
.40	4K
.40	5K
.40	6K
.40	7K
.40	8K
.40	9K
.40	10K

TABULATED DATA FOR FIG. 24

Observed variations in generated voltage versus grid bias for sample no. 5, section 2, vibrating in horizontal plane at frequency of 4300 cps with .008 inches peak-to-peak amplitude.

Grid Bias (volts)	Generated rms volts in plate circuit
0.0	.012
-1.5	.015
-3.0	.018
-4.5	.022
-6.0	.025
-7.5	.025
-9.0	.023
-10.5	.010
-12.0 (cut off)	.000

TABULATED DATA FOR FIG. 25

Dynamic Transfer Characteristics for section 2 of sample 5 with B+ held constant by $E_{bb} = +220$ volts d-c.

Instantaneous Grid Bias (volts)	Instantaneous Plate Current (ma.)
0	4.900
-1.5	4.000
-3.0	3.100
-4.5	2.200
-6.0	1.500
-7.5	0.900
-9.0	0.030
-10.6	0.005
-12.0 (cut off)	0.000

TABULATED DATA FOR CALIBRATION CURVE OF FIG. 32

Drive voltage = .25 volts rms
Y-axis attenuation ratio = 10:1
Resultant deflection sensitivity = .125 rms volts/inch
Drive source: General Radio 1302-A Oscillator
Voltage monitor: Ballantine 304 Vacuum Tube Volt Meter

Drive Voltage Frequency (cycles per second)	Scope Deflection (inches)
30	2
35	2
40	2
45	2
50	2
55	2
60	2
70	2
80	2
90	2
100	2
150	2
200	2
250	2
300	2
350	2
400	2
500	2
600	2
700	2
800	2
900	2
1000	2
1500	2
2000	2
2500	2
3000	2
3500	2
4000	2
5000	2
6000	2
7000	2
8000	2
9000	2
10000	2

SAMPLE DATA SHEET

Tube Type 6SN7-GTA Section Number 1 Sample Number 1

Tube Manufacturer Sylvania Plane of Vibration Horizontal

Amplitude of vibration .008 inches Plate Voltage + 230 V.D.C.

Grid Bias -9.0 V. D. C. Voltage Generated in plate circuit

Frequency of Vibration	Generated Voltage (rms volts)	Frequency of Vibration	Generated Voltage (rms volts)
200	.000	6000	.030
250	.000	7000	.025
300	.000	8000	.010
350	.000	9000	.000
400	.025	10000	.000
530	.025		
540	.031		
550	.018		
560	.020		
600	.020		
630	.010		
660	.000		
700	.010		
730	.020		
750	.010		
800	.012		
850	.025		
900	.020		
950	.020		
1000	.063		
1100	.025		
1200	.062		
1300	.137		
1350	.162		
1400	.087		
1450	.063		
1500	.060		
1600	.060		
1700	.050		
1800	.100		
2000	.250		
2200	.112		
2400	.037		
2500	.237		
2700	.037		
3300	.113		
3800	.125		
4200	.100		
4500	.089		
5000	.050		

SAMPLE DATA SHEET

Tube Type 6SN7-GTA Section Number 1 Sample Number 1

Tube Manufacturer Sylvania Plane of Vibration Vertical

Amplitude of vibration .008 inches Plate Voltage + 230 V. D. C.

Grid Bias -9 V. D. C. Voltage Generated in plate circuit

Frequency of Vibration	Generated Voltage (rms volts)	Frequency of Vibration	Generated voltage (rms volts)
200	.000	6000	.025
250	.000	7000	.010
300	.000	8000	.020
350	.000	9000	.000
400	.000	10000	.000
530	.000		
540	.000		
550	.000		
560	.000		
600	.000		
630	.000		
660	.000		
700	.000		
730	.000		
750	.000		
800	.000		
850	.020		
900	.020		
950	.020		
1000	.050		
1100	.030		
1200	.062		
1300	.137		
1350	.150		
1400	.162		
1450	.187		
1500	.175		
1600	.275		
1700	.300		
1800	.100		
2000	.150		
2200	.110		
2400	.112		
2500	.040		
2700	.112		
3300	.150		
3800	.100		
4200	.038		
4500	.075		
5000	.059		

SAMPLE DATA SHEET

Tube Type 6SN7-GTA Section Number 2 Sample Number 1

Tube Manufacturer Sylvania Plane of Vibration Vertical

Amplitude of Vibration .008 inches Plate Voltage + 230 V.D.C.

Grid Bias -9.0 V.D.C. Voltage Generated in plate circuit

Frequency of Vibration	Generated Voltage (rms Volts)	Frequency of Vibration	Generated Voltage (rms Volts)
200	.000	6000	.020
250	.000	7000	.010
300	.000	8000	.020
350	.000	9000	.000
400	.000	10000	.062
530	.000		
540	.000		
550	.010		
560	.000		
600	.020		
630	.010		
660	.000		
700	.000		
730	.000		
750	.000		
800	.010		
850	.000		
900	.000		
950	.000		
1000	.020		
1100	.020		
1200	.125		
1300	.050		
1350	.062		
1400	.062		
1450	.087		
1500	.063		
1600	.040		
1700	.040		
1800	.062		
2000	.050		
2200	.090		
2400	.265		
2500	.030		
2700	.025		
3300	.100		
3800	.087		
4200	.038		
4500	.100		
5000	.050		

SAMPLE DATA SHEET

Tube Type 6SN7-GTA Section Number 2 Sample Number 1

Tube Manufacturer Sylvania Plane of Vibration horizontal

Amplitude of Vibration .008 inches Plate Voltage + 230 V.D.C.

Grid Bias -9.0 V.D.C. Voltage Generated in plate circuit

Frequency of Vibration	Generated Voltage (rms volts)	Frequency of Vibration	Generated Voltage (rms volts)
200	.000	6000	.010
250	.000	7000	.000
300	.000	8000	.000
350	.000	9000	.000
400	.010	10000	.060
530	.020		
540	.025		
550	.020		
560	.023		
600	.021		
630	.050		
660	.000		
700	.000		
730	.000		
750	.000		
800	.000		
850	.000		
900	.000		
950	.000		
1000	.000		
1100	.000		
1200	.025		
1300	.062		
1350	.060		
1400	.037		
1450	.040		
1500	.020		
1600	.020		
1700	.030		
1800	.090		
2000	.020		
2200	.060		
2400	.200		
2500	.040		
2700	.030		
3300	.036		
3800	.036		
4200	.090		
4500	.100		
5000	.062		

BIBLIOGRAPHIES

Alpert, N. Microphonics Tester for Vacuum Tubes
Electronics, V. 23, No. 3, pp 70 - 9 (1950)

Anonymous, Electronics at Work, Electronics, V. 28, No. 2, p. 185 (1955)

Boast, W. B., Principles of Electric and Magnetic Fields
N. Y. Harper and Brothers, 1948, pp 109-113

Chaffee, E. L. A Simple Harmonic Analysis
Rev. Sci. Inst., V. 7, p. 384, October 1936

Chaffee, E. L., Theory of Thermionic Vacuum Tubes
N. Y., McGraw-Hill, 1933, pp 147, eq. 114

Eaglesfield, C. C. Vibration Tests for Valves,
Wireless Engineer, V. 30, No. 3, pp 57 - 60 (1953)

Evaluation of Mechanical Design Level of Electronic Equipment Leading to Vibration and Shock Design Criteria. Wright Air Development Center Contract No. AF 33(616) - 223, ARF Project Number K044-1.

Langford and Smith, Radiotron Designer's Handbook
N. Y., Radio Corporation of America, 1953, Section 19, pp 1408 - 18

Mintz, F. and Levine, M. B., Testing of Airborne Electronic Components. Electronics V. 28, No. 3, pp 181-84 (1955)

Rothstein, J. Microphonic Electron Tube
U. S. Pat. 2,389,935, Nov. 27, 1945

Ryder, J. D., Electronic Fundamentals and Applications.
N. Y. Prentice-Hall, 1950, pp 174 - 176

Smith, L. F., Radiotron Designers Handbook, Sydney, Australia, The Wireless Press, 1942.

Stubner, F. W. Acceleration Effects on Electron Tubes
Bell System Tech. Jour., V. 32, No. 5, pp 1203 - 29 (1953)

Waynick, A. H. Reduction of Microphonics in Triodes
Jour. of Appl. Phys., V. 8, No. 2, pp 239 - 45 (1947)

Wenzel, J. A. and Waynick, A. H., Microphonism in the Dynamically Operated Planar Triode, Proc. I.R.E., V. 38, p. 527 (1950)

Wenzel, J. A. and Waynick, A. H. Microphonism in the Dynamically Operated Planar Triode, I. R. E., V. 38, No. 5, pp 524 - 32 (1950)

Young, J. R. A Method of Measuring the Screen Potential of Cathode Ray Tubes Memo Report No. EC-18, Electron Physics Research Laboratory, The Knolls, New York (1952)

Young, J. R. A Versatile Electrostatic Voltmeter R. L. Report No. 898, Electron Physics Research Laboratory, The Knolls, New York (1953)

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