USE OF AN ELECTRICAL MODEL IN THE INVESTIGATION OF COUPLING BETWEEN THE EARTH AND AN ELECTROMAGNETIC VIBRATOR

By

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USE OF AN ELECTRICAL MODEL IN THE INVESTIGATION

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PREFACE

As research engineer with the Exploration Research Division of Continental Oil Company, I was assigned as project engineer in the application of analog model techniques developing the design of an improved electromagnetic vibrator with a capability of increased energy output at higher seismic frequencies. The principle developed and tested at that time has since been applied to later model hydraulic vibrators and has proved successful for some time.

I am indebted to many people who helped in the project through constructive participation. Among fellow engineers, I would particularly like to thank Graydon Brown, Langdon Berryman, Delbert Fair, and Jim Cole for their interest and encouragement. For many long hours in accumulating data from various tests, I would like to give credit to Doyle Schaal and R. L. Pitman. For equally long hours in converting a truly rough draft into a final professional thesis, I would like to thank Nancy Edmondson, with Ruby Ashworth assisting. For permission to use the material contained in this thesis, I am grateful to Continental Oil Company and, in particular, to John M. Crawford and W. E. N. Doty of the Research Laboratories. I would also like to thank Tom Sigler and Bob Whittenburg of Continental Pipe Line Company for many considerations which made the completion of this work possible. In particular, indebtedness is acknowledged to Dr. H. L. Jones for his patient encouragement, not only during the writing of this thesis, but throughout my career in the graduate school of Oklahoma State University.

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CHAPTER I

INTRODUCTION

In the course of development of techniques for the VIBROSEIS[1] method of exploration for oil, it was decided to make a more thorough investigation of the coupling between the earth and the energy source, the vibrator. It was hoped that such a study would indicate a more efficient means for energy transfer between the two. Initial assumptions as to the earth itself, looking at the earth from the vibrator source, considered it as a distributed spring-mass system perhaps similar to a long transmission line and exhibiting similar characteristics. Maximum energy transfer, then, would dictate an impedance match between vibrator source and the earth.

It was further desired to increase the energy transfer at the higher seismic frequencies. This would result in greater ability to resolve small geological features which might be of interest as oil-bearing traps. It was

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[1]VIBROSEIS is a patented process of Continental Oil Company, Ponca City, Oklahoma.

also known that high attenuation, compared to that at lower frequencies, resulted in the passage of such frequencies through the earth.

In addition, it was desirable to investigate the field worthiness of high thrust electromagnetic vibrators which were just then making an appearance on the commercial market.

CHAPTER II

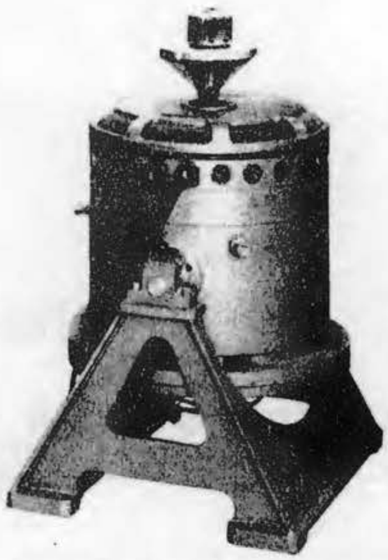
INITIAL GROUND INVESTIGATIONS

Initial investigations were carried out using an electromagnetic vibrator manufactured by and purchased from the Savage Company of London, England. The vibrator is shown in Figure 1.

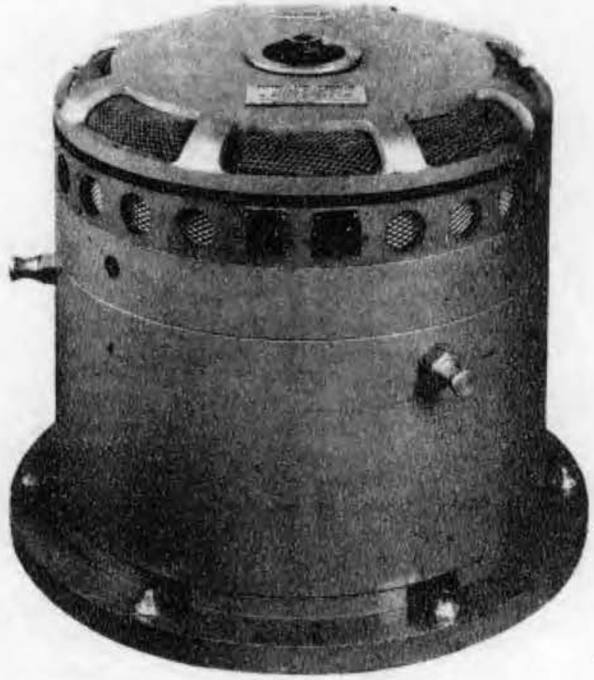
Equipment

The vibrator was powered by a one-kilowatt audio amplifier which was also purchased from the same company (Figure 2). The vibrator and power amplifier were truck mounted, with associated gasoline driven A.C. and D.C. generators, which supplied field excitation for the vibrator and 220 volts, A.C., 60-cycle power for the amplifier. Specifications of the vibrator and the amplifier are contained in the appendix.

The vibrator design was similar in construction to the old-type externally excited audio speaker (Figure 3). Its natural resonance was about 30 cycles per second prior to the addition of a 60-pound reaction mass attached directly to the coil former. Addition of this extra mass reduced the resonance to twelve cycles per second and brought about a need



V1000 WITH TRUNNION MOUNT
AND 8" DIA. TABLE



V1000B — 750 lb. thrust VIBRATORS

Figure 1. Savage Electromagnetic Vibrator

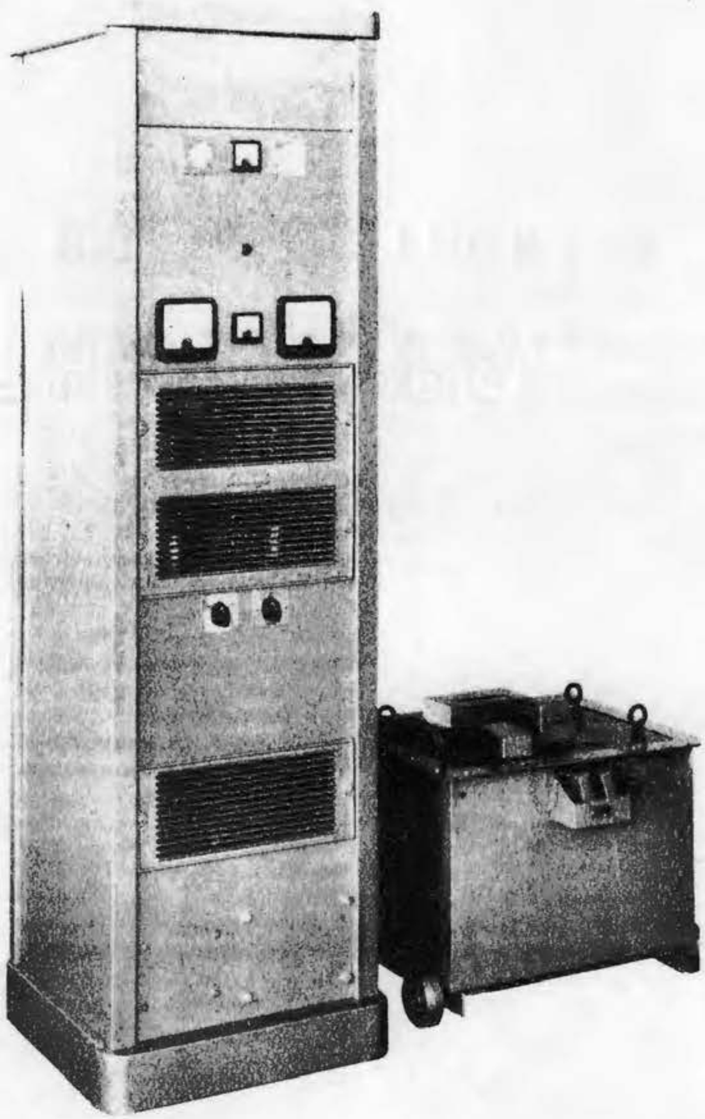


Figure 2. Vibrator Power Amplifier (1000 Watt) and Output Transformer

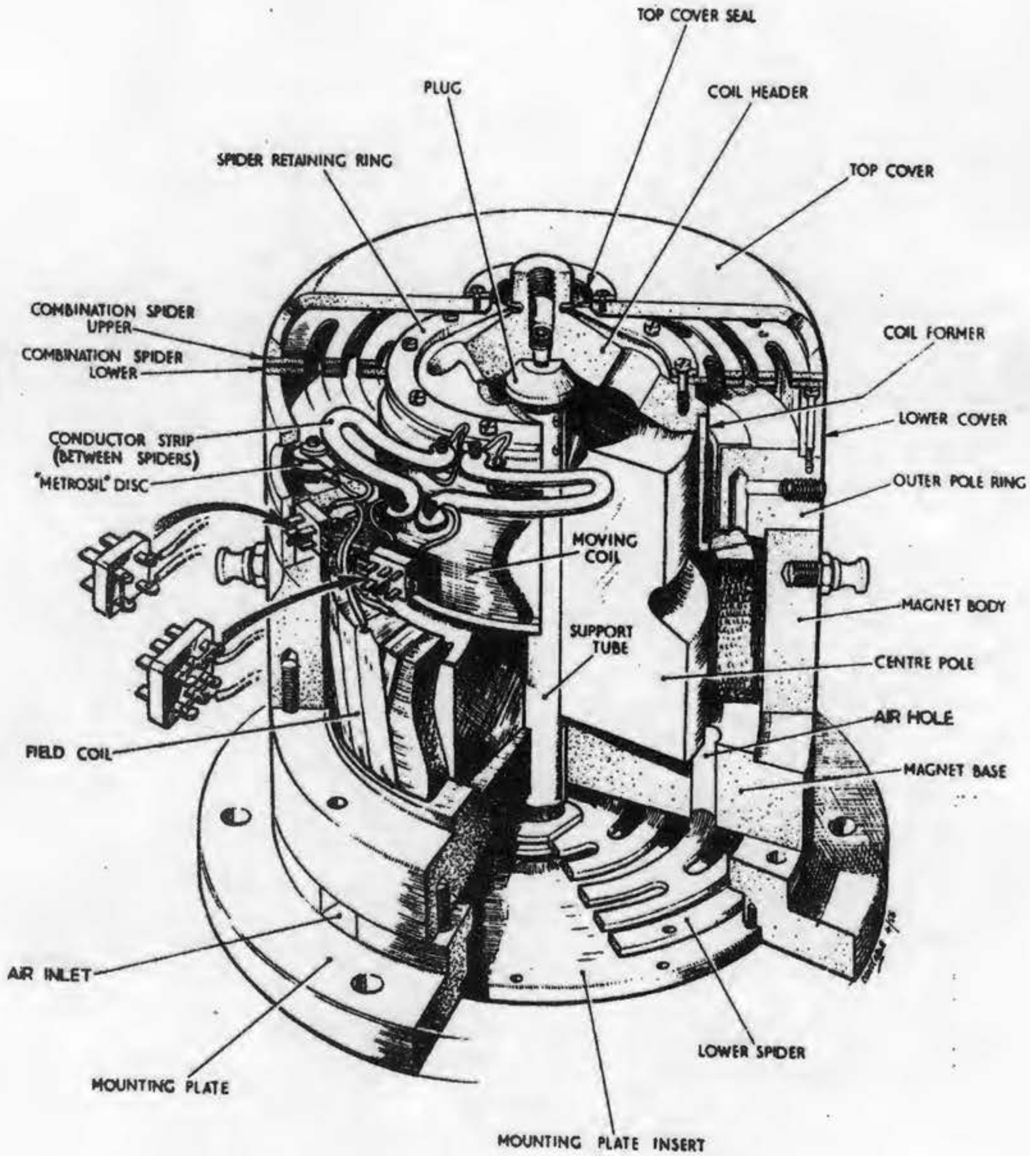


Figure 3. Break-away Drawing of Vibrator Showing Internal Structure

for recentering the coil in the air gap. An additional spring was positioned between the reaction mass and the top surface of the vibrator to recenter the coil. This caused an upward shift in resonance again to 16 cycles per second. This spring was initially a small innertube inflated to sufficient pressure to recenter the coil in the air gap. The addition of another 40-pound (weight) mass again reduced the resonance to about twelve cycles after recentering with the improvised innertube spring. This was the finalized arrangement used in subsequent tests. The total vibrator weight was increased to about 1,200 pounds, with the addition of a steel baseplate attached to the base of the vibrator.

The vibrator exhibited a constant load to the driving amplifier except around the resonant frequency; so the force developed was essentially constant and equal to the equation, F = BLNI, where I was constant except around resonance. This, of course, is the force which is developed across the 100-pound mass, as well as across the base of the vibrator and therefore applied to the earth itself. Actually, we came to speak of the force seen at the 100-pound mass as the reaction force. Figure 4 shows characteristic force versus frequency curves for various-sized reaction masses. The frequency response of the power amplified, loaded with a ten-ohm resistance, is also displayed. Note that its response is essentially flat

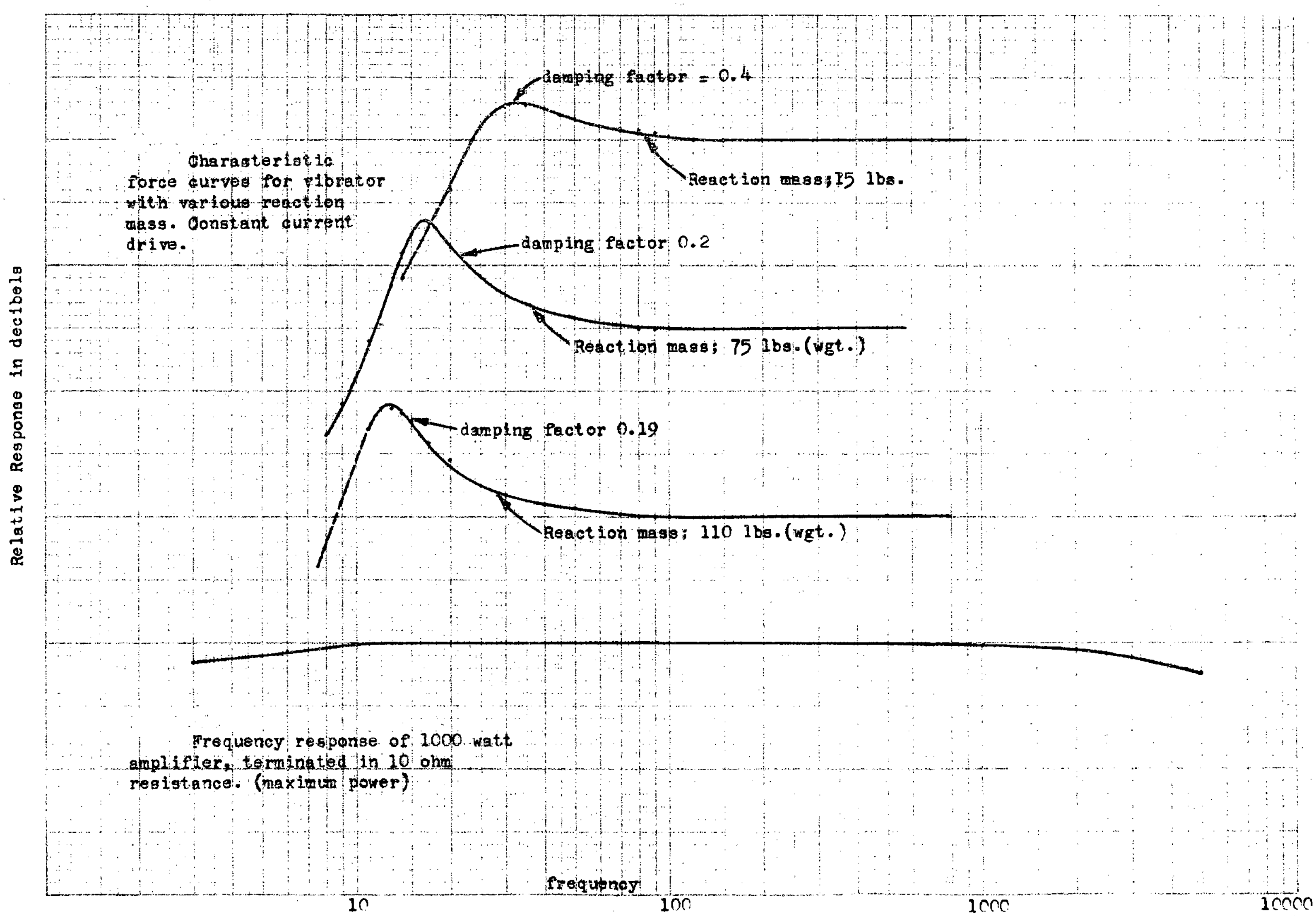


Figure 4. Characteristic Force Curves of Vibrator and Frequency Response of Amplifier

between the limits of two cycles per second to five kilocycles per second.

Initial Investigations

A series of tests were undertaken in an attempt to determine the nature of the motion imparted to the ground by the electromagnetic vibrator. A velocity pickup was attached directly to the baseplate of the vibrator itself, and readings of velocity were observed at this point. The force on the reaction mass was also monitored and was found to remain as in Figure 4. A Hewlitt-Packard oscillator was used as an input to the power amplifier, and the vibrator was driven with a constant current input over the range of 15 to 400 cycles. Drive was essentially constant current except again around resonance of the reaction mass.

First observations were made of displacement, velocity and acceleration of the baseplate in an area known as Peter's Corners, Oklahoma. Results of these first tests are shown in Figure 5. A rather sharp resonance appeared around 35 cycles per second; and it was observed that the acceleration or force curve approached a zero slope at higher frequencies, while the velocity curve approached a six db per octave slope in the same region.

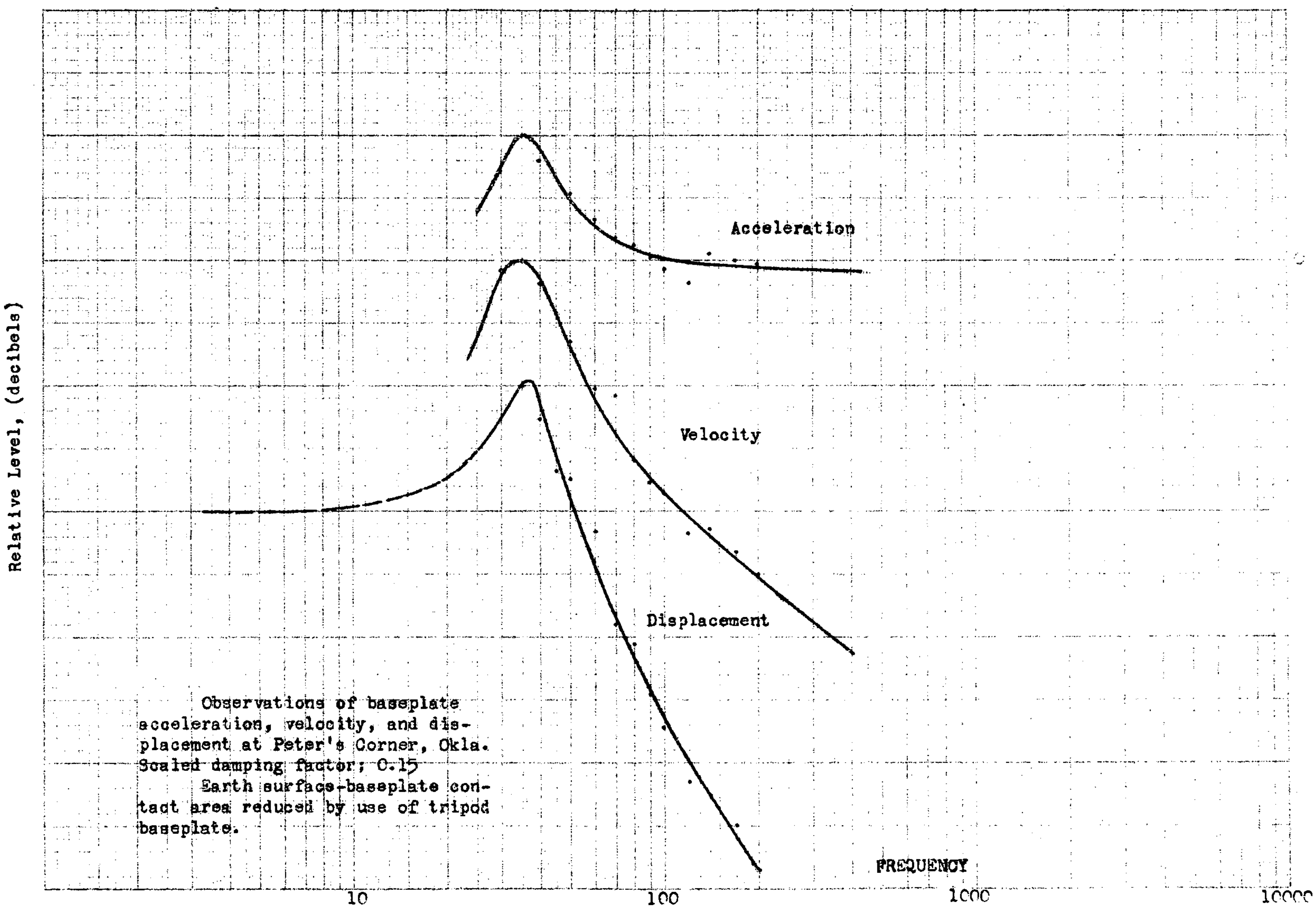


Figure 5. Baseplate Observations at Peter's Corners, Oklahoma

The rather sharp baseplate resonance was unexpected, and further investigations were initiated at a second site in Ponca City to see if the same effect would be present or whether the sharp resonance was characteristic of the Peter's Corners area only. The results of the Ponca City test as seen in Figure 6 were similar. Again, a sharp resonance at about 35 cycles per second was observed on both acceleration and displacement curves. The question arose as to whether ground motion itself was of a similar nature. To investigate this, a seisphone was buried about two feet below the baseplate of the vibrator at the Ponca City site; and a second jug (seisphone) was also placed on the surface about five feet from the baseplate. The tests were then rerun. Both seisphones had their own natural resonance at about 17 cycles per second. Figure 7 shows the velocity curves obtained at the baseplate and from the surface seisphone. It was again observed that a resonance around 35 cycles existed, and an attempt to approximate a six db per octave slope was apparent on either curve. The notch at about 150 cycles in the curve from the surface seisphone was assumed to be due to the arrival of an out-of-phase surface wave. Results of the buried seisphone were not obtained at this time, as trouble developed in the phone, and it had to be dug up and sent to the laboratory for repairs.

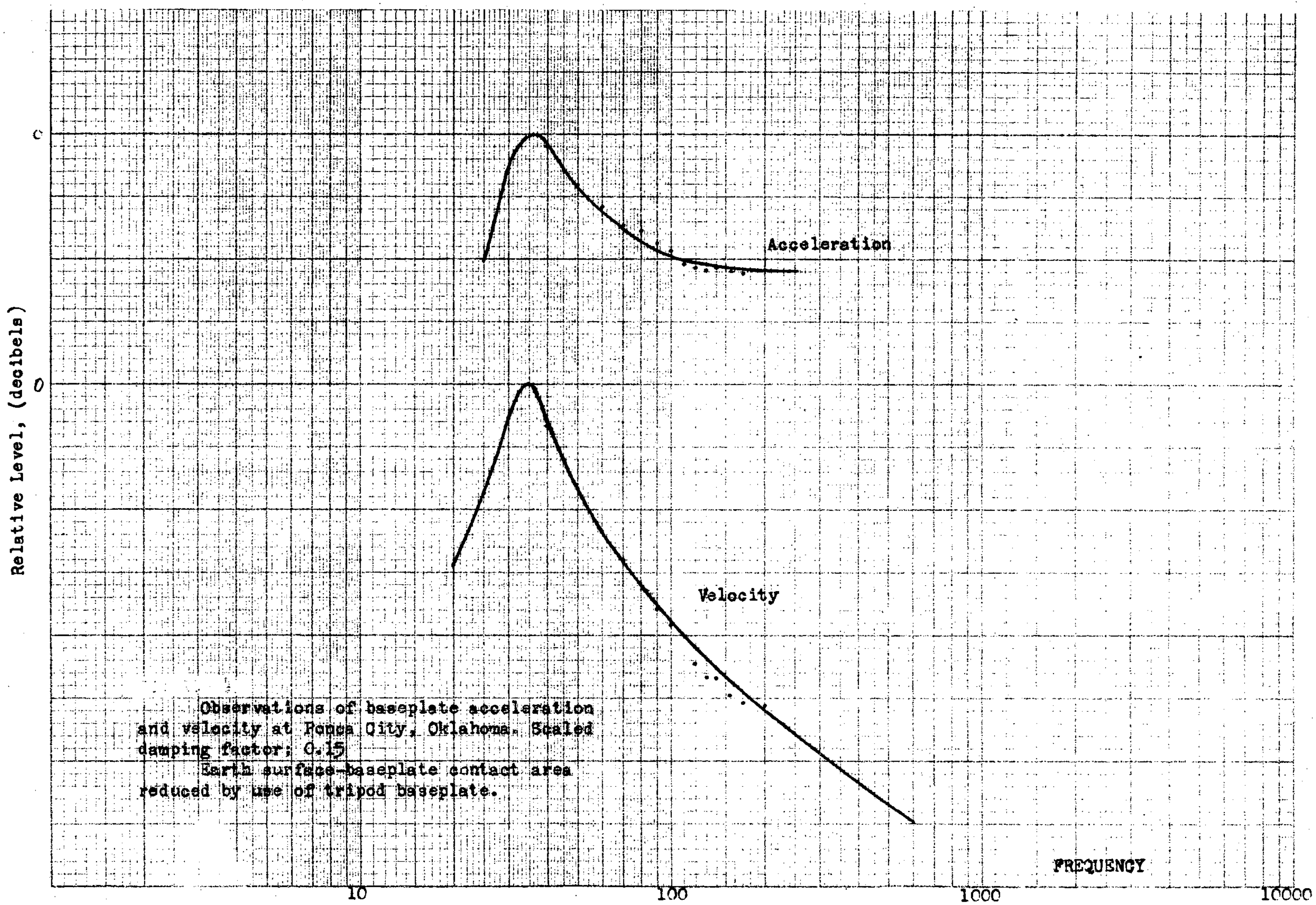


Figure 6. Baseplate Observations at Ponca City, Oklahoma

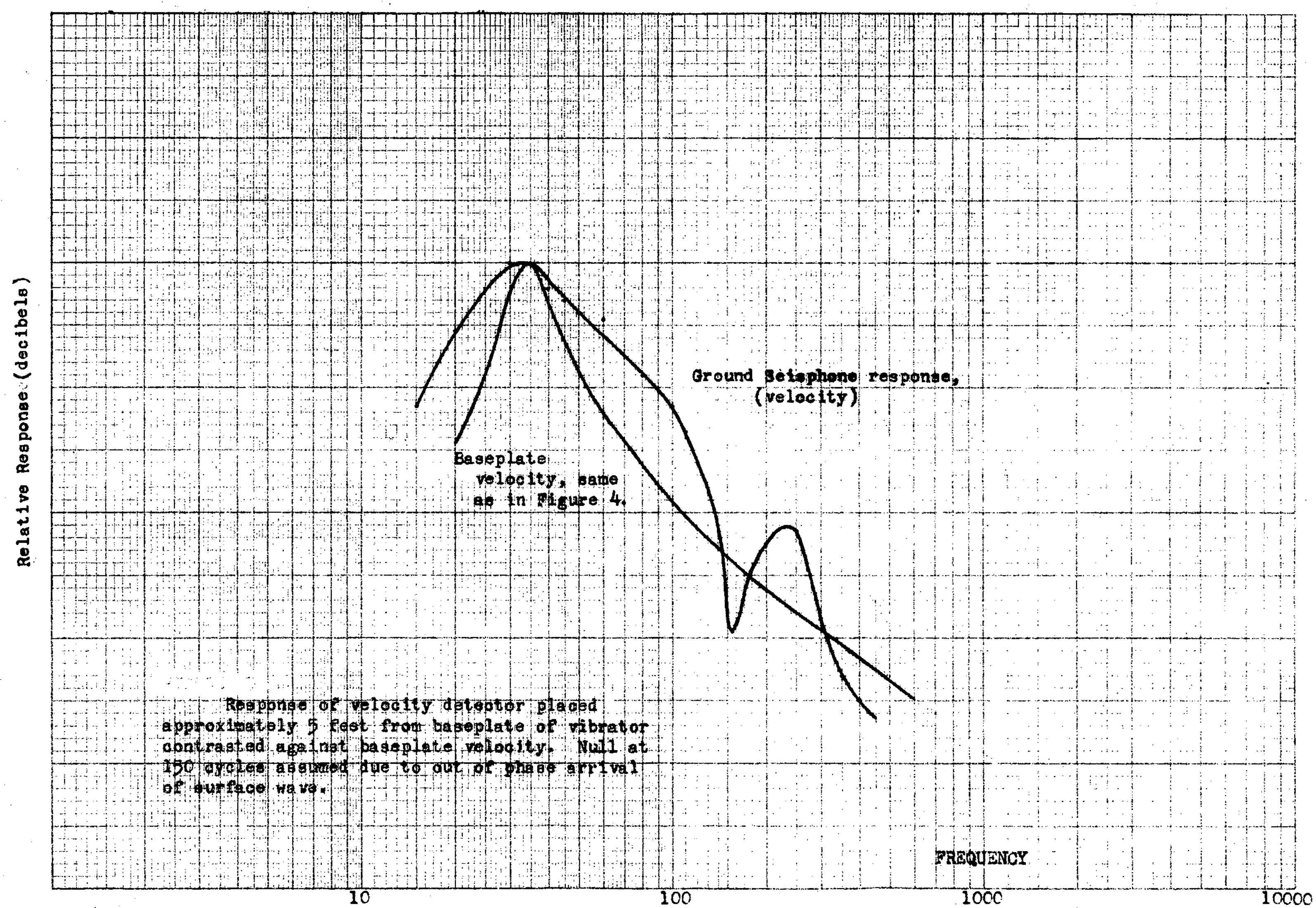


Figure 7. Baseplate Versus Surface Velocity Curves

During the following evening, a hard freeze with temperatures in the neighborhood of zero to ten degrees Fahrenheit arrived in Ponca City. When tests were resumed the following day (ambient temperature about 10°F.), it was observed that the resonant point of the baseplate and ground velocities had shifted upward to about 45 cycles per second as shown in Figure 8 (ground velocity was monitored through the buried seisphone). Since the position occupied by the vibrator was only five feet from that of the previous day, change in resonance was suspected of being related to some change in the earth. Temperature was immediately suspected. Apparently the stiffness of the ground had changed.[1] Further, the shape of the velocity curves obtained to date were now recognized to approximate those which could be expected from a very simple spring-mass system.

If such a simple system could approximate the earth system, then its resonance would be determined from the equation:

---

[1]One difference in the equipment did exist from the previous day's test. The tripod baseplate had been removed. This effectively had increased the contact area between the vibrator and the earth. Therefore, the possibility existed that this could have increased the stiffness of the earth and in a simple system would account for some increase in the natural period of resonance.

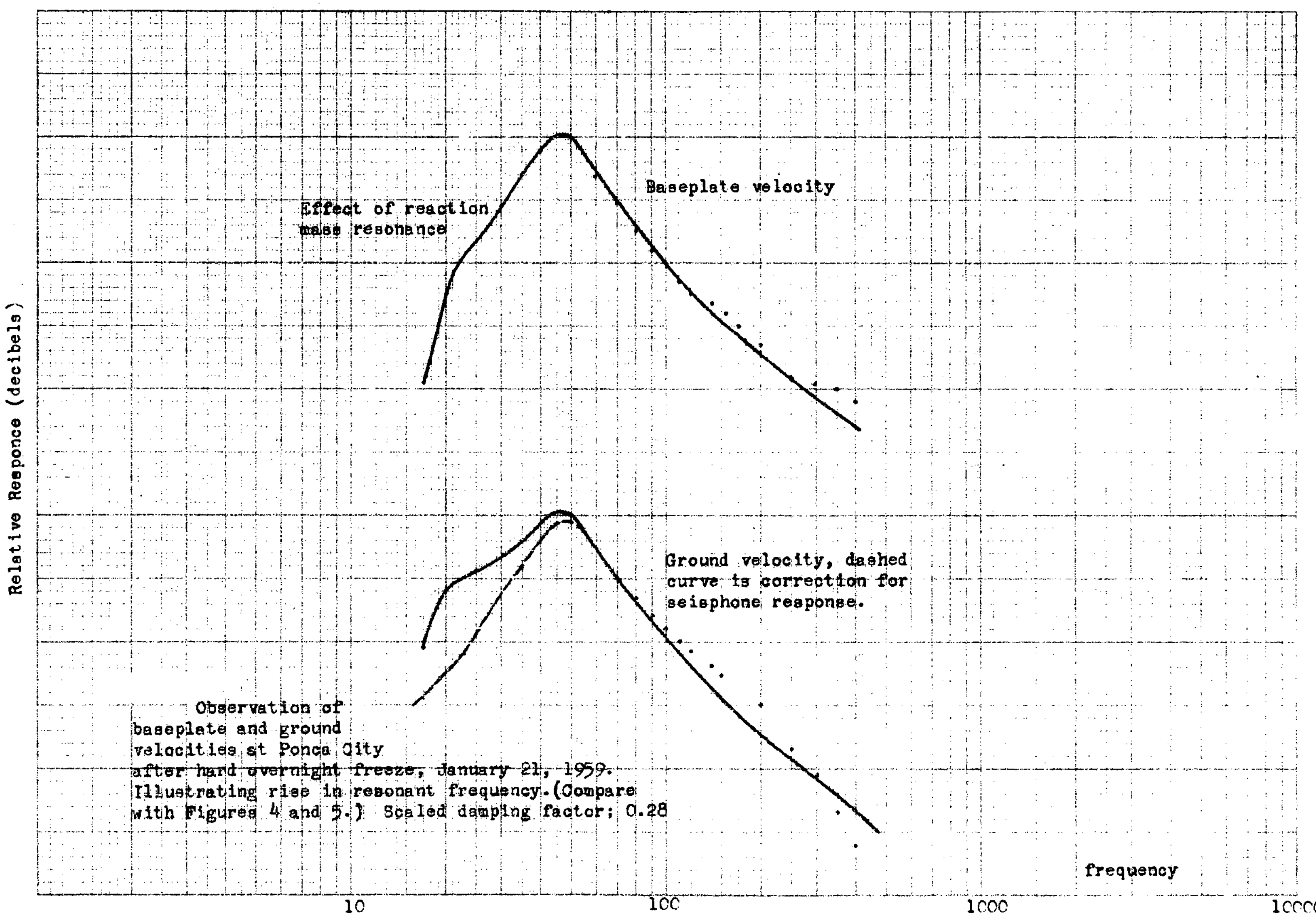


Figure 8. Effects of Freeze Upon Observed Baseplate and Ground Velocities

$$f'_{res} = \frac{1}{2\Pi} \cdot \sqrt{\frac{K_e}{M_e}}$$

where K_e is the spring constant of the earth in the near vicinity of the vibrator and M_e is the mass of the vibrator. Obviously, anything affecting these parameters would affect the resonant frequency. A freeze could therefore be expected to increase K_e and thus shift the resonant frequency upward as was observed. It was further reasoned that, if this were the case, then ground resonance might be controllable.

The simplest way to test this idea was by increasing the vibrator mass. In a first test, the mass was doubled by strapping large lead slugs to the sides of the vibrator. This effectively increased the mass without changing the baseplate area. The results are shown in Figure 9. The interesting point is that the frequency of resonance was shifted in a manner predictable from the simple relation:

$$f'_{res} = 0.707 f'_{res}, \text{ where } f'_{res} = \frac{1}{2\Pi} \cdot \sqrt{\frac{K_e}{M_e}}$$

In subsequent tests, mass was increased by placing large steel plates beneath the vibrator. It was impossible with the plates on hand, however, to maintain the same contact area between the baseplate and the ground; so there was no

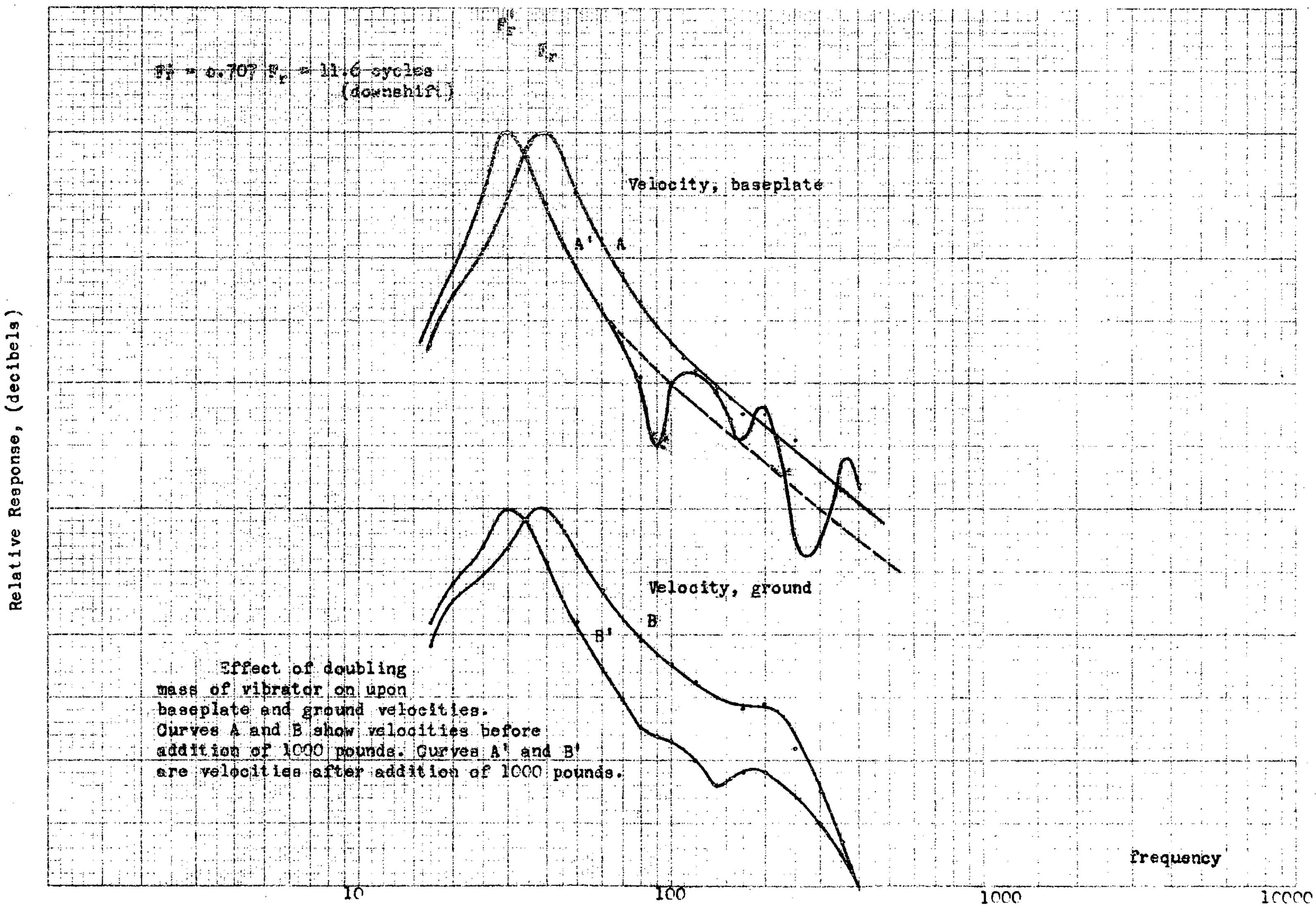


Figure 9. Curves Showing Effect of Doubling Vibrator Mass

correlation between these tests and the first test. Neither could intimate contact be assured between the plates themselves nor with the ground; and as a result, secondary (parasitic) resonances occurred. Figure 10 shows a plot of the resulting baseplate and ground velocities. Ignoring the effects of secondary resonances, the usual trend in the curves is apparent. However, since the spring constant of the earth is a function of the baseplate area in contact with the surface, prediction of results by the above simple relationship was impossible, because knowledge of the contact area was lacking. This information was lacking because of the irregularity of the surfaces of the slabs as well as the earth. Note, however, that an increase in damping factor, n, is apparent. This is as would be expected from the formula:

$$n = \frac{f_e}{2\sqrt{M_e K_e}}$$

An attempt was made to determine the relationship between baseplate area and ground resonance (or, inadvertently, the relation of area to K_e). A test was made in which the area of the baseplate was drastically reduced by the addition of three cylindrical feet about three inches in diameter to the baseplate. Figure 11 shows the result. Downshifting did occur, as was predicted, but not in proportion to the ratios of the contact areas. From this, it is reasoned that

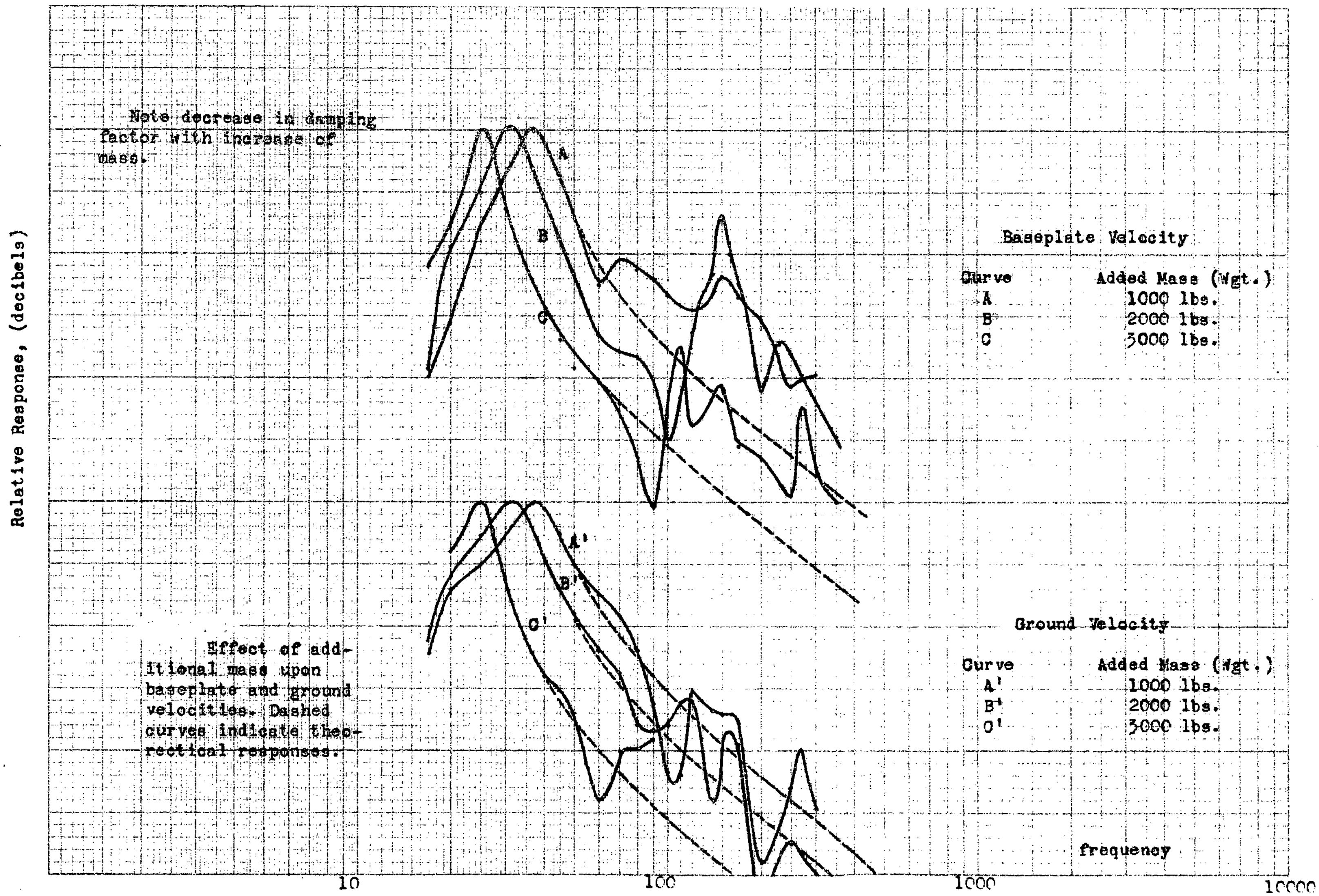


Figure 10. Effect of Vibrator Mass Upon Baseplate and Ground Velocities

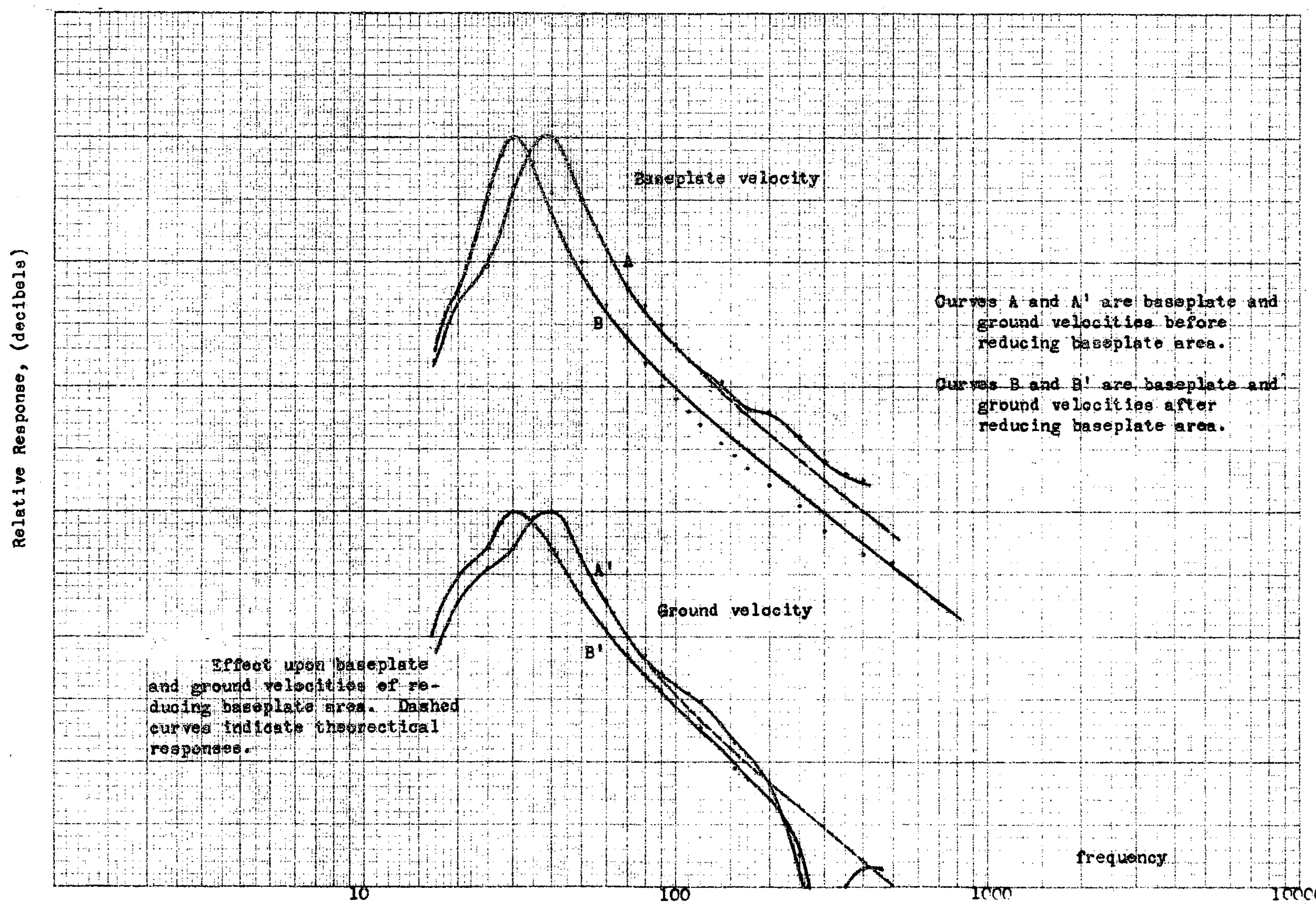


Figure 11. Effect of Baseplate Area Upon Resonance

an "effective" contact area must exist which was apparently not the area of the vibrator baseplate.[2] In other words, the earth's surface surrounding the baseplate contributes to the determination of the "effective" spring constant.

In another test, the spring constant of the ground was changed by placing a rubber mat beneath the vibrator. The results, as shown in Figure 12, again show the expected down-shift of resonance frequency.

In a final test, the effect of ground freeze upon resonance was observed, while the ground was experiencing a complete cycle through a hard freeze to a muddy thaw. Velocity measurements were made during the entire cycle with the vibrator in exactly the same position. The results are plotted in Figure 13.

Results of Initial Ground Tests

Throughout all tests, the most important observation was that the vibrator-earth system performed as though the earth exhibited the characteristics mainly of a simple spring. In addition, the tests produced the following results:

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[2]The overlay of points in the B and B' curves represents a check on the reproducibility of a velocity plot at particular surface position. The curves were initially run, and then the vibrator was lifted and repositioned as closely as possible in exactly the same spot. A second set of curves was then rerun.

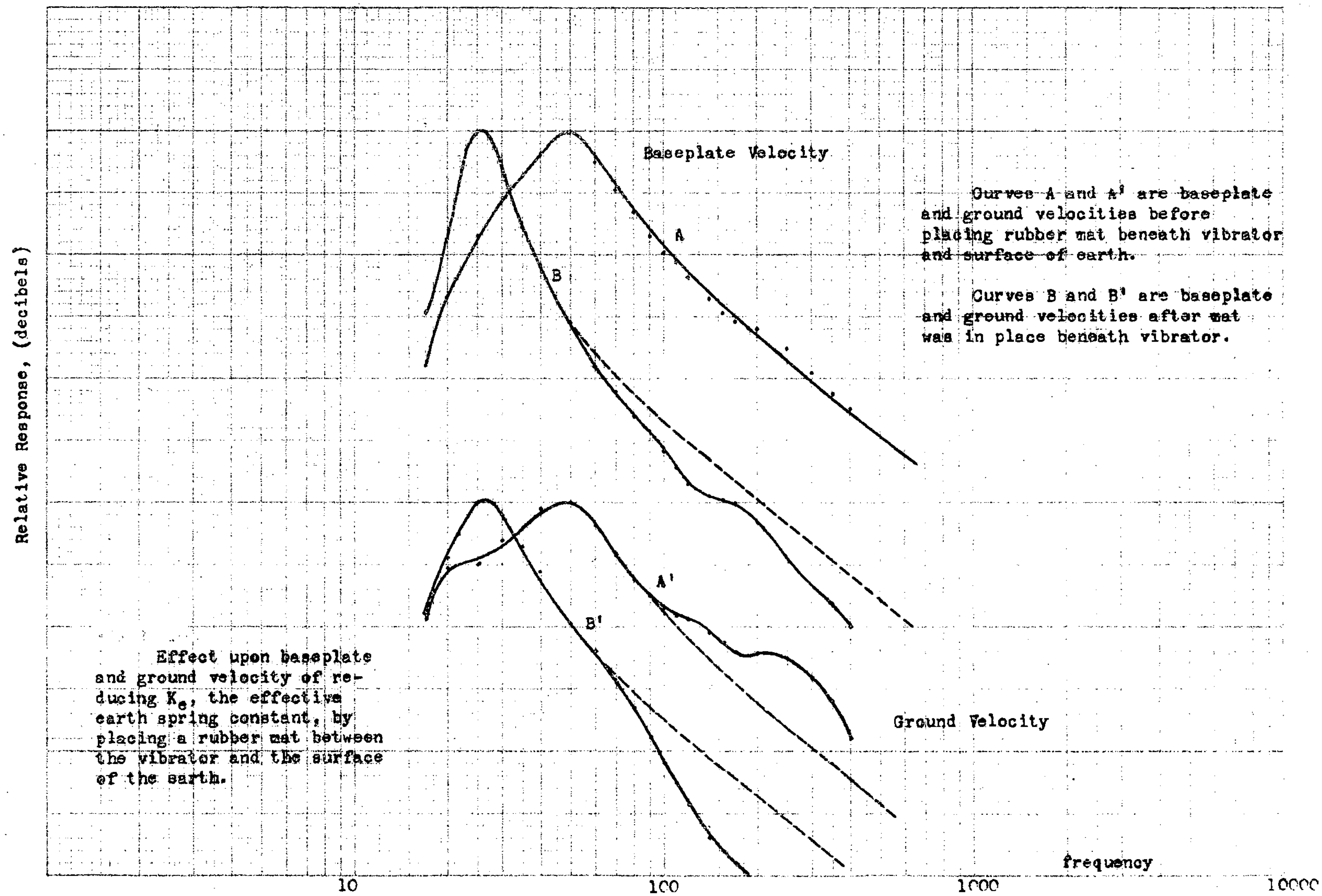

Figure 12. Results of Changing Effective Earth Spring Constant

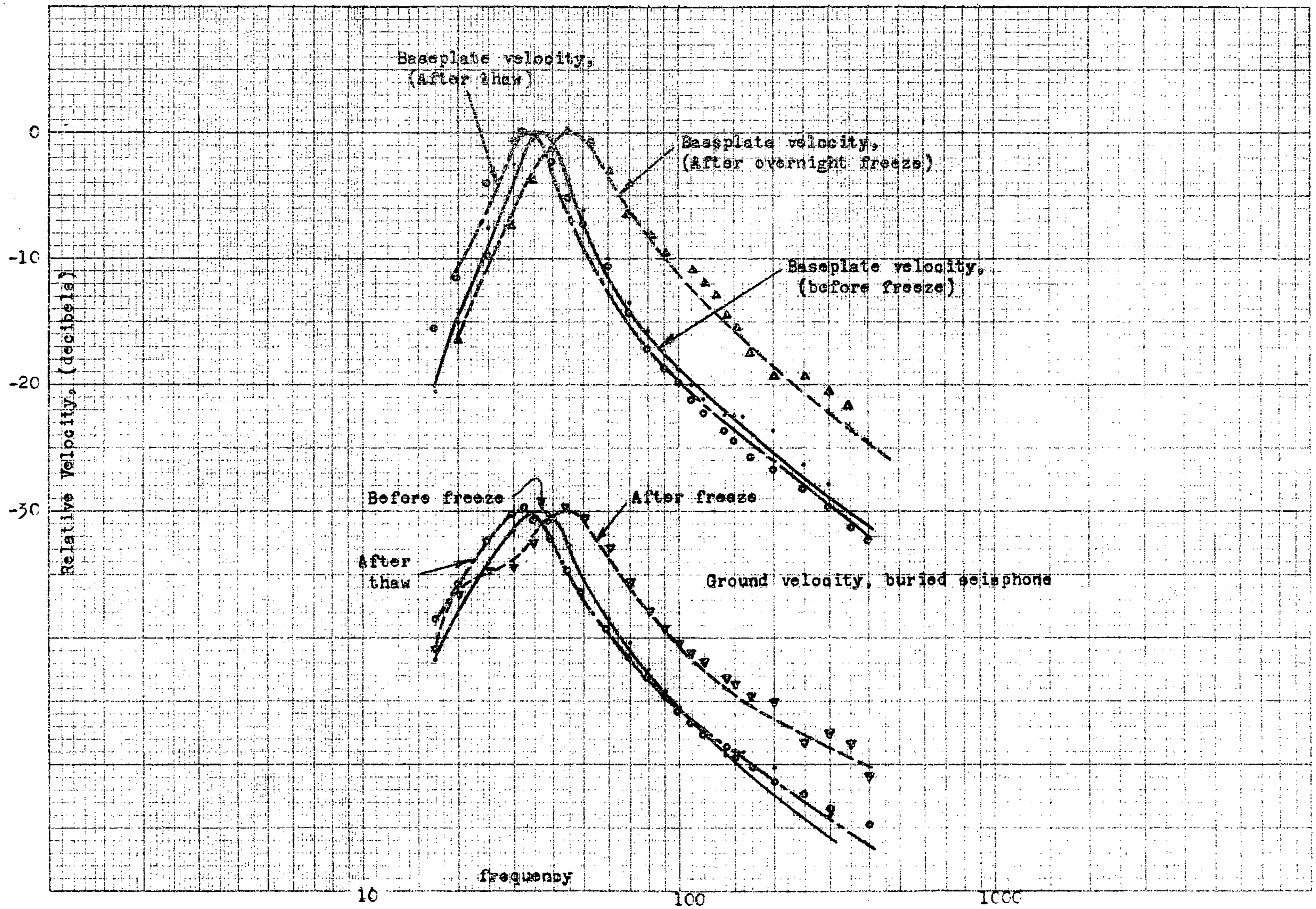

Figure 13. Observations of Ground Resonance Throughout a Freeze-Thaw Cycle

a. The ground was rather sharply resonant, between 35-50 cycles per second. This resonance varied over a period of days, being highest when surface was frozen to a depth of about three inches.

b. Baseplate resonance and ground resonance were coincident in all tests; and, although ground velocity and baseplate velocity curves were not identical beyond the resonance point, a similarity did exist.

c. Control of ground resonance was obtained by additional vibrator mass, by changing the area of the baseplate, and by addition of a plastic mat beneath the baseplate. For example, doubling the mass shifted the resonant frequency downward by an amount predictable by considering the vibrator-earth system as a simple spring-mass system.

CHAPTER III

THEORETICAL CONSIDERATIONS

Consider the simple system comprised of a simple spring, a mass, and associated viscous losses under the influence of a force, F(t), acting upon the mass (Figure 14). Writing the equation for motion, then, we obtain:

$$\left(Mp + \frac{K}{p} + f\right)v(t) = F(t)$$

and solving for v(t), velocity, as measured at the mass, M:

$$v(t) = \frac{F(t)p}{(Mp^2 + fp + K)}$$

and this may be rearranged in the form:

$$v(t) = \frac{F(t)p}{K\left[\frac{Mp^2}{K} + \frac{fp}{K} + 1\right]}$$

and further:

$$\frac{v(t)}{F(t)} = \frac{1}{\sqrt{MK}}\left[\frac{\sqrt{\frac{M}{K}}p}{\frac{M}{K}p^2 + \sqrt{\frac{M}{K}} \cdot \frac{f}{\sqrt{MK}}p + 1}\right]$$

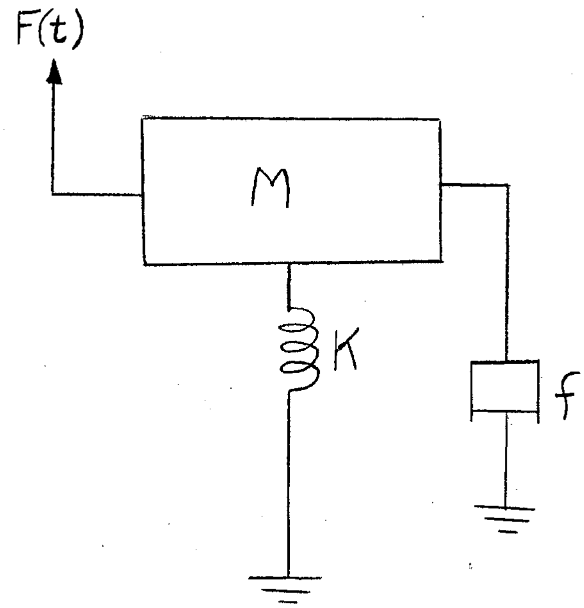

Figure 14. Simple Spring-Mass System

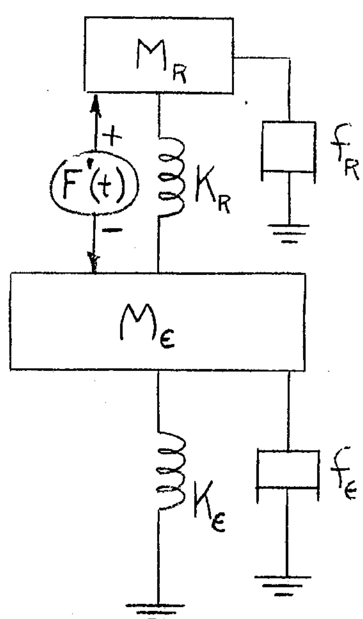

Figure 16. Schematic of Earth-Vibrator System

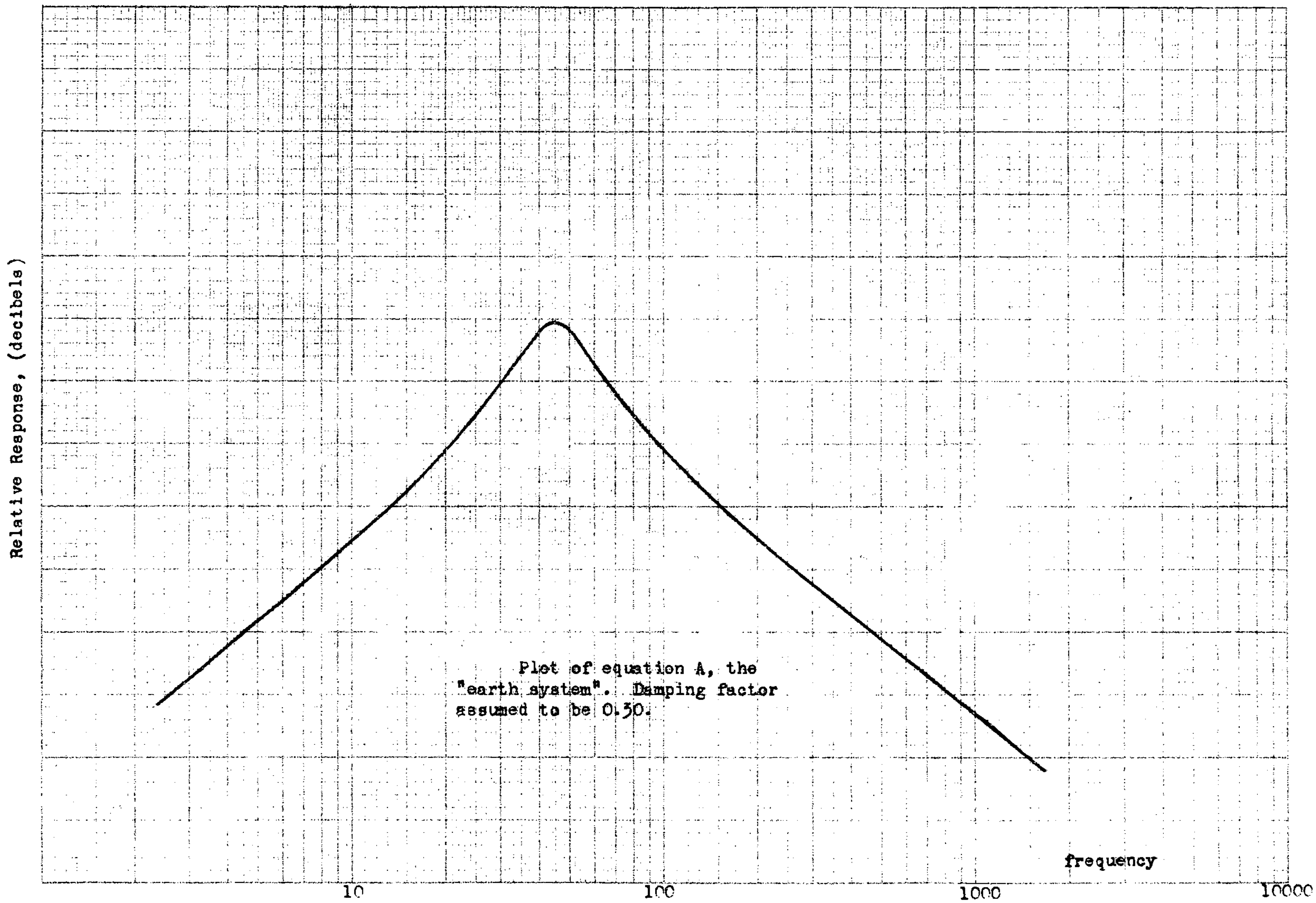

Figure 15. Plot of Equation A

This equation is of the standard form:

$$\frac{Tp}{(T^2p^2 + 2nTp + 1)}$$

where:

$$T = \frac{M}{K} \text{ and } \frac{f}{\sqrt{MK}} = 2n, \text{ or } n = \frac{f}{2\sqrt{MK}}$$

If, now, F(t) is a sinusoidal driving force, such that F(t) = Asin wt, then the steady-state response of equation "A" is well-known and, plotted upon semilog graph paper, appears in Figure 15. A damping factor equal to a value of 0.30 was assumed for the plot. It will be seen from previous tests (see Figure 8) that this was a realistic assumption. Changing the damping factor through changes of M or K only results in a change in the slope of the curve since the maximum is determined by viscous losses only.[1] Therefore, we are at liberty to control the "sharpness" of the resonance by adjustments of M or K without reduction in the maximum value of velocity obtained at resonance. In simpler terminology, we can control the "Q" of the system.

All the baseplate velocity curves observed empirically were seen to approximate the curve of Figure 15. Therefore,

---

[1]At resonance, regardless of the magnitudes of M and K, $pM = -\frac{K}{p}$, and $v(t)_{max}$ equals F(t)/f.

it was concluded that the earth could be represented by such a simple system. Further, if the driving force, F(t), could be properly described, then it was concluded that the entire earth-vibrator system would be described. The driving force should, it was reasoned, reflect the characteristics imparted to it by the properties of the reaction mass system. Such a system is shown schematically in Figure 16. For simplification, f_r was allowed to act upon M_r only. In reality, it effects both M_r and M_e; but since the displacement of M_e is very small for all frequency and since f_e is very large with respect to f_r, the approximation effects the final results very little. The force generator is applied between the two masses, which is the rigorously correct situation. Again, however, since the displacement of M_r is very much greater than that of M_e, the system can be replaced to a first approximation by the system shown in Figure 17, where F(t) must now reflect the influence of the motion imparted to the reaction mass, M_r, by the force generator, F'(t). F(t), then, the force applied to the earth system, becomes that which is developed across the reaction mass due to its velocity. That this is true becomes obvious when it is observed that the force applied to M_e utilizes M_r for reaction purposes. If M_r were to remain fixed, then the problem of deriving $v_e(t)$, earth or baseplate velocity, would become very simple. However, the force generator imparts

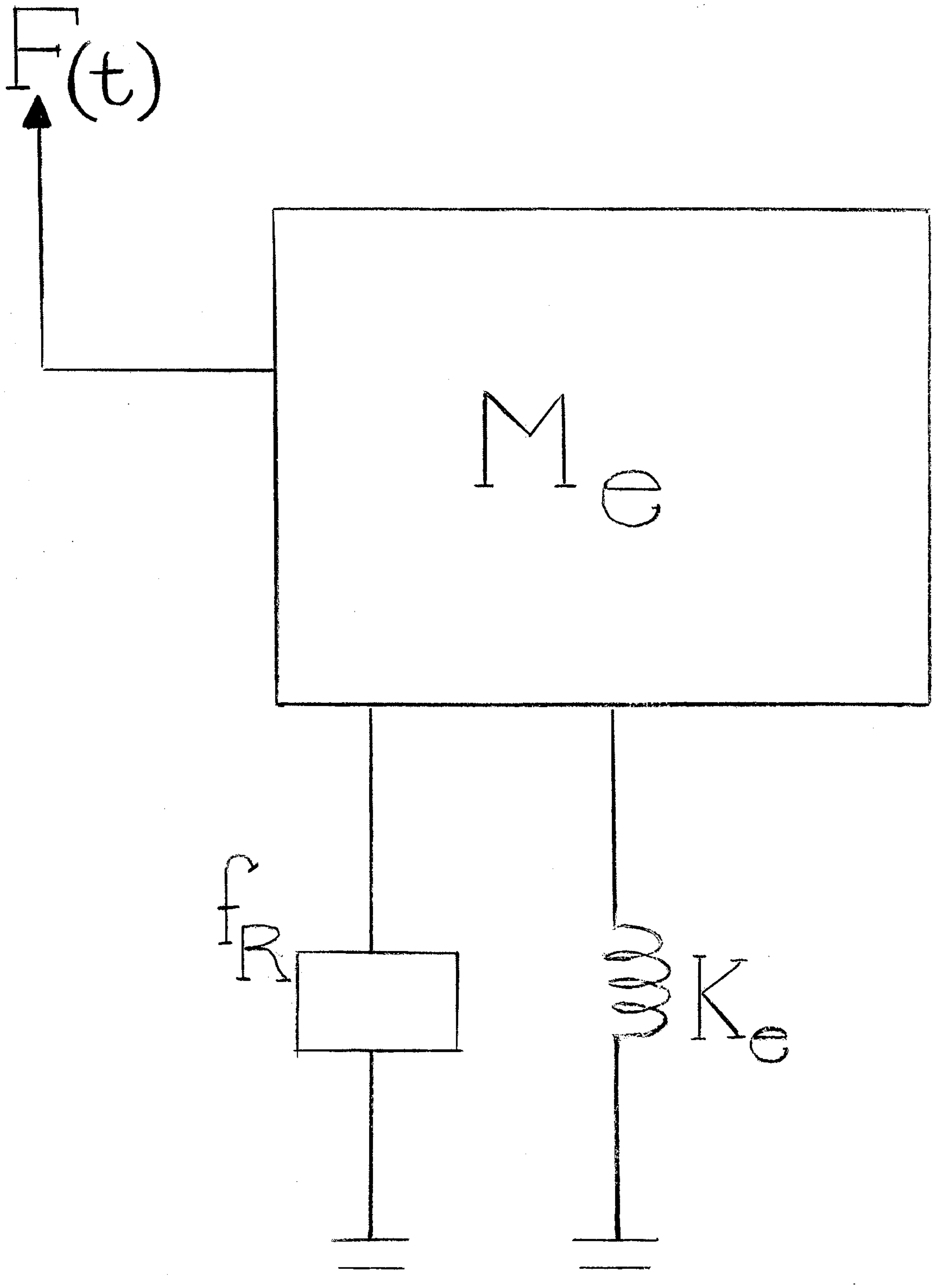

Figure 17. Simplified Earth-Vibrator System

motion to M_r, which effectively modifies the force applied to M_e. Looking back, then, from M_e, we are interested in the force developed and modified due to the motion imparted to M_r. To obtain this force to a first approximation, we can assume M_e to be fixed in space and then compute the velocity of M_r under the influence of the force $F'(t)$. $F(t)$, then, the force seen looking from M_e towards M_r, is given by:

$$Z_{M_r}(p) \cdot v_r(t) = F(t)$$

where $v_r(t)$ is the velocity of M_r (determined assuming no motion at M_e) and $Z_{M_r}(p)$ is the mechanical impedance of M_r and is equal to:

$$Z_{M_r}(p) = pM_r$$

Therefore:

$$F(t) = v_r(t) \cdot pM_r$$

and then, from equation A:

$$v_r(t) = \frac{F'(t)}{\sqrt{M_r K_r}} \left[\frac{\sqrt{\frac{M_r}{K_r}}\, p}{\frac{M_r}{K_r} p^2 + \sqrt{\frac{M_r}{K_r}} \, \frac{f_r}{\sqrt{M_r K_r}} p + 1} \right]$$

and then by substitution:

$$F(t) = \frac{F'(t)\ pM_r}{\sqrt{M_rK_r}} \left[\frac{\frac{\sqrt{M_r}}{K_r}p}{\frac{M_r}{K_r}p^2 + \frac{\sqrt{M_r}}{K_r}\frac{f_r}{\sqrt{M_rK_r}}p + 1} \right]$$

$$= F'(t) \left[\frac{\frac{M_r}{K_r}p^2}{\frac{M_r}{K_r}p^2 + \frac{\sqrt{M_r}}{K_r}\frac{f_r}{\sqrt{M_rK_r}}p + 1} \right] \qquad \text{EQUATION B}$$

Letting $T = \frac{\sqrt{M_r}}{K_r}$, the equation is seen to be of the form:

$$\frac{F(t)}{F'(t)} = \frac{T^2p^2}{T^2p^2 + 2nTp + 1}$$

This is the transfer function between the driving force, $F'(t)$, and the force seen at the reaction mass, M_r. If now, $F'(t)$ is a sinusoidal force, Asin(wt), then the steady-state response is readily plotted using the Bode (logarithmic) method. The result is shown in Figure 18. This is, then, to a first approximation, the force which will be applied to the earth system. The earth or baseplate velocity, $v_e(t)$, will also be described by equation A, such that:

$$v_e(t) = \frac{F(t)}{\sqrt{M_eK_e}} \left[\frac{\frac{\sqrt{M_e}}{K_e}p}{\frac{M_e}{K_e}p^2 + \frac{\sqrt{M_e}}{K_e}\frac{f_e}{\sqrt{M_eK_e}}p + 1} \right]$$

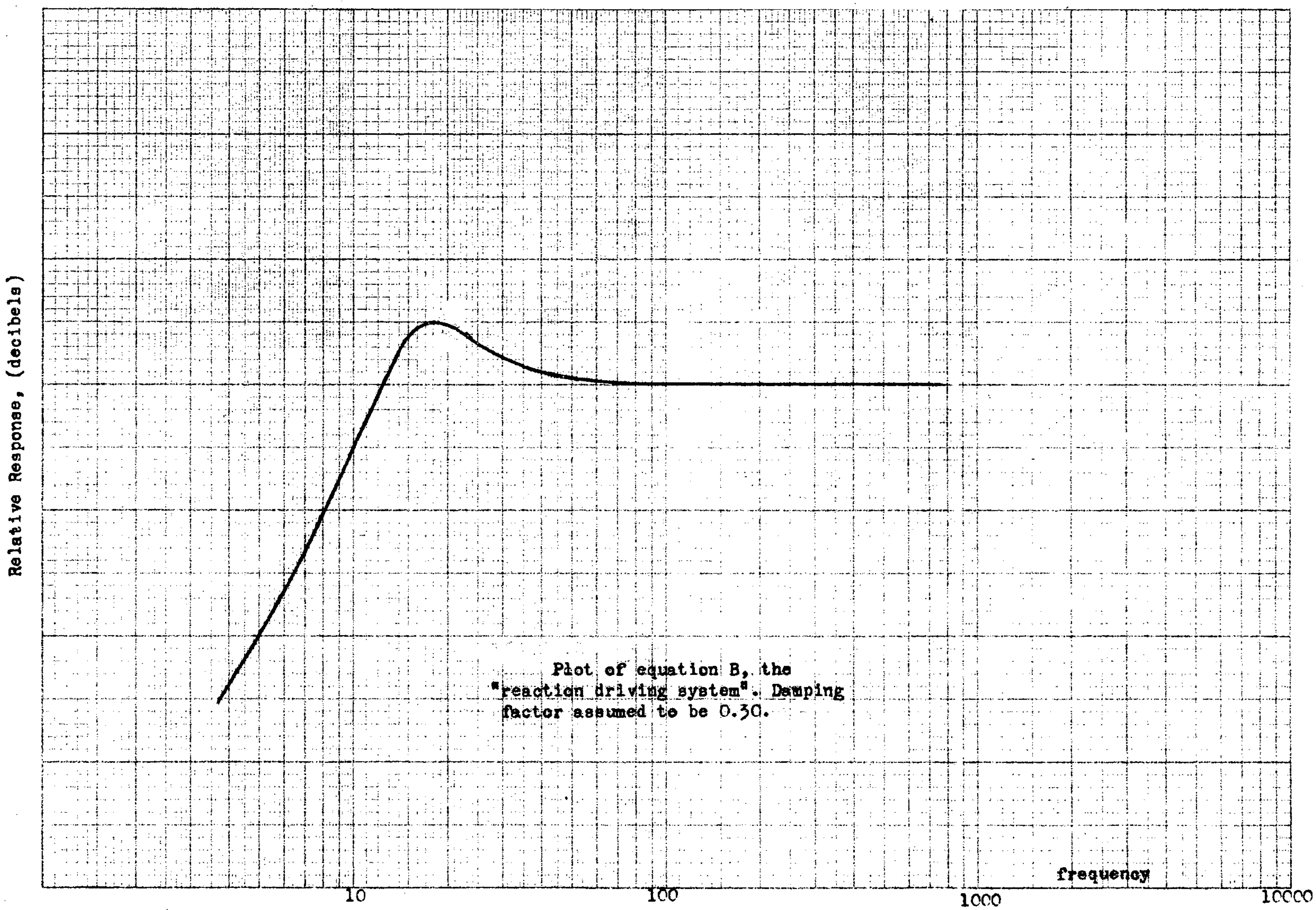

Figure 18. Plot of Equation B

and by substituting the value of F(t) from Equation B, an expression for $v_e(t)$ is obtained.

$$v_e = \frac{F'(t)}{\sqrt{M_e K_e}} \left[\frac{\sqrt{\frac{M_e}{K_e}}\,p}{\frac{M_e}{K_e}p^2 + \sqrt{\frac{M_e}{K_e}}\,\frac{f_e}{\sqrt{M_e K_e}}\,p + 1} \right] \left[\frac{\frac{M_r}{K_r}p^2}{\frac{M_r}{K_r}p^2 + \sqrt{\frac{M_r}{K_r}}\,\frac{f_r}{\sqrt{M_r K_r}}\,p + 1} \right]$$

EQUATION C

Equation C, now, is of the standard form:

$$v_e(t) = \frac{F'(t)}{\text{Constant}} \left[\frac{T_e p}{T_e^2 p^2 + 2n_e T_e p + 1} \right] \left[\frac{T_r^2 p^2}{T_r^2 p^2 + 2n_r T_r p + 1} \right]$$

and if F'(t) is sinusoidal, then the steady-state response may be obtained from a Bode plot as in Figure 19. It should be remembered that this result was obtained by ignoring the motion of the earth system mass, since its motion is very small. Particularly, the result (and the assumption) is valid if the respective resonances of the earth and reaction systems are displaced considerably from each other in frequency. Under such conditions, the response of either system contributes little to the other.

In order to check the validity of Equation C, let's consider the entire system as shown in Figure 16 and write the differential equations involving the velocities of both masses. In "p" operator form, the equations are:

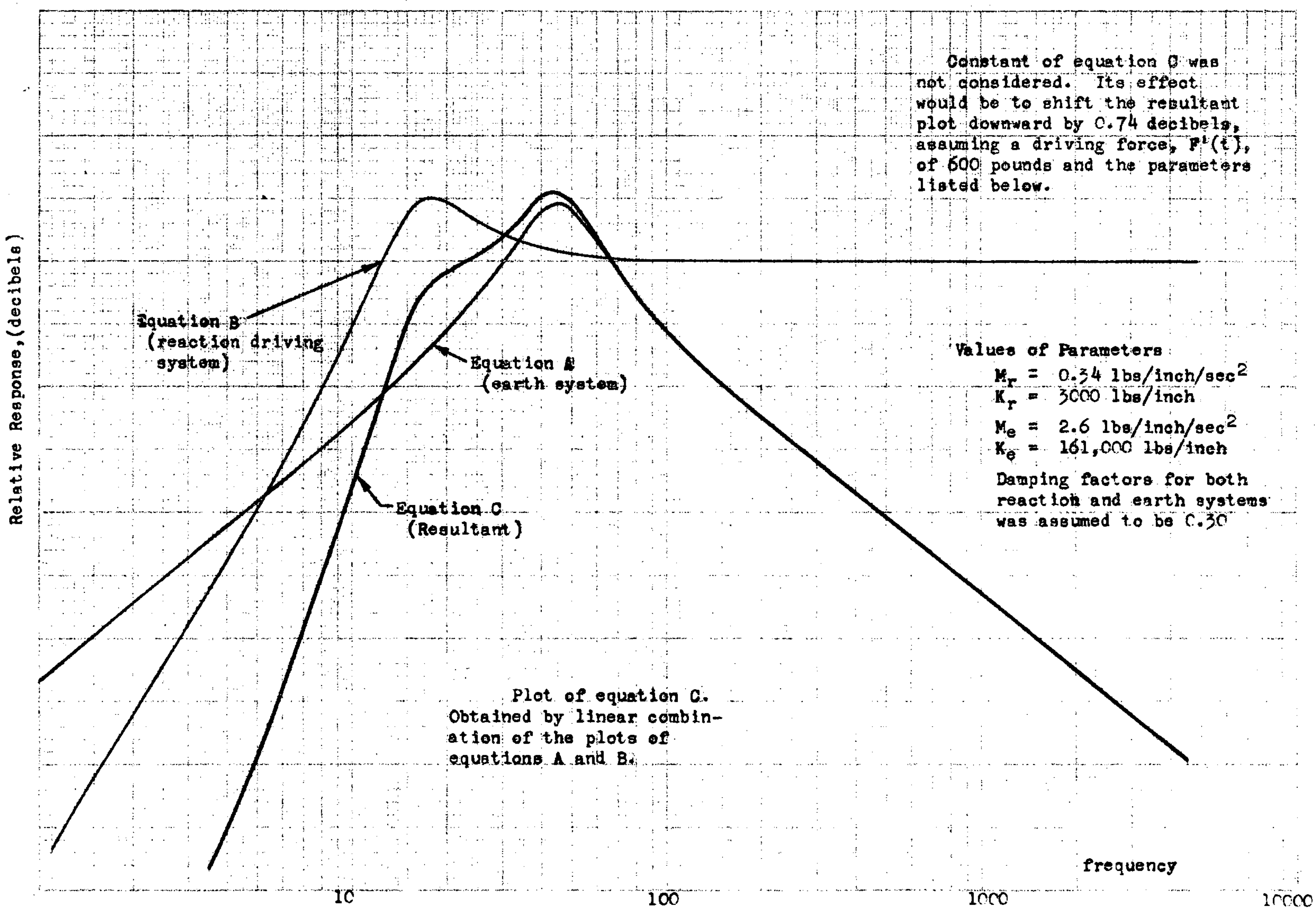

Figure 19. Plot of Equation C

$$\left[pM_r + \frac{K_r}{p} + f_r\right] v_r(t) - \left[\frac{K_r}{p}\right] v_e(t) = F'(t)$$

and:

$$-\left[\frac{K_r}{p}\right] v_r(t) + \left[pM_e + \frac{(K_e + K_r)}{p} + f_e\right] v_e(t) = -F'(t)$$

In determinate form, the solution for $v_e(t)$ is:

$$\frac{\begin{vmatrix} (pM_r + \frac{K_r}{p} + f_r) & +F'(t) \\ -\frac{K_r}{p} & -F'(t) \end{vmatrix}}{\begin{vmatrix} (pM_r + \frac{K_r}{p} + f_r) & -\frac{K_r}{p} \\ -\frac{K_r}{p} & \left[pM_e + \frac{(K_e + K_r)}{p} + f_e\right] \end{vmatrix}} = v_e(t)$$

Evaluating the determinate, we obtain,

$$\frac{-F'(t)\left[M_r p + \frac{K_r}{p} + f_r\right] + F'(t)\left[\frac{K_r}{p}\right]}{\left[M_e p + \frac{(K_e + K_r)}{p} + f_e\right]\left[M_r p + \frac{K_r}{p} + f_r\right] - \frac{K_r^2}{p^2}} = v_e(t)$$

and after performing the indicated operations and collecting terms, the following equation is obtained:

$$\frac{-F'(t)\left[M_r p + f_r\right]p^2}{M_eM_rp^4+(M_eF_r+M_rF_e)p^3+(M_eK_r+M_rK_e+M_rK_r+f_ef_r)p^2+ +(K_ef_r+K_rf_r+K_rf_e)p+K_eK_r} = v_e(t)$$

EQUATION C-1

Consider now the denominator of Equation C-1 by itself. If we can resolve it into two quadratics, then it will be a simple matter to obtain the steady-state response. If we can make an intelligent guess, we might determine one of the quadratics; and then by division, a check can be made on the accuracy of our guess. Therefore, let's try dividing the quartic by the quantity, $(M_rp^2 + f_rp + K_r)$:

$$\begin{array}{l}
\underline{M_ep^2 + f_ep + (K_e + K_r) \qquad \div \qquad /M_rp^2 + f_rp + K_r} \\
M_eM_rp^4+(M_ef_r+M_rf_e)p^3+(M_eK_r+M_rK_e+M_rK_r+f_ef_r)p^2+(K_ef_r+K_rf_r+K_rf_e)p+K_eK_r \\
\underline{M_eM_rp^4+(M_ef_r)p^3 \qquad +(M_eK_r)p^2} \\
\qquad + (M_rf_e)p^3 \qquad +(M_rK_e+M_rK_r+f_ef_r)p^2+(K_ef_r+K_rf_r+K_rf_e)p \\
\qquad \underline{+ (M_rf_e)p^3 \qquad\qquad +(f_ef_r)p^2 \qquad\qquad +(K_rf_e)p} \\
\qquad\qquad\qquad +(M_rK_e+M_rK_r)p^2 \quad + \quad (K_ef_r+K_rf_r)p \quad + K_eK_r \\
\qquad\qquad\qquad \underline{+(M_rK_e+M_rK_r)p^2 \quad + \quad (K_ef_r+K_rf_r)p \quad + K_eK_r+K_r^2} \\
\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad -K_r^2
\end{array}$$

It is seen that a remainder exists equal to:

$$\frac{-K_r^2}{M_rp^2 + f_rp + K_r}$$

Therefore, if K_r^2 is added to constant term of the quartic, such that:

$$\text{Constant} = (K_e K_r + K_r^2)$$

then the quartic can be factored into two quadratics:

$$\left[M_e p^2 + f_e p + (K_e + K_r)\right] \text{ and } (M_r p^2 + f_r p + K_r)$$

The addition of K_r^2 to the constant term of the quartic will have little over-all effect on the equation if it can be shown that in the real situation K_e is very much greater than K_r such that the quantity, $K_e K_r$, will be at all times very much larger than K_r^2.

From the empirical curves of Figures 8, 12, and 13, it is observed that earth resonance occurs, generally, between the limits of 30 to 50 cycles per second, with the mass, M_e, used in the tests of approximately 1,200 pounds (weight). Substituting into the equation:

$$f(\text{resonance}) = \frac{1}{2\Pi} \cdot \sqrt{\frac{K_e}{M_e}}$$

we can determine the variation of K_e as the resonant frequency varies within the above limiting values. A comparison of the values of $K_e K_r$ and K_r^2 for expected values of K_e can then be tabulated as in Table I below.

From the tabulation in Table I, it is readily seen that the addition of K_r^2 to the constant term, K_eK_r, will change the value of the term by an insignificant amount.

TABLE I

VARIATION OF K_eK_r AND K_r^2 FOR VARYING VALUES OF K_e

Resonant Frequency	K_e	K_r	K_eK_r	K_r^2	$\frac{K_eK_r}{K_r^2}$
30	104×10^3	3×10^3	31.2×10^7	9×10^6	34.5
40	185×10	3×10	55.5×10	9×10	61.7
50	288×10	3×10	86.4×10	9×10	96.0

As a result, Equation C-1 can now be rewritten in the terms of the quadratic factors of its denominator as:

$$v_e(t) = \frac{-F'(t)\left[M_r p + f_r\right] p^2}{\left[M_r p^2 + f_r p + K_r\right]\left[M_e p^2 + f_e p + (K_e + K_r)\right]}$$

which will give a very close approximation to the solution so long as the condition that K_e be very much larger than K_r is met. Rearranging the equation into standard form, we obtain:

$$v_e(t) = \frac{K\left[\frac{M_r}{f_r}p + 1\right]\sqrt{\frac{M_r}{K_r}}p}{\left[\frac{M_r}{K_r}p^2 + \sqrt{\frac{M_r}{K_r}}\frac{f_r}{\sqrt{M_r K_r}}p + 1\right]} \circ \frac{\left[\sqrt{\frac{M_e}{(K_e + K_r)}}p\right]}{\left[\frac{M_e}{(K_e+K_r)}p^2 + \sqrt{\frac{M_e}{(K_e+K_r)}} \circ \frac{fe}{\sqrt{M_e(K_e+K_r)}}p + 1\right]}$$

EQUATION D

where the constant, K, is $F'(t)f_r\sqrt{M_eM_rK_r(K_e+K_r)}$

The steady-state response of this equation is plotted in Figure 20, using again the Bode or logarithmic techniques. The overshoots at the resonant points are dependent upon the value of the damping constants, n_r and n_e, where:

$$n_r = \frac{f_r}{2(\sqrt{M_rK_r})} \quad \text{and} \quad n_e = \frac{f_e}{2\left[\sqrt{M_e(K_e + K_r)}\right]}$$

It was also assumed that T_e was less than T_r and T_r was less than T (or $w < w_r < w_e$), which was the actual situation.

A comparison now between Figure 20 and Figure 19, the approximate solution, reveals that the main difference is that the left hand skirt of Figure 20 breaks back from a slope of 18 decibels per octave to twelve decibels per octave for frequency values less than:

$$f = \frac{f_r}{2\pi M_r}$$

A second difference between the two plots lies in the fact that different values for damping constants were used in the two figures. Those used in Figure 20 are more in keeping with information obtained from earlier ground tests. The values of all parameters used in making the plot in Figure 20 were as below:

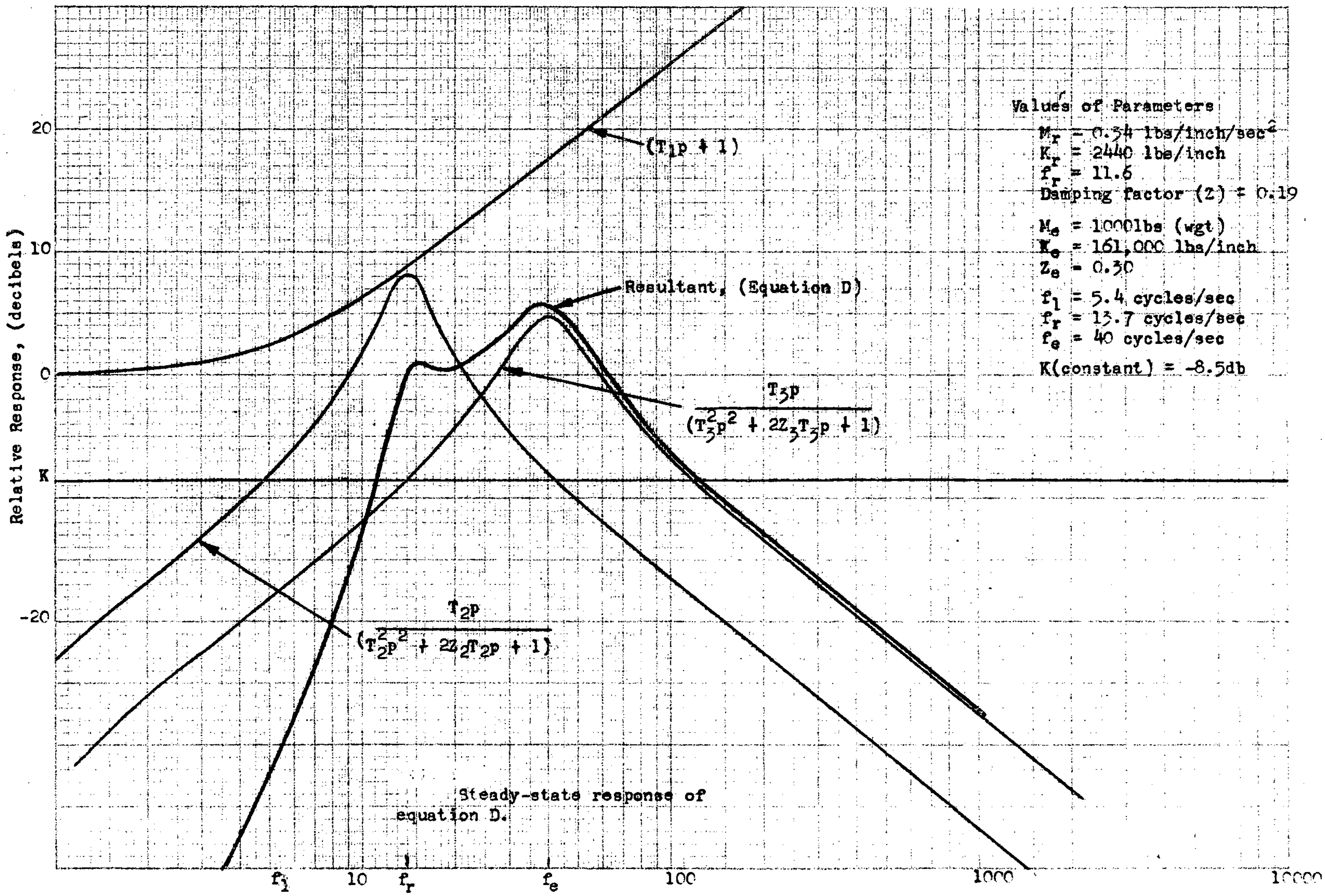

Figure 20. Steady-State Response of Equation D

M_r = 130 lbs. mass (weight)

K_r = 2,440 lbs./inch^2

f_r = 11.6 ohms

n_r = 0.19

M_e = 1,000 lbs. (weight)

K_e = 161,000 lbs./inch^2

n_e = 0.30

Constant Term = 8.5 db

Frequencies of effective time constants were:

f = 5.4 cycles/second

f_r = 13.7 cycles/second

f_e = 40 cycles/second

CHAPTER IV

ELECTRICAL MODEL INVESTIGATIONS

Originally, because of the difficulty presented by the quartic in the denominator of Equation C-1, representing the solution for $v_e(t)$, it was decided to obtain the solution through the use of an analogous electrical model.

Development of the Electrical Model

By examination of the mechanical equations on pages 34 and 36 the "dual" or equivalent electrical equations can be directly written as:

$$\left[L_r p + \frac{1}{C_r p} + R_r\right] i_r(t) - \left[\frac{1}{C_r p}\right] i_e(t) = E(t)$$

and:

$$-\left[\frac{1}{C_r p}\right] i_r(t) + \left[L_e p + \left(\frac{1}{C_r} + \frac{1}{C_e}\right)\frac{1}{p} + R_e\right] i_e(t) = -E(t)$$

From these analogous equations, the dual circuit was formed (see Figure 21). This circuit can be rearranged

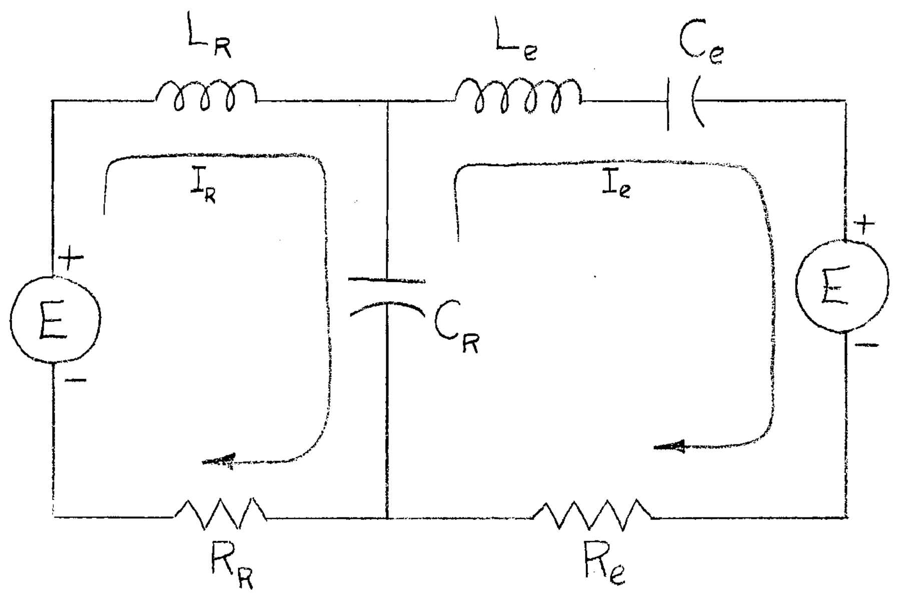

Figure 21. "Dual" of Mechanical Equations

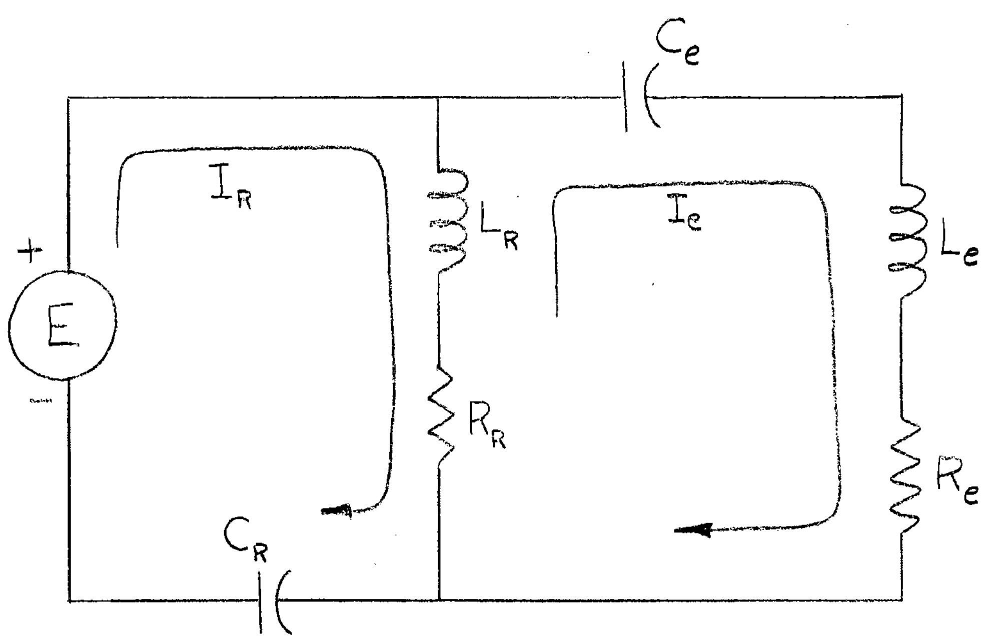

Figure 22. Rearranged "Dual" Circuit

as in Figure 22, since the magnitudes of the voltage generators are equal. Notice that the force applied to the earth loop is developed across L_r, the analog of reaction mass, in series with R_r, the viscous force of the reaction system. This force, then, will reflect the characteristics of the current through the common branch; and if iL_r is large with respect to iR_r, the force applied to the earth loop is essential only to that developed across the reaction mass. This bears out the assumption made previously on page 29.

To check the validity of the single generator circuit shown above, let's write the equations for the two current loops indicated. The equations are:

$$\left[pL_r + \frac{1}{C_r p} + R_r\right] i_r(t) - \left[pL_r + R_r\right] i_e(t) = E(t)$$

$$-\left[pL_r + R_r\right] i_r(t) + \left[(L_e + L_r)p + \frac{1}{C_e p} + (R_e R_r)\right] i_e(t) = 0$$

Substituting the mechanical equivalents and developing the determinate form, we obtain:

$$\frac{\begin{vmatrix} (M_r p + \frac{K_r}{p} + f_r) & +E \\ -(M_r p + f_r) & 0 \end{vmatrix}}{\begin{vmatrix} \left[M_r p + \frac{K_r}{p} + f_r\right] & -(M_r p + f_r) \\ -(M_r p + f_r) & \left[(M_e + M_r)p + \frac{K_e}{p} + (f_e + f_r)\right] \end{vmatrix}} = v_e(t)$$

Evaluating the determinate, we obtain:

$$\frac{+E(M_r p + f_r)}{(M_r p+\frac{K_r}{p}+f_r)\left[(M_e+M_r)p+\frac{K_e}{p}+(f_e+f_r)\right] - (M_r p+f_r)^2} = v_e(t)$$

Expanding the denominator and collecting terms, the following expression for $v_e(t)$ is obtained:

$$\frac{+F(M_r p + f_r)p^2}{M_r M_e p^4+(M_r f_e+M_e f_r)p^3+(M_r K_e+M_e K_r+M_r K_r+f_r f_e)p^2+(K_r f_e+K_r f_r+K_e f_r)p+K_e K_r}$$

EQUATION E

Note that this equation is identical to Equation C-1, with the exception of the sign, which merely indicates that the velocity of M_e was assumed to have the wrong direction. Therefore, the single generator circuit is the equivalent of the double generator "dual."

It was necessary to determine the values of the inductances, capacitances, and resistances which were to represent their mechanical counterparts in the single generator "dual." Determination of these parameters was made from a knowledge of the mechanical system and from empirical velocity curves, obtained in the initial ground experiments.

1. M_e, the mass in contact with the earth's surface was simply the total mass of the vibrator exclusive of the reaction

mass. This amounted to 1,200 pounds in weight and to 3.1 lbs./inch/sec.^{2} mass. Therefore, the electrical analog was equal to 3.1 henrys.

2. K_e, the spring constant of the earth, was determined from the relation:

$$T_e^2 = \frac{M_e}{K_e + K_r}$$

which is, since K_e is much greater than K_r, equal to M_e/K_e. Further, since $T_e = 1/2\Pi F_e$, by substitution, we see that:

$$F_e = \frac{1}{2\Pi} \cdot \frac{\sqrt{K_e}}{\sqrt{M_e}}$$

In the initial ground investigations, now, resonance was observed throughout a frequency range of 35 to 45 cycles per second under varying ground conditions. Using, then, an average value of 40 cycles per second and substituting into the above equation after solving for K_e, we obtain:

$$K_e = 4\Pi^2 F_e^2 M_e$$

$$= 4 \cdot (9.86) \cdot (1600) \cdot (3.1)$$

$$= 185{,}000 \text{ lbs./inch}$$

The value of C_e, the analog of K_e, is the inverse of K_e:

$$C_e = 1/K_e = 1/(1.85 \times 10^5)$$

$$= 5.4 \text{ uf}$$

3. The viscous force, f_e, involved in the earth system was determined by solving the equation:

$$2T_e n_e = \frac{\sqrt{M_e}}{\sqrt{K_e + K_r}} \cdot \frac{f_e}{\sqrt{M_e(K_e + K_r)}}$$

for f_e. Further, since $T_e = \sqrt{M_e/K_e}$ and K_e is very much greater than K_r:

$$f_e = 2n_e(\sqrt{M_e K_e})$$

From Figure 13, the curves for baseplate velocity give scaled values of n_e of 0.2 at 35 cycles per second and 0.3 at 45 cycles per second. Substituting then:

$$f_e = 2(2\text{x}10^{-2})\ \left[3.1(18.5\text{x}10^{2})\right]$$

$$= 300 \text{ ohms} = R_e \text{ (for } n_e = 0.2 \text{ at 35 cycles)}$$

$$R_e = 450 \text{ ohms (for } n_e = 0.3 \text{ at 45 cycles)}$$

4. In a similar manner, M_r, K_r, and f_r, were determined with their analogous counterparts, L_r, C_r, and f_r.

$$M_r = \frac{130}{32\text{x}12} \text{ lbs/in/sec} = 0.34 \text{ henrys} = L_r$$

$$K_r = 4\Pi\ M_r F_r^2 = 2{,}440 \text{ lbs/in}$$

$$C_r = 1/K_r = 410 \text{ uf } (F_r = 13.5 \text{ cycles})$$

$$f_r(\text{for } n_r = 0.3) = 2n_r(\sqrt{M_r K_r})$$

$$= 19.2 \text{ ohms} = R_r$$

With the above values for the circuit parameters, the "dual" becomes as seen in Figure 23.

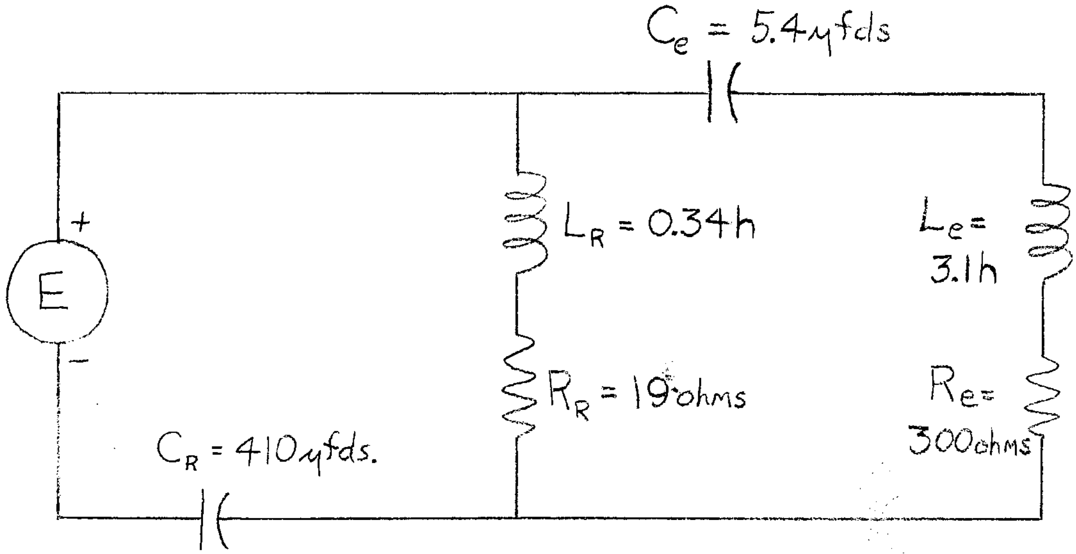

Figure 23. "Dual" Circuit with Values of Parameters

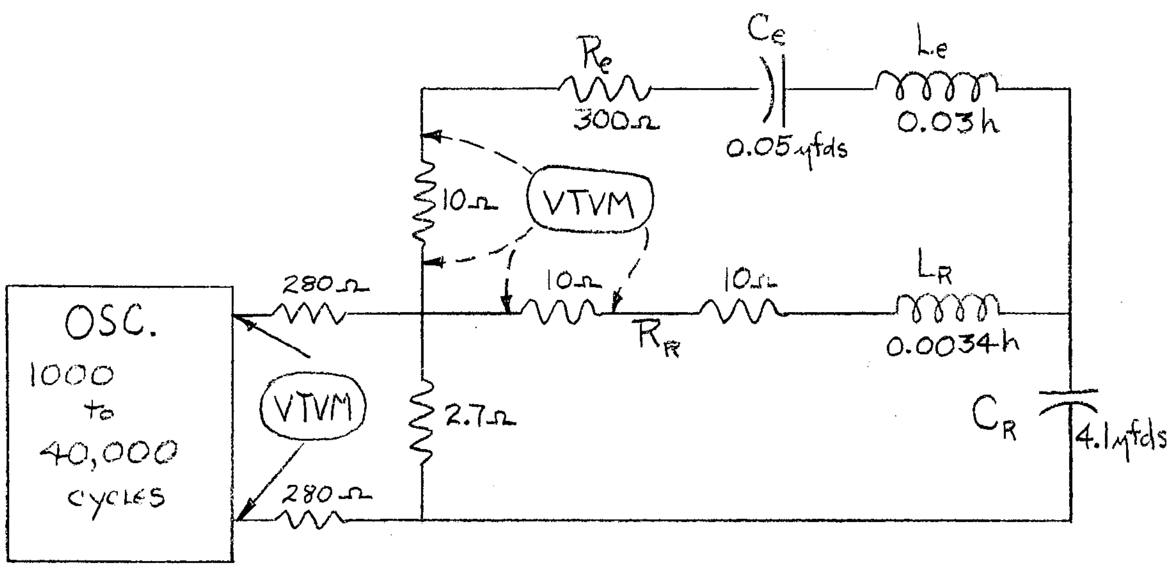

Figure 24. Finalized Electrical Model

In order to obtain convenient values of capacitance, the frequency ordinate was multiplied by a scaling factor of 100. Thus all values of capacitance and inductance were divided by 100. Resistance values, however, being frequency independent, retained the same magnitudes. The circuit, as finally constructed, appeared as in Figure 24. The balanced network was placed across the output of the oscillator for impedance matching purposes and to assure a low impedance source so far as the drive to the analog circuit was concerned.

Results of the Model Tests

Figure 25 shows the frequency response of the finalized electrical model. The upper curve is the velocity response (analog) for the reaction mass. The lower curve represents the response of the earth's system. Note the similarity to the theoretical curves of Figures 19 and 20, as well as the empirical results of Figures 8 and 12. The latter two figures do not show the pronounced effect of reaction mass resonance upon the baseplate velocity curves that is observed in the electrical model. This was attributed to the fact that the reaction mass used during these tests was 110 pounds as compared to the 130-pound value used in the analog model. A hint of the effect is present in the curves, however.

A second model was constructed as in Figure 26. This

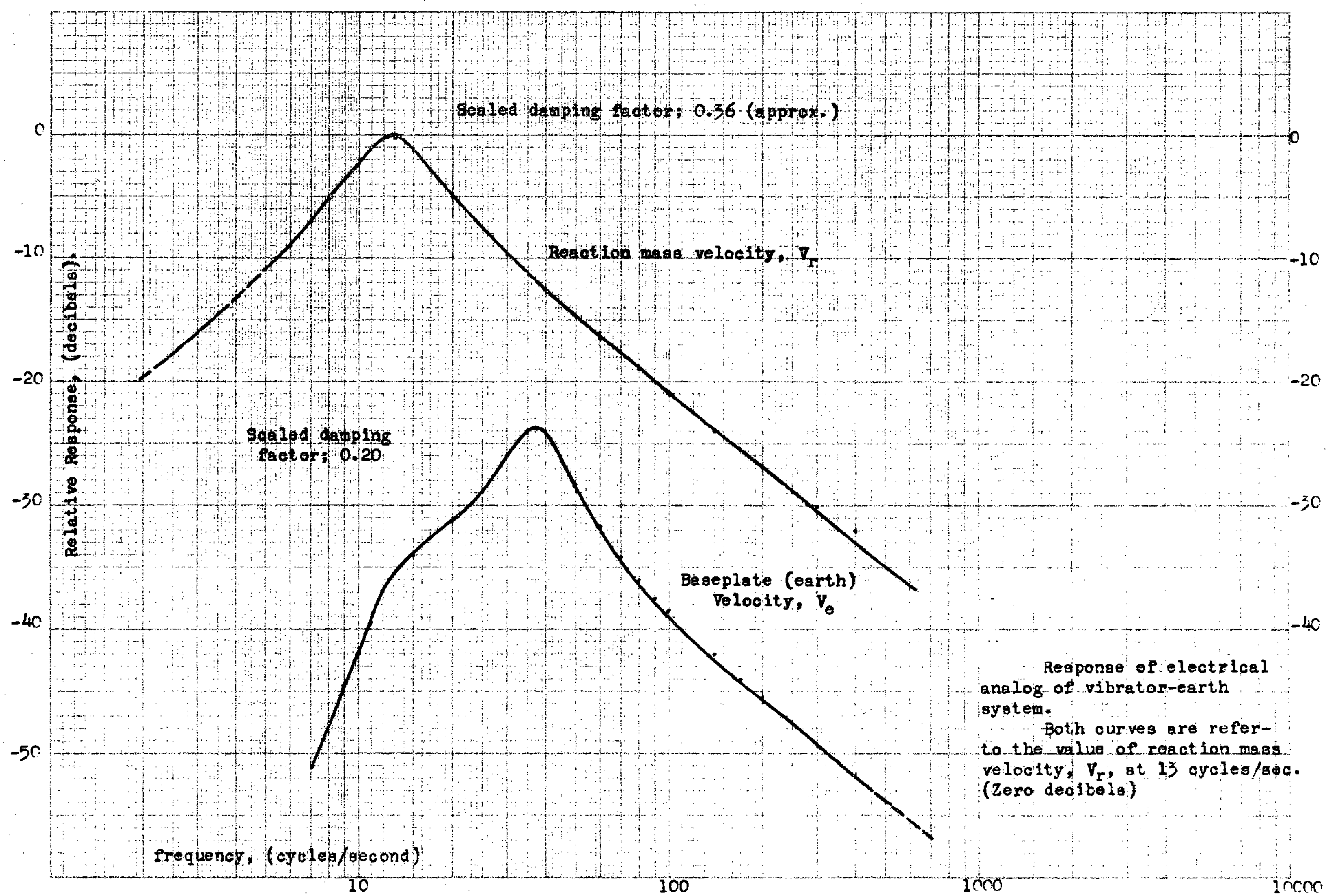

Figure 25. Frequency Response of Electrical Model

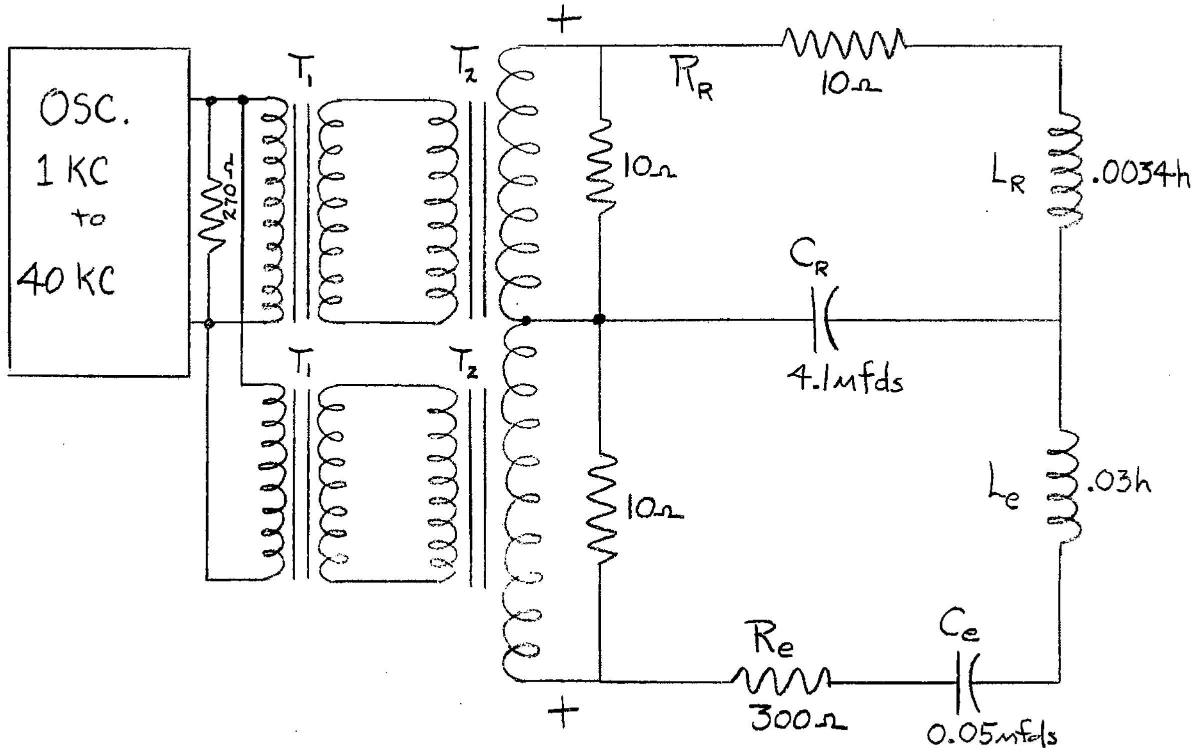

Figure 26. Double Generator Electrical Model

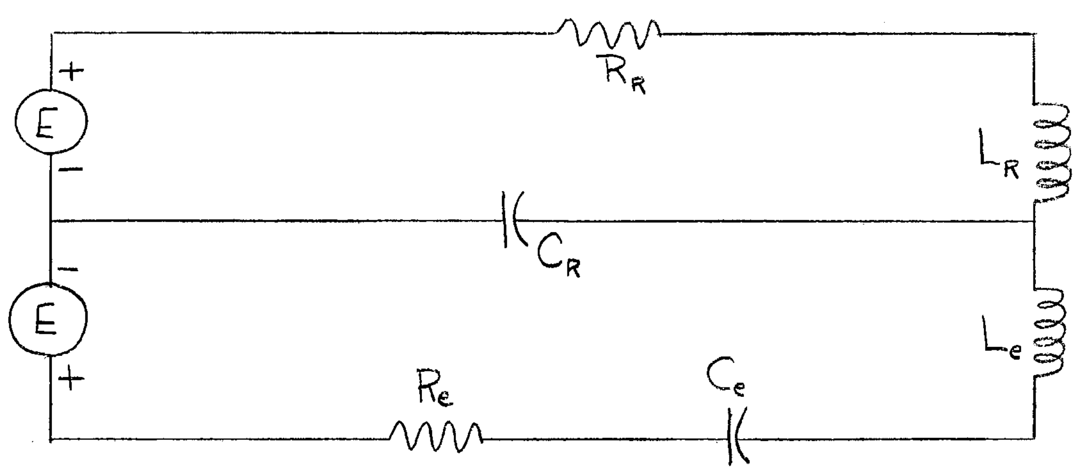

Figure 27. Double Generator "Dual"

circuit is the practical equivalent of the double generator dual originally developed from the analogous electrical equations. This dual circuit is reproduced in Figure 27. The response of this circuit is shown in Figure 28. Note that it is identical to the single-ended circuit response of Figure 25 and serves as a check again on its validity.

Development of the Inverted Model

Since a working model of the earth-vibrator system had been satisfactorily proved, it offered an inexpensive and convenient means of investigating the effect of parameter changes on system response. It had first been recognized, early in the initial ground tests, that the earth appeared to respond as a simple mass, spring, viscous system. It was further realized that control of the earth system resonance would, perhaps, yield a means of controlling the frequency spectrum imparted to the earth. In particular, it was desirable to increase the energy imparted above 50 cycles per second, inasmuch as normal attenuation through the earth increases with frequency; and, further, resolution in seismic exploration is a function of wave length of the probing wave front. Therefore, the construction of a vibrator with a small baseplate mass and with a large reaction mass was considered. However, since such a machine was not available commercially and the

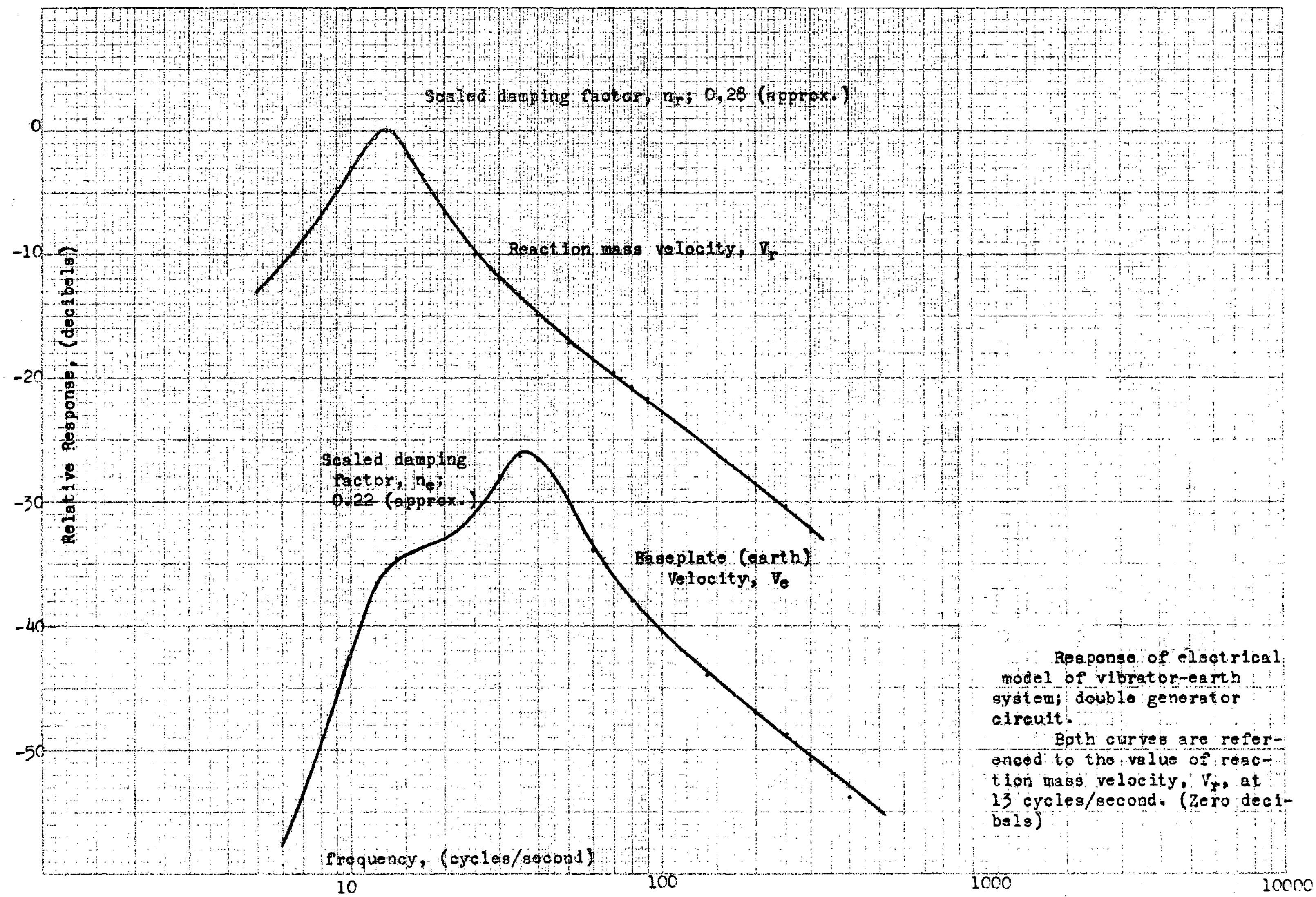

Figure 28. Steady-State Response of Double Generator Model

design or even modification of existing vibrators would represent considerable expense, a decision on development was delayed in lieu of more theoretical and experimental evidence to assure success. The electrical model now offered an excellent tool to further investigation of this idea.

A second analogous circuit was devised and was referred to as the "inverted vibrator analog." As the name implies, it corresponded to physically inverting the vibrator such that the reaction mass would be in contact with the earth's surface, while the very heavy frame would become the reaction mass. To have actually inverted the vibrator would have been impossible with the equipment then at hand. The inverted analog appeared as in Figure 29. The response of this network is shown in Figure 31. It is observed that resonance of the earth's system now occurs in the vicinity of 100 cycles per second (real frequency). Further, the change in damping factor, n_e, with change in L_e, has allowed a slower roll-off in velocity above and below resonance than was the case with the normal configuration. This was an additional, though predictable, bonus in the expected results.[1] Notice also that

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[1]Since the damping factor, n_e, is determined from the equation:

$$n_e = \frac{f_e}{2\sqrt{M_e K_e}}$$

if now f_e and K_e are held constant, n_e will vary inversely

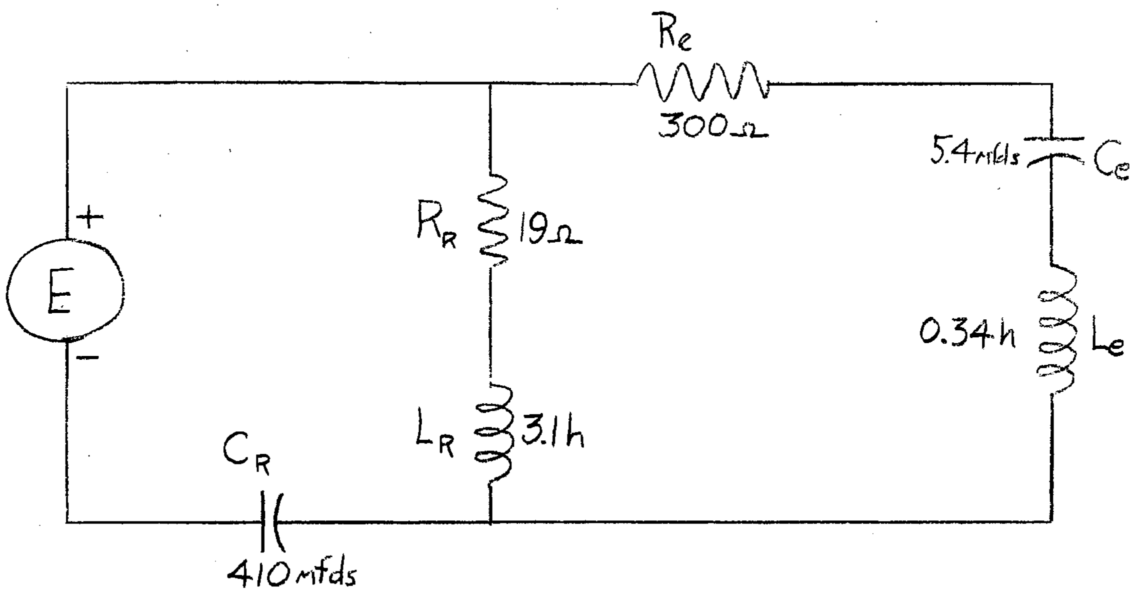

Figure 29. Inverted Vibrator "Dual" Circuit

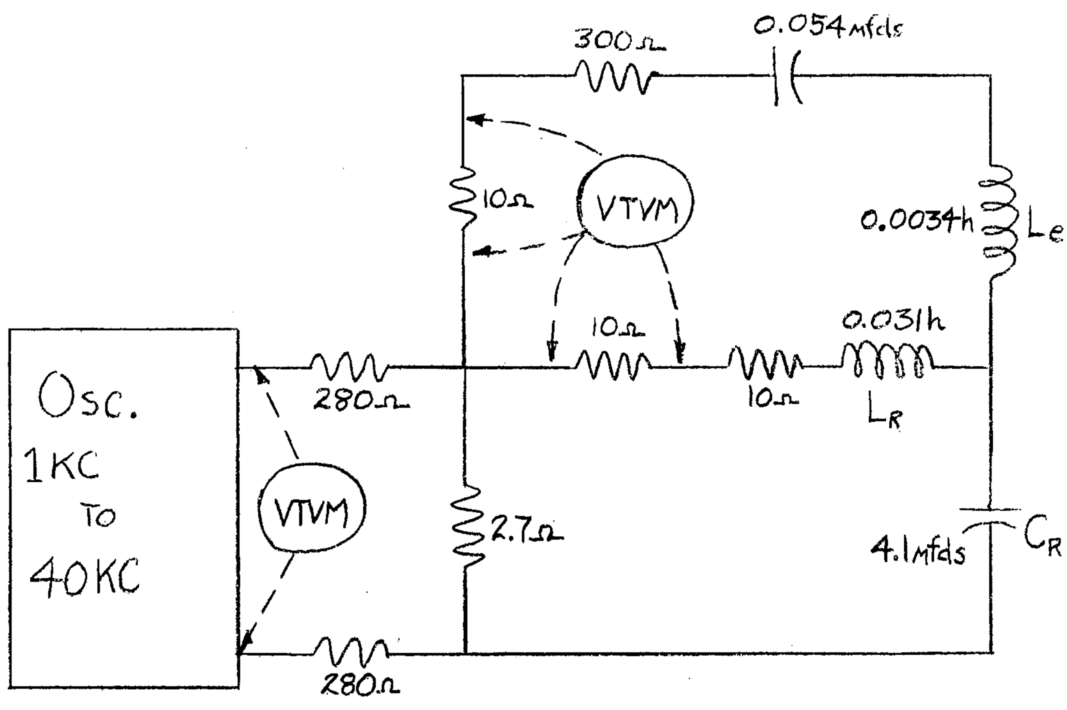

Figure 30. Finalized Inverted Electrical Model

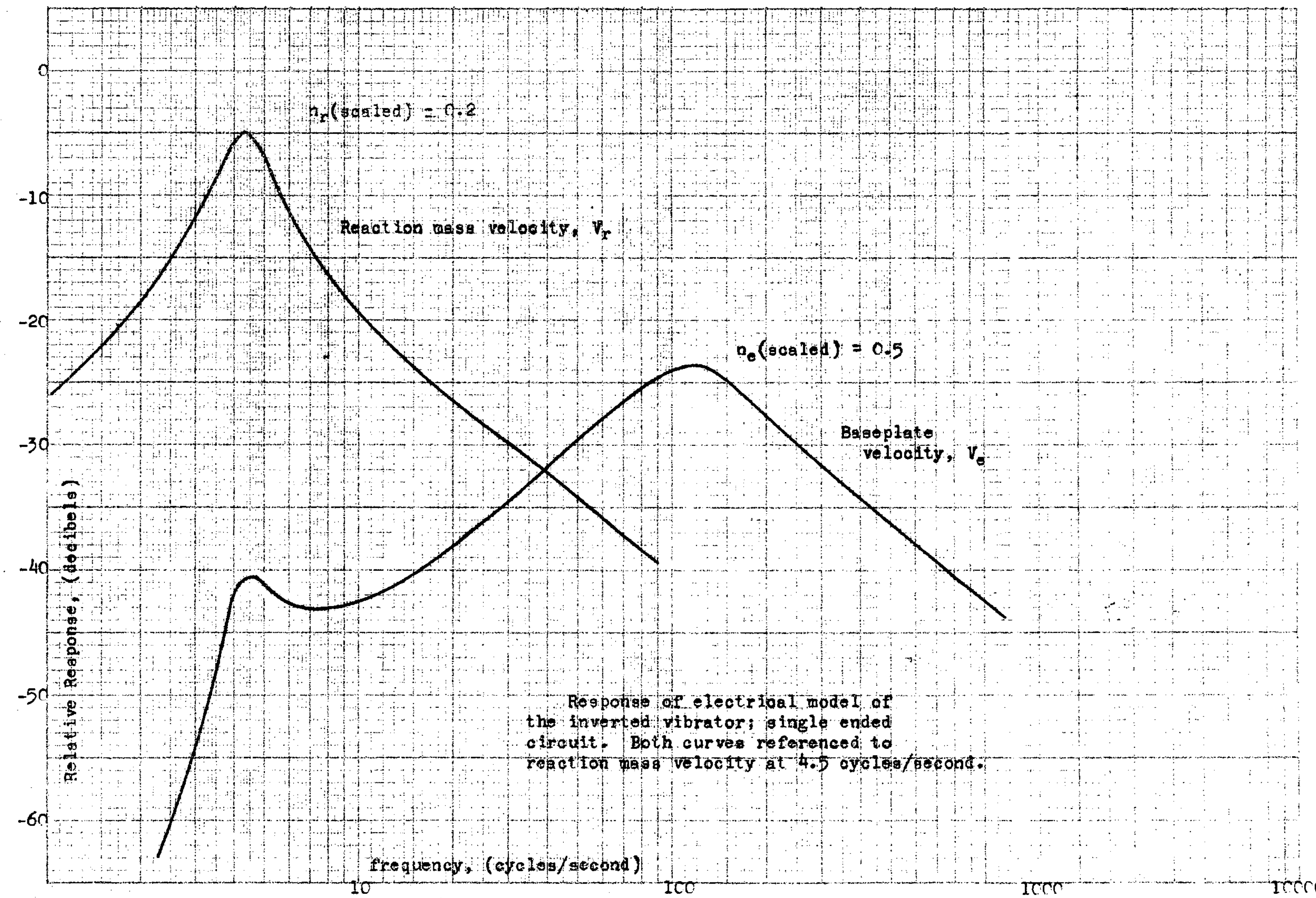

Figure 31. Response of Inverted Electrical Model

the maximum earth velocities are the same in both the normal and inverted configurations. This is, of course, in accordance with the theory, because during resonance in either case, only f_e governs the magnitude of velocity and retains the same magnitude. However, peak reaction mass velocity will be seen to be down five decibels from its value in the normal mode. This was because the resistance of the 0.03 henry coil was of consequence when placed in the reaction circuit.

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as the square root of M_e. Thus, for the normal configuration:

$$n_e = \frac{300}{2\left[\sqrt{(3.1)(185,000)}\right]} = 0.198$$

while for the inverted case:

$$n_e = \frac{300}{2\left[\sqrt{(.34)(185,000)}\right]} = 0.60$$

CHAPTER V

CONSTRUCTION AND TESTS OF AN INVERTED VIBRATOR

Confronted with the encouraging results from the electrical model, it was decided to construct a vibrator of the inverted type through modifications to the existing Savage equipment. Structural changes were, however, necessary to strengthen the vibrator before it could be turned upsidedown. In the inverted position, the entire weight of the vibrator would be supported by the reaction mass through the coil header assembly. Lateral stability and lateral positioning of the coil in the gap assembly would depend, as in the normal position, upon two laminated, concentric springs attached at their centers to the coil assembly and at their peripheries to the vibrator frame. A natural weakness existed in the coil header assembly, inasmuch as the area utilized for attachment of the reaction mass was very small. As a result, any lateral torques would probably cause damage to the header. Otherwise, it appeared that the existing vibrator would structurally withstand the stresses involved in the inverted attitude.

To strengthen the coil header, it was machined to allow the attachment of a heavy, steel collar to which the reaction mass was affixed. The reaction mass was machined to a conical shape, with its base area being equal to the baseplate area of the vibrator in its normal position.[1] The conical shape, besides giving the required base area, yielded the maximum strength of any configuration considered for the mass.

Under the full weight of the vibrator, it was also necessary to recenter the coil, vertically, within the gap structure. To do this, a large rubber innertube was utilized between the cone-shaped reaction mass and the top of the vibrator frame. By pressurizing the tube, the heavy vibrator was readily supported and the coil recentered. Further, since a large area was presented by the innertube to the surfaces of both the vibrator frame and the reaction mass, the required inflation pressure was very small. As a result, the additional spring constant represented by the tube little changed the value of the over-all constant acting in the reaction system.

Direct measurement of the velocity of the cone-shaped mass was difficult once the vibrator was inverted, since all exposed surfaces were covered by the rubber innertube.[2] To

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[1]This would allow direct comparison with previous results with the vibrator in the normal position, since K_e, the earth spring constant could be assumed to be the same in either case.

[2]It should be pointed out that, although the conical mass has been referred to as "the reaction mass" in the preceding discussions, this was true only in the normal position. Once

measure the parameter, a hole was drilled through the baseplate; and an accelerometer was attached directly to the coil and spring support assemblies. This allowed direct measurement of velocities of the conical mass (at the apex) but did subject these measurements to the effects of parasitic vibrations within the coil and spring assemblies themselves.

One last small modification was necessary to the vibrator before it could be inverted. It involved assuring that the field coil was rigidly affixed to the frame so as to prevent any movement which might stress the electrical connections and thus produce a possible fault.

A sketch of the vibrator as it appeared after modification is seen in Figure 32. Figure 33 is a drawing of the entire truck-mounted arrangement used during field tests showing the vibrator, power amplifier and its transformer, gas driven A.C. and D.C. generators, and winching and "gin-pole" arrangements for handling of the vibrator in the field.

Inverted Vibrator Tests

The first test of the inverted vibrator was made just outside of the laboratory building at Ponca City. This was

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the vibrator was inverted, the conical mass became the "earth system mass" and the mass of the vibrator frame became the "reaction" mass.

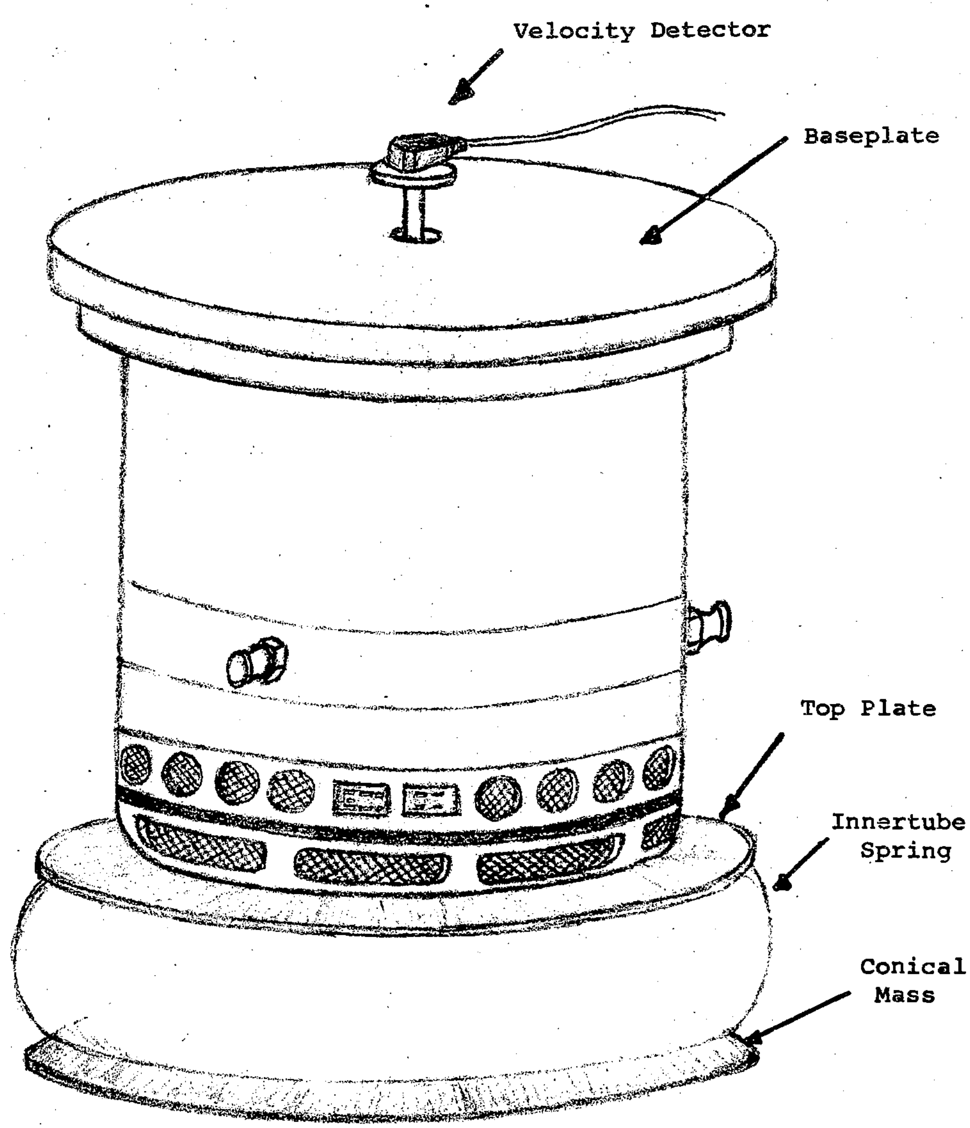

Figure 32. Modified Vibrator

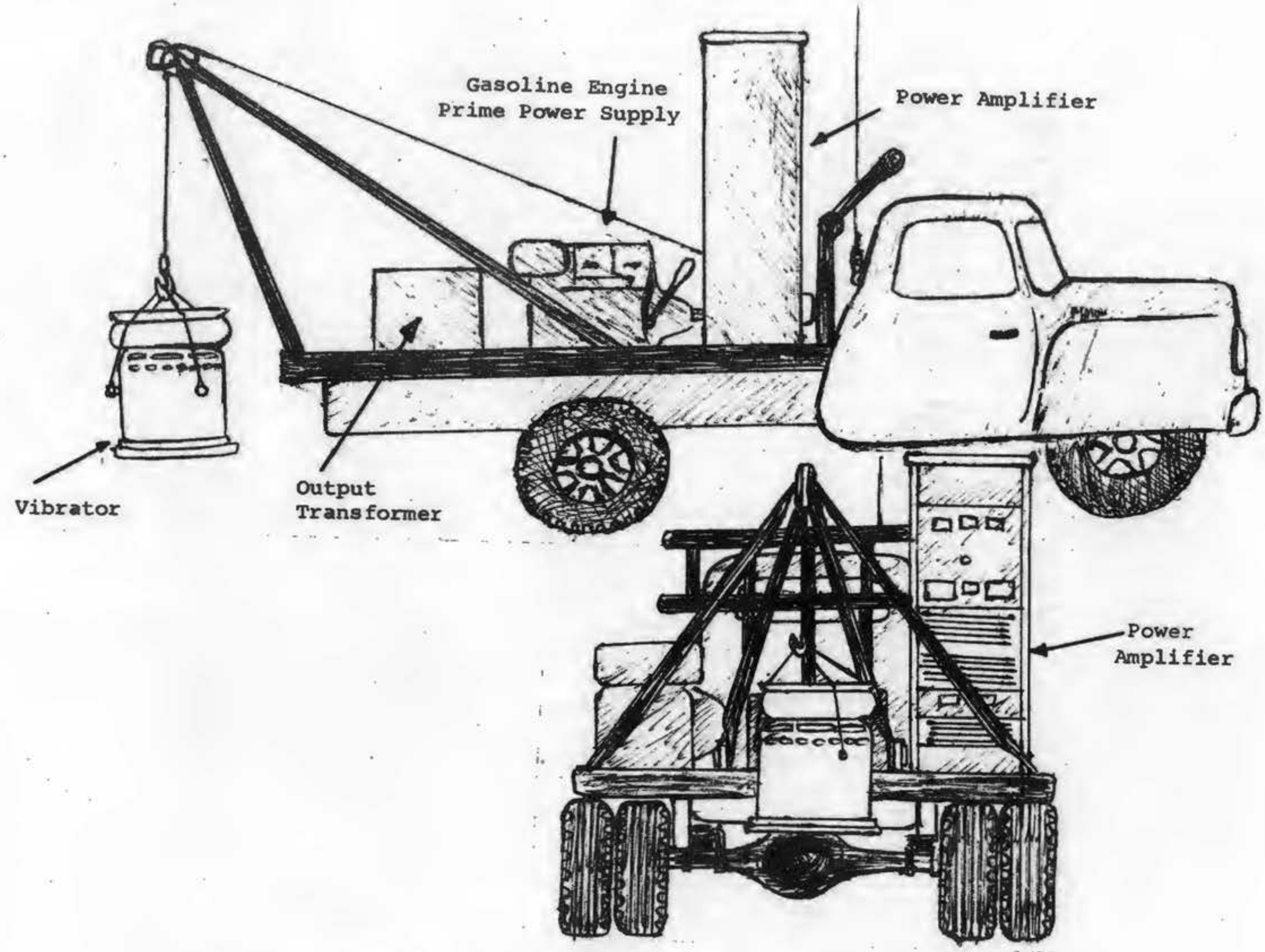

Figure 33. Sketch of Truck Mounted Field Equipment

not the exact location as was used in the original ground tests, being removed by about 100 yards from the earlier site.[3] The result of this first test is shown in Figure 34. It is observed that the curves closely follow the anticipated results as predicted from the analog model. The results, of course, are not in perfect agreement with the model results. For instance, maximum velocity values are not the same for both the inverted and normal positions. This tends to lead to the conclusions that viscous forces were different, depending upon the size of the earth mass, M_e. The shape of the inverted velocity curve indicates a resonance in the neighborhood of 70 cycles per second rather than the 100-cycle per second resonance as predicted by the model. However, there is evidence that parasitic resonances within the coil assembly (at the point where V_e was measured) may have interfered with a true peak reading at some higher frequency. A peripheral seisphone set out alongside the baseplate gave a response, however, which indicated that a truncated curve did in fact exist in the ground. Extrapolation, as shown in the figure, would give

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[3]At the time of these first inverted tests, modifications were being made to the truck mounted equipment, and the power amplifier had been removed to the laboratory. Since the portable power generators were therefore not available, tests were restricted to an area serviced by commercial power. Thus the tests were made just outside of the lab building where power was obtained through extension cords.

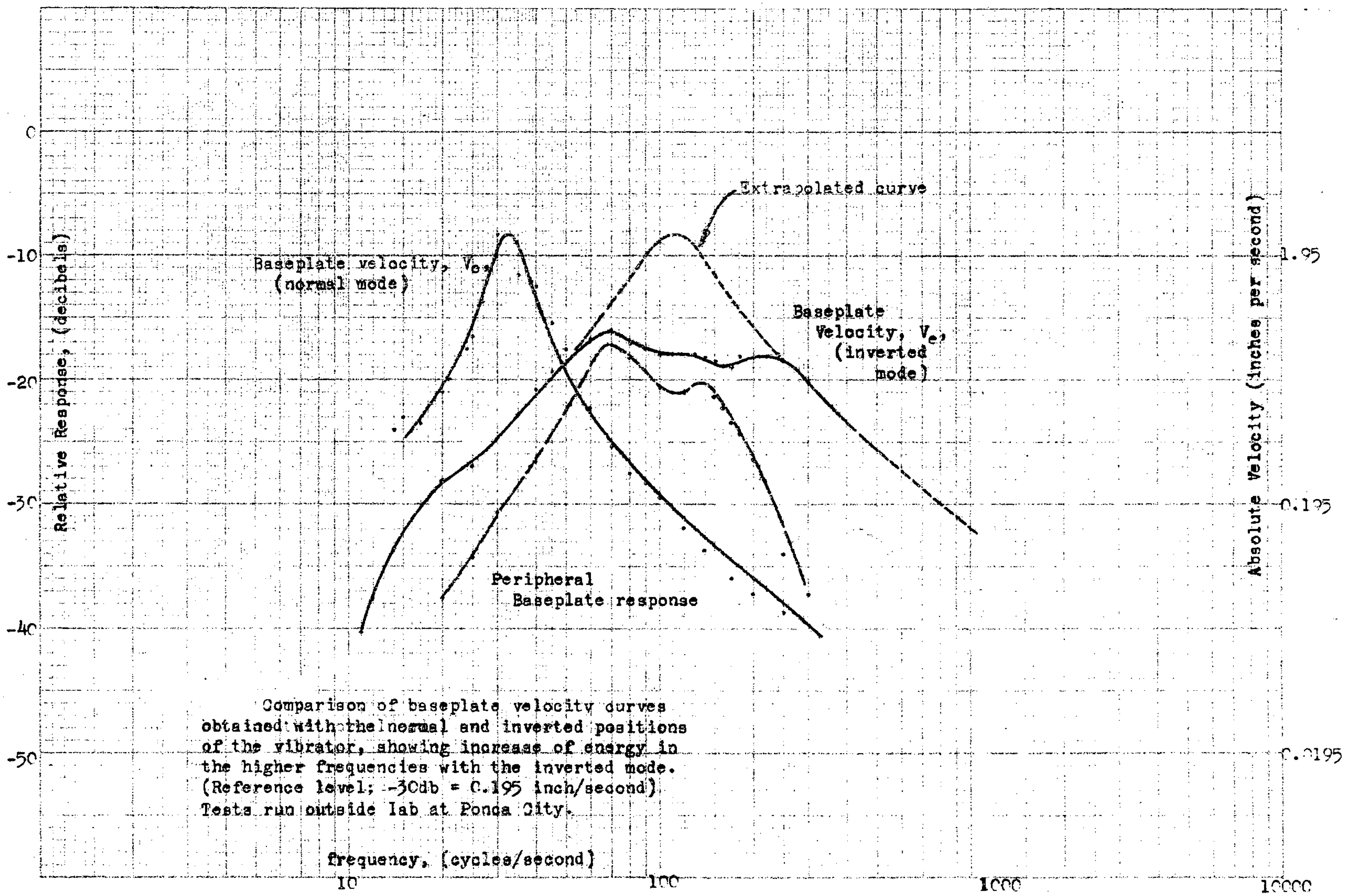

Figure 34. Comparative Tests of Normal and Inverted Vibrators

a resonant point more nearly in keeping with expected results anticipated from the analog. The slopes of this curve are also more in agreement with the electrical model. In spite of the apparent discrepancies, it is obvious that the resonance of the earth system has been shifted upward in accordance with the theory; and further, considerably more usable energy has been made available at the higher frequencies. Figure 35 is a similar test showing absolute magnitude curves of reaction velocities, both modes, along with the corresponding baseplate velocity for the inverted mode.[4]

After portable power was again available, another series of tests were made at the same location at Ponca City where the original tests were performed. These tests, therefore, provided a direct comparison with the initial experiments. Figures 36 and 37 show the resulting plots of baseplate and reaction mass velocities. Notice that in Figure 36 the maximum velocities are nearly the same for the normal or inverted positions. In addition, the resonant frequency is more in keeping with the model studies, if the obvious parasitic is ignored. Further, the curves resulting from the seisphones indicate an increased energy in the ground at the higher frequencies and nearly

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[4]The change in reference levels (at 30 decibels) between Figure 36 and 37 should cause no confusion. A decade attenuator was used between the velocity transducer and the VTVM used to measure decibels. In the test of Figure 37, the attenuation was ten times as great as in Figure 36.

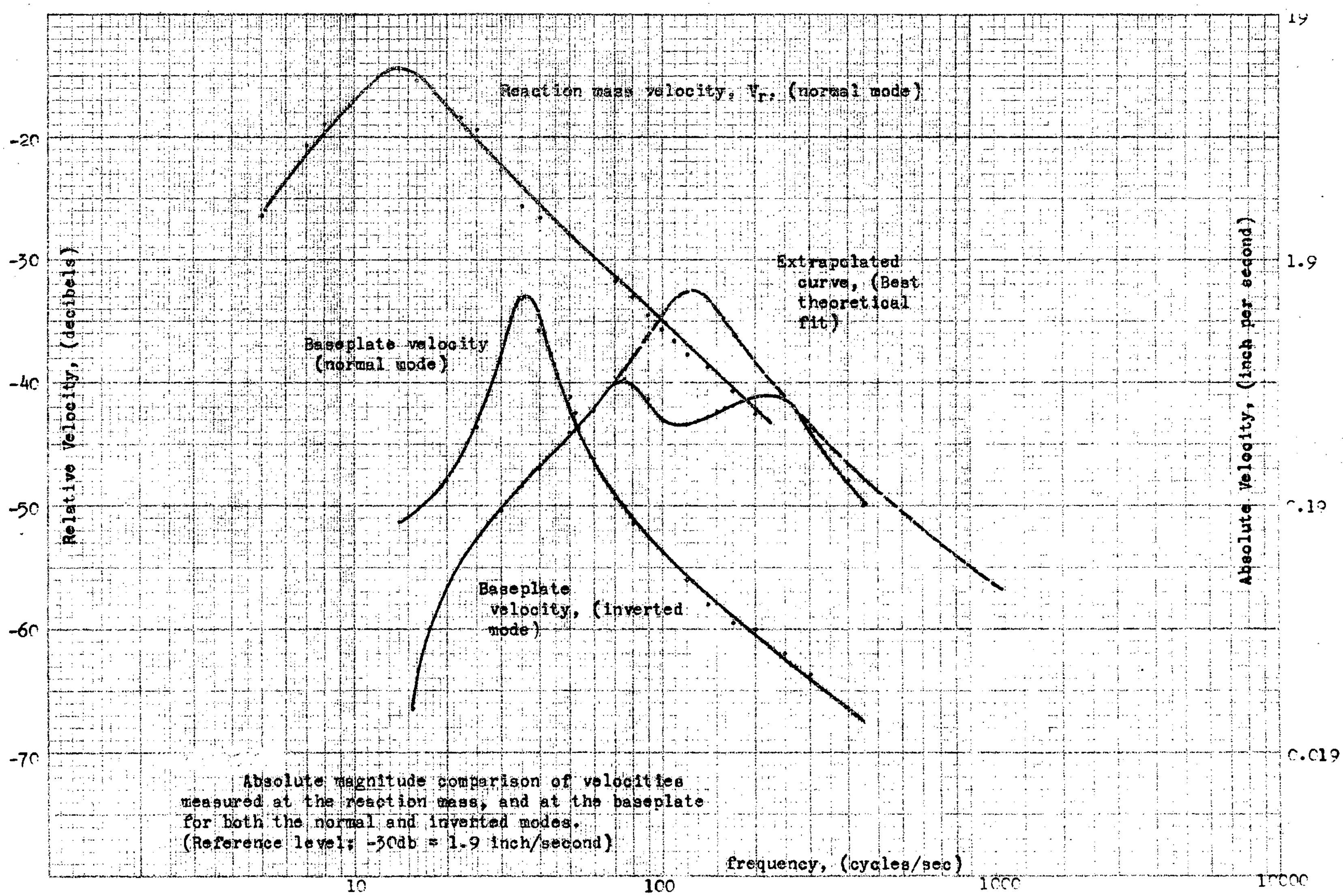

Figure 35. Absolute Velocity Comparisons Between Normal and Inverted Modes

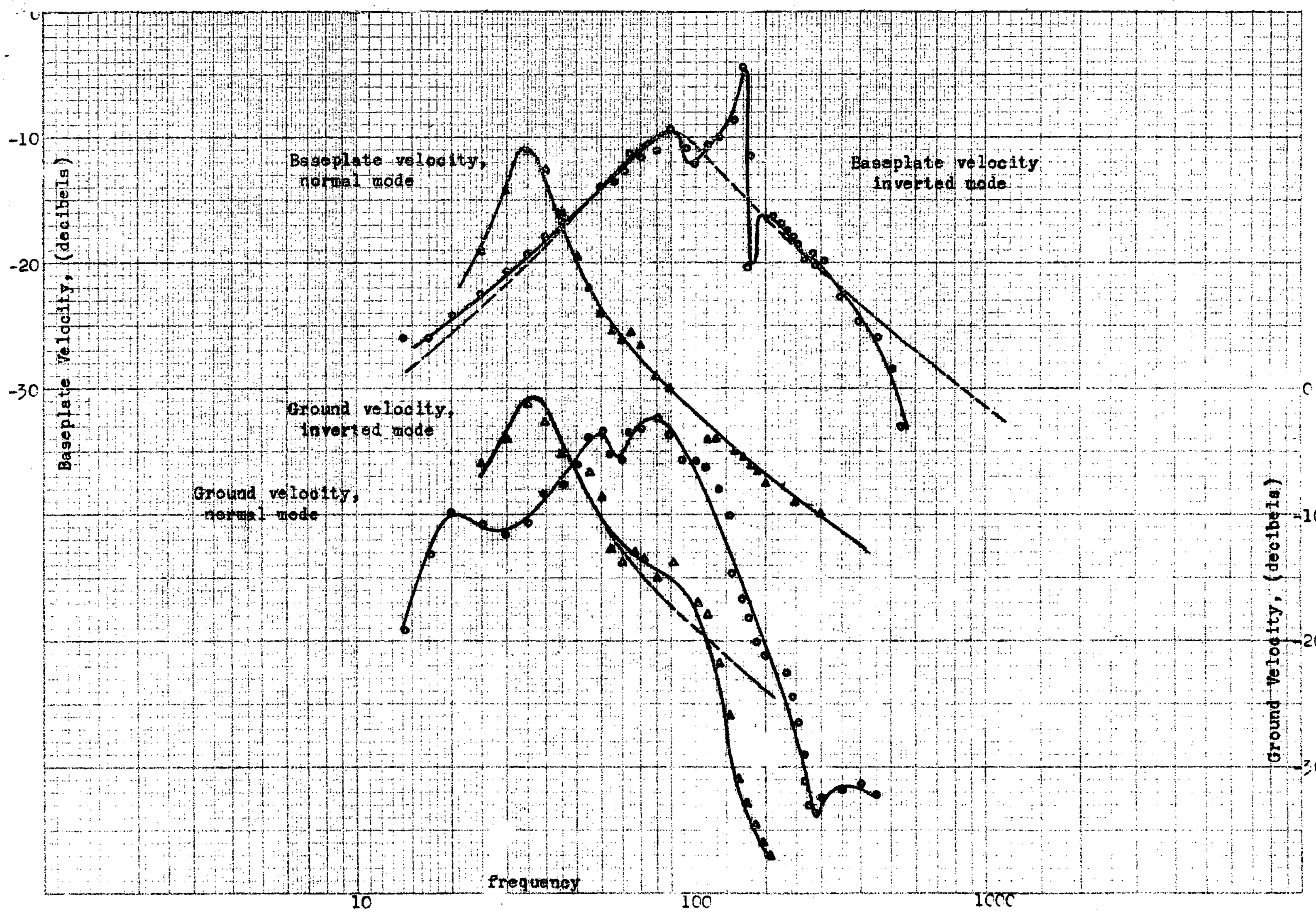

Figure 36. Inverted and Normal Mode Baseplate and Ground Velocity Comparison

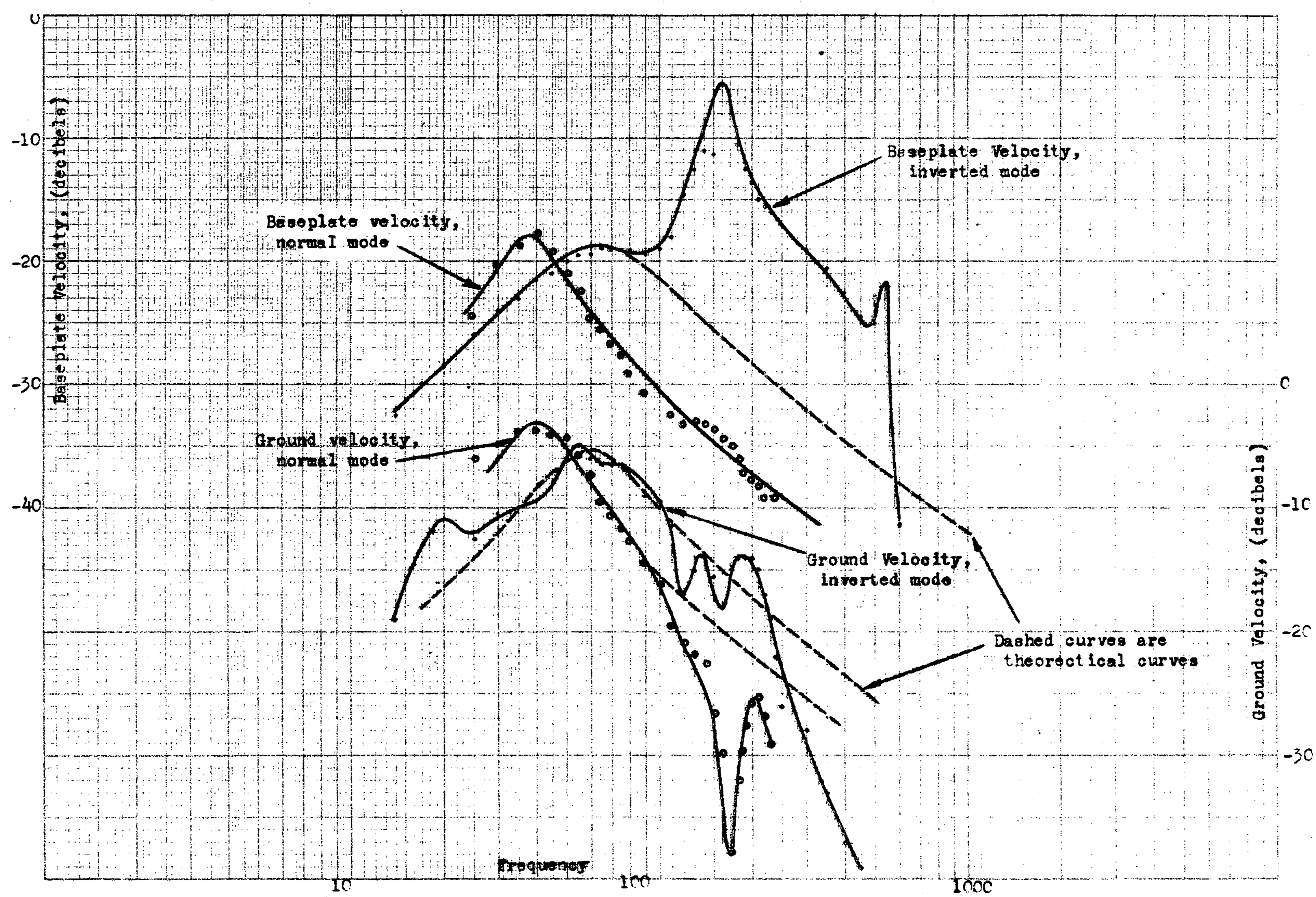

Figure 37. Inverted and Normal Mode Velocity Comparisons

identical maximums.

Figure 37 is a similar test which was run at a different ground surface position. The curve representing baseplate velocity is again effected by parasitics, but again an upward shift in energy distribution is clearly observed. Maximum velocities recorded in either position are also observed to be of nearly the same magnitude if the distorting parasitics are ignored.

CHAPTER VI

SEISMOLOGICAL SUBSURFACE SURVEY USING THE INVERTED VIBRATOR AS AN ENERGY SOURCE

It remained, now, only to make comparative geophysical field tests using the vibrator in both the normal and inverted attitude to assure the credibility of preceding theoretical and experimental work. The area selected for these tests was in the vicinity of Orlando, Oklahoma, and was chosen because the subsurface geology was well-known. The VIBROSEIS method was used, aided by multipattern shot arrangements and utilizing standard compositing techniques during recording.

It is not the purpose of this paper to discuss the VIBROSEIS technique. It will suffice to say that it is a technique making use of cross-correlation principles and has proven to be quite successful. The end result of the process is a standard multi-trace seismogram from which subsurface geology is inferred from the arrival times of the reflections from subsurface features.

The ability to resolve these subsurface features is a function of the wave lengths of the probing seismic wave fronts. Therefore, an increase in the resolution of a seismic record can be construed as an indication that higher frequencies were propagated into the earth and reflected back to the recording equipment. Further, the fundamental period of the reflections and their character will be an index to the frequencies involved. From the final field tests, then, it was anticipated that a marked improvement in resolution would result when utilizing the inverted vibrator. This would be adequate final evidence that higher frequency energy had been generated.

Orlando Field Tests

The layout of the Orlando test spread is diagrammed in Figure 38. A 20-position vibrator pattern was offset approximately 1,000 feet from the recording array, which consisted of ten signal gathering knots equidistantly spaced along 200 feet of multiconductor phone cable. At each knot, two 50-foot strings of seisphones were connected, each string incorporating ten equally spaced, electrically paralleled "jugs." In all, then, the recording nest comprised 200 phones distributed over an area 100 by 200 feet in extent. It will further be seen, from the figure, that the individual composite signals from each knot were separately brought into a 40-channel magnetic recorder located in the recording truck.

At the recording truck, a synchronizing signal was generated and transmitted via VHF radio to the vibrator truck where it was used to control the vibrator. This signal consisted of a continuous train of sine waves covering a spectrum

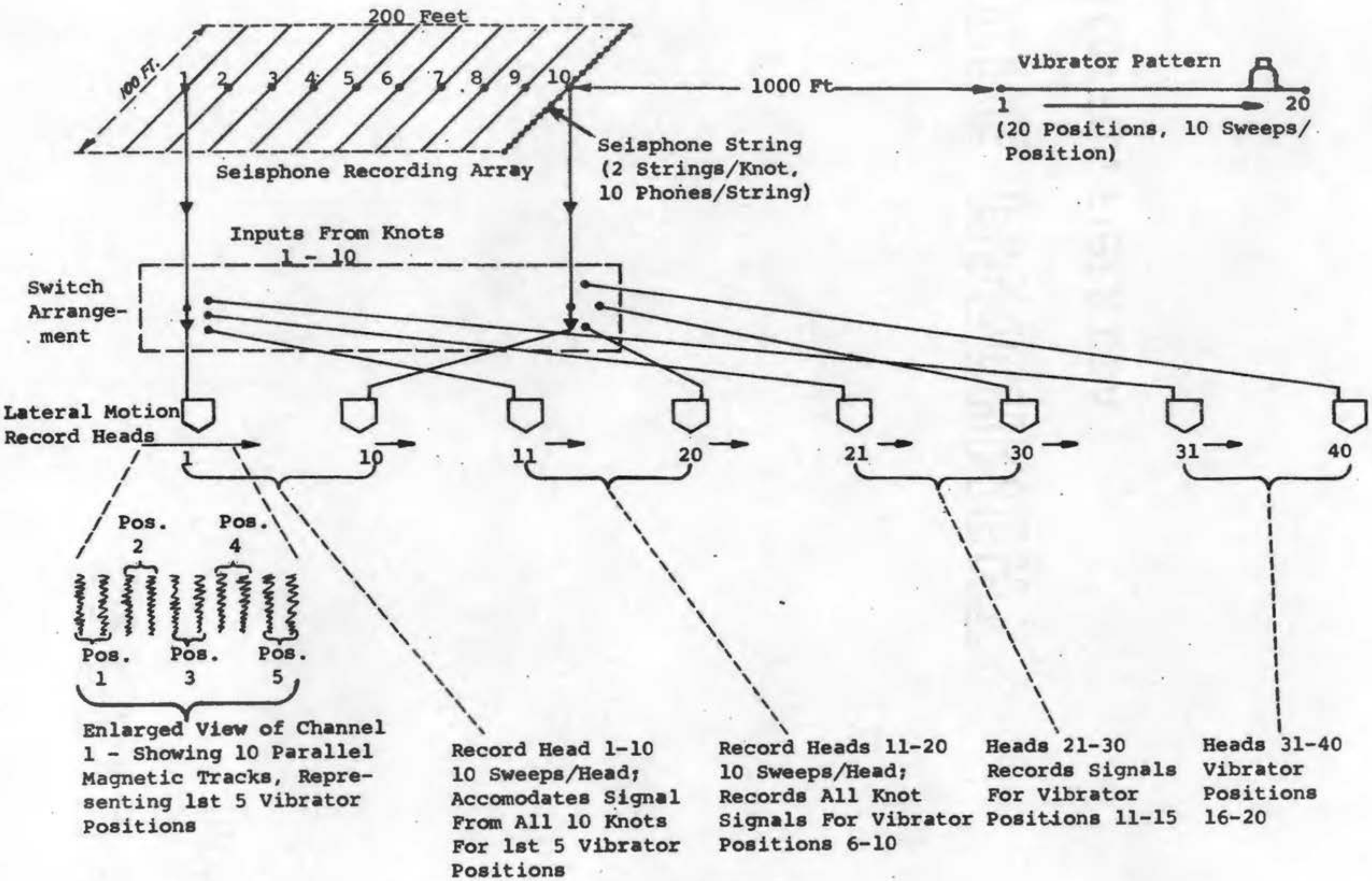

Figure 38. Layout and Recording Technique of Orlando Test

from 20 to 120 cycles per second. During a "shot," the vibrator was progressively moved along the 20-position source pattern. At each position, two control sweeps were transmitted from the recording truck to the vibrator, which converted the signal to seismic energy. Simultaneously, the returning, reflected, subsurface, seismic signals were recorded on the magnetic recorder.

Notice the manner in which the knot signals were wired to the 40-channel recorder. Knot No. 1 will be seen to be routed through a switching arrangement to record head Nos. 1, 11, 21 and 31. In a like manner, knot No. 2 was connected to record head Nos. 2, 12, 22 and 32. This pattern was repeated as all knot signals were brought into the recorder.

The mechanical mounting of the record heads used with the magnetic drum recorder permitted lateral movement of the record heads transverse to the direction of recording. This allowed ten side-by-side magnetic tracks to be recorded with each head, a track being recorded for each of ten lateral, fixed positions which could be randomly selected.[1] With this arrangement, the incoming knot signals from the seisphone array were assembled and recorded in the following manner:

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[1]This lateral type of magnetic recording is a patented process of Continental Oil Company, Ponca City, Oklahoma.

1. Signals arriving from knot No. 1, representing seismic arrivals associated with vibrator positions 1 through 5, were recorded with head No. 1, lateral positions 1 through 10.
2. Signals from knot No. 1, associated with vibrator positions 6 through 10, were recorded by record head No. 11.
3. Similarly, return energy from vibrator positions 11 through 15, arriving via knot No. 1, was recorded on the ten lateral positions of record head No. 21.
4. Finally, arrivals at knot No. 1, resulting from synchronous energy from vibrator positions 16 through 20 were recorded with head No. 32.

In a like manner, signals arriving from knots 2 through 10 were recorded on similarly assigned record heads. Therefore, by the time the vibrator has reached the last position in the source pattern, a 400-track magnetic tape recording had been assembled. This tape was then returned to the lab for further processing.

During processing, the 400-track record was scanned by forty playback heads, each of sufficient width to "read out" ten recorded channels at one time. Since the seismic signals generated by the vibrator at all positions of the source pattern[2] were identical, the received energy from ten independent frequency sweeps was effectively linearly added by the technique.[3] The 40 signals obtained in this manner were next correlated again in groups of ten against the original vibrator drive signal. The 40-trace record obtained after correlation represented, for each trace, five vibrator positions and ten individual frequency sweeps.

A four-part compositing operation followed correlation. Referring to Figure 39, Part I is seen to consist of signal traces Nos. 1 through 10; Part II comprises traces Nos. 11 through 20; Part III encompasses traces Nos. 21 through 30; and lastly, Part IV is composed of signals from channel Nos. 31 through 40. These individual parts were now operated upon the following fashion:

1. Parts I and II were combined by electrically adding trace No. 1 to trace No. 11, trace No. 2 to trace No. 12, etc., up to trace No. 10 combined with trace No. 20. This resulted in

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[2]The array patterns used at both the vibrator end and seisphone end of the field configuration were used to obtain directivity to the wanted signals while maintaining maximum cancellation and insensitivity to unwated signals.

[3]Patented process of Continental Oil Company. Signal increases as an arithmetic progression, while noise increases as a geometric progression where $r = \sqrt{2}$.

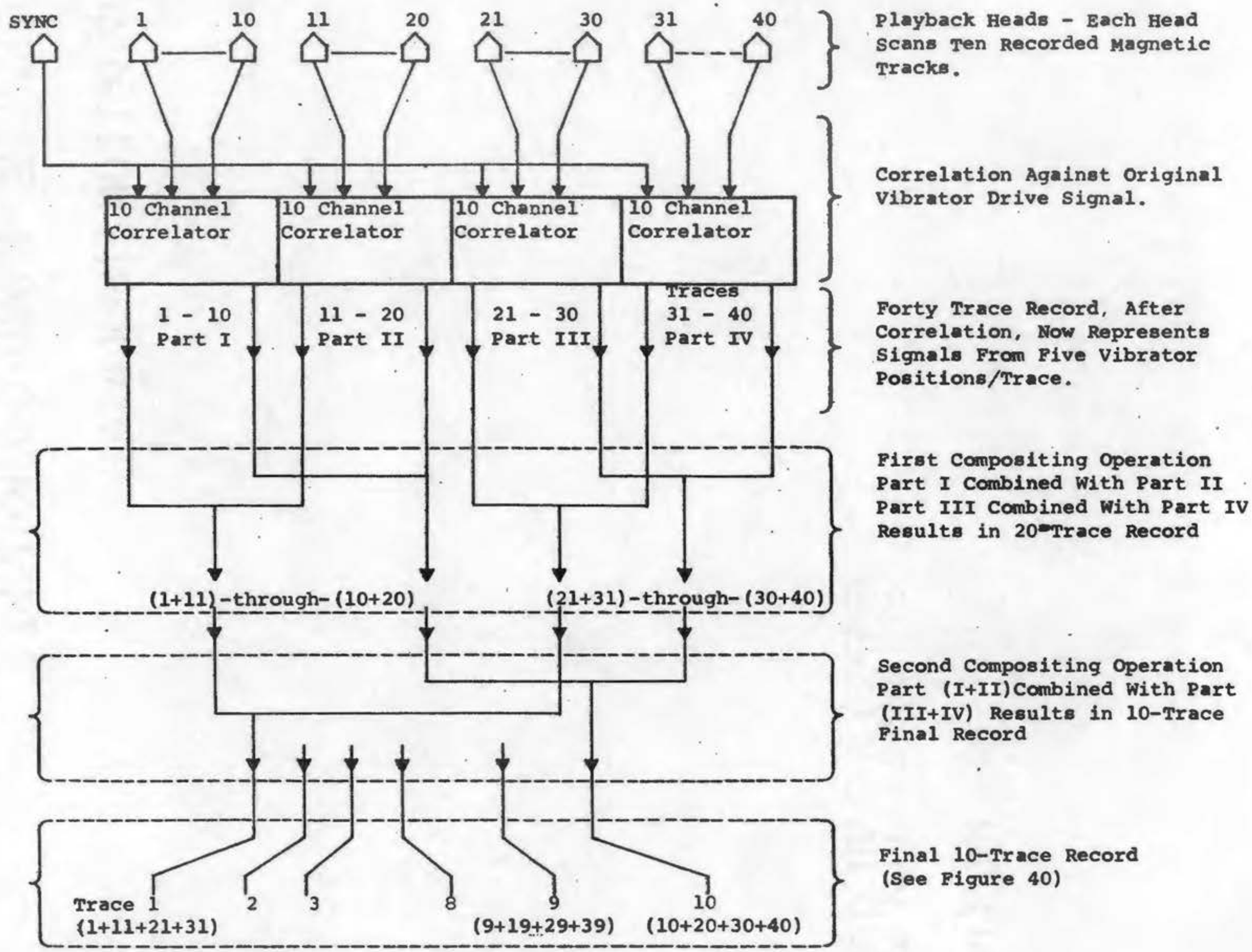


Figure 39. Playback Technique for Correlation and Compositing of Orlando Tests

a ten-trace record in which each trace represented the combined received energy from 20 synchronous vibrator sweeps and the record as a whole representing the first ten positions in the source pattern.

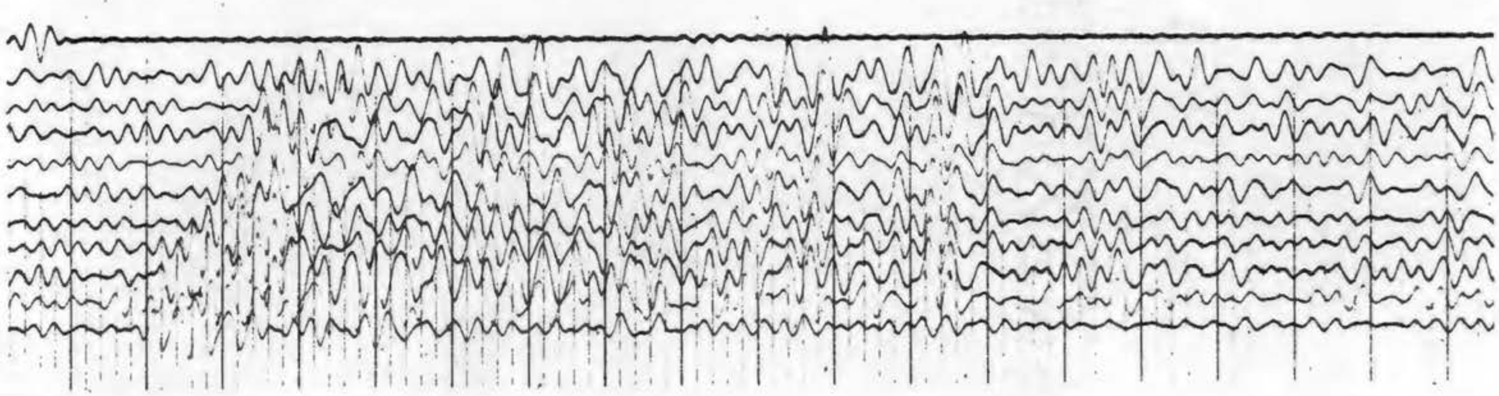
2. Parts III and IV were combined in an identical manner, trace No. 21 being added to trace No. 21, trace No. 22 to trace No. 32, trace No. 23 to trace No. 33, etc., up to channel No. 30 and to No. 40. This resulted in a second ten-trace record, which represented the combined received energy from vibrator positions Nos. 11 through 20.

The 2 ten-trace records were now added together, giving a final ten-trace record in which each trace represented the combined energy from the entire 20 vibrator positions, comprising 40 synchronous sweeps through the spectrum defined from 20 to 120 cycles per second. Graded mixing was avoided on this final record so as to circumvent any of the controversial arguments attendant with its use.

Results of Orlando Field Tests

The final records of the Orlando tests are shown in Figure 40. The records were processed in the manner described in the preceding section. The upper ten-trace record is the result

FINAL RECORD - NORMAL MODE →



FINAL RECORD - INVERTED MODE →

Figure 40. Final Ten Trace Records of Orlando Field Test

obtained using the vibrator in the normal position. The lower record resulted from rerunning the identical test but with the vibrator now in the inverted position. The results speak for themselves. A decided increase in resolution can be observed on the record made with the vibrator inverted. Further, the main arrivals in this record have a shorter fundamental period, indicating again that higher frequency energy was more predominant in this case.

CHAPTER VII

RESULTS AND CONCLUSIONS

The most significant result was the design of an improved electromagnetic vibrator for use in the geophysical program of the Continental Oil Company. This improved vibrator incorporated the principle of the light baseplate, a concept heretofore unknown, and a direct result of the theoretical, experimental, and electrical model studies outlined in the foregoing chapters. The use of this principle results in an improved transference of energy from the vibrator to the earth at the higher seismic frequencies.

Following the early field tests described in Chapter VI, considerably more testing was undertaken to further improve the equipment and techniques. In addition, the first efforts were begun to adapt the "light baseplate principle" to the larger and more powerful hydraulic vibrator routinely in service at that time. Because of the complexity of these machines, this proved to be a considerable undertaking; but eventually, through the combined efforts of the engineering staff of the Exploration Division, the project was successfully concluded. Since then, the inverted vibrator principle has been utilized successfully in many parts of the world.

Another result of the work described herein was the confidence and experience gained in approaching a difficult problem through the use of model techniques. Considerable time and money was conserved through the insight resulting from the electrical analog studies. Further, it was readily possible in later studies to vary all parameters in an attempt to optimize the over-all system.

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APPENDIX

GENISCO-SAVAGE MODEL V1000 VIBRATOR

A cylindrical electromechanical transducer of extremely rugged construction, designed for laboratory and production-line vibration, fatigue testing and general vibration analysis.

Special features include:

- Very Light Moving Coil Assembly
- High Thrust-to-Weight Ratio
- Automatic Impedance Matching
- Excellent Output Waveform
- Pure Collinear Motion

The Model V1000 vibrator produces continuous alternating thrust of ±550 lb. force at 1000 watts control power. Unit construction and precision design assures easy maintenance. No routine servicing is required. The vibrator has been stress-tested to withstand continuous operation at accelerations of 100 G.

A highly-efficient electro magnet, which has a flux density in the air gap of 100,000 lines-per-inch^2, is energized by a specially-designed coil, fully interleaved and vacuum-impregnated.

Full protection of the armature coil against high voltage surges is provided. The field coil is energized from a separate D.C. field supply (see Technical Data Sheet on D.C. Field Supply Type 1000).

The most impressive feature about this vibrator is the achievement of a practically flat frequency/impedance characteristic above the resonance of the sprung mass of the moving parts. Out of the sprung mass resonant area, normally in the region of 25-30 cps, which naturally is lowered by the added weight of the test object, the impedance settles down to 10 ohms and climbs slowly to 13 ohms between 150 and 2000 cps and thence to 17 ohms only at 5000 cps. This unique feature permits continuous or automatic cycling throughout this frequency range without the necessity of continual change of driver amplifier output impedance matching. This has been largely due to copper-plating the pole faces. The copper-plated pole faces have the effect of enabling the full useful output of the machine to be used at higher frequencies. This design feature together with others makes this vibrator the most efficient electromagnetic transducer yet manufactured.

The armature coil assembly consists of a very stiff magnesium header attached to a light alloy former on which is wound a multi-layer winding of silicone-enameled wire secured with special heat-resistant cement. Design and fabrication techniques have reduced eddy-currents to a very low level.

This particular model vibrator has successfully been operated at reduced ambient pressure of up to (1 x 10-6 m.m. Hg.) corresponding to altitudes of 100 miles plus.

These tests were conducted using a 20 lb. specimen and vibrating this unit through the frequency range of 5 to 2000 cps at acceleration levels of: (10 G for 8 hr. continuously, 15 G for 3 hr. continuously) and at full rated output for periods of up to 1 hr.) Conventional method resonant search sweeps and duration tests were included, with no adverse effects to the vibrator.

A novel method of suspension which offers maximum radial stiffness is employed. The net effect of this suspension is to produce a table with a sprung mass resonance at 20 cps and which is rugged enough to withstand side loads introduced by adverse loading configurations. (Tests performed with purposely off-centered loads of 4 lb. with 4" offset between C.G. of load and table, and driven at full rated output, have indicated that no detectable lateral movement takes place. A 500 power microscope was used to observe these tests.)

(This equipment is manufactured in England by the W. Bryan Savage Company and is sold and serviced in the United States by Genisco, Incorporated, Log Angeles, California.)

SPECIFICATIONS

RATED THRUST:	± 550 lb.
FREQUENCY RANGE:	5-5000 cps.
MAXIMUM EXCURSION:	0.6" double amplitude.
MAXIMUM CONTINUOUS INPUT:	1000 watts.
MAXIMUM PERMITTED ACCELERATION (UNLOADED):	100 G.
MAXIMUM ADDED WEIGHT (SPECIMEN) WITHOUT EXTERNAL SUPPORT:	20 lb.
WEIGHT OF MOVING ELEMENT:	12.87 lb.
MOUNTING PROVISIONS:	Single driving stud (as illustrated) for mechanical fuse or push rod application. Mounting table can be provided upon request.
TABLE DIAMETER (OPTIONAL):	8" diameter table with tapped mounting holes for securing specimen fixture to table. (Mounting table available at additional cost).
FIELD COIL CURRENT:	1.8 amps at 220 volt D.C. nominal.

NOTE: This Model V1000 vibrator is ideally suited for use with the Model KM2S or Model KLF amplifier and D.C. Field Supply Type 1000 to provide a ± 550 lb. thrust vibration system.

DIMENSIONS:	Diameter: 23" Height Overall: 20" Mounting Holes: 6-5/8" diameter holes on 21-1/4" Bolt Circle
WEIGHT:	Approximately 1000 lbs.

GENISCO-SAVAGE MODEL KLF AMPLIFIER

The Model KLF amplifier meets the demand for a low frequency power supply for vibration and fatigue testing in conformance with all procedures of MIL-E-5272A, MIL-E-005272B, MIL-E-5422D and similar military and commercial specifications. Special features include low distortion, exceptionally high reliability due to tube and circuit design considerations, good stability by feed-back circuitry, good output voltage regulation, and a multi-ratio output transformer to facilitate correct matching to the load. No electrolytic condensers are used in any high voltage circuit.

Several convenient "built-in" features are incorporated into the amplifier design, such as continuously indicating output level meters and the amplifier tube current meters for checking the tube performance prior to and during operation. Two, three or more of these amplifiers may be used together to obtain multiples of the power rating.

Optional features include specially stabilized A.C. power units for regulating line voltage and output monitors for continuous indication of voltage, current, volt-amps and impedance.

A six and one-half foot console contains all the amplifier components with the exception of the output transformer, which is in a separate steel case. Vertical panel construction affords easy access to all components. Tubes are accessible from the front of the panel and protected by quick-release grilled covers. Numerous built-in safety features provide maximum equipment and personnel safety.

(This equipment is manufactured in England by the W. Bryan Savage Company and is sold and serviced in the United States by Genisco, Incorporated, Los Angeles, California.)

SPECIFICATIONS

OUTPUT:	1000 watts at 50, 100 or 200 volts. Secondary load 2.5, 10 or 40 ohms.
FREQUENCY RANGE:	6 to 2000 cps at 1000 watts. 3 cps at 100 watts. 3000 cps at 800 watts. 5000 cps at 400 watts. Note: Power attenuation is approximately 3 db per octave below and above rated frequency range.
GAIN:	81 db.
SENSITIVITY:	0.050 volts R.M.S. into 600 ohms for full output.
TOTAL HARMONIC DISTORTION:	Less than 2 1/2 per cent at 1000 watts. 10-1000 cps. Distortion is correspondingly lower with reduced power.
OUTPUT REGULATION:	9 per cent change in voltage, no load to full load.
NOISE LEVEL:	-70 db.
INPUT POWER SUPPLY:	200-250 volt, 50-60 cps, single-phase. (The equipment can be modified (optional) for

	115 volt single-phase operation.
INPUT POWER CONSUMPTION:	Full Power: 2.75 KVA Quiescent: 1.22 KVA High Voltage "Off": 463 volt amps.
OUTPUT STAGE QUIESCENT CURRENT:	180 ma.
DIMENSIONS:	Amplifier Rack: 78" high by 22 3/4" wide by 20 3/4" deep. Transformer: 22 3/4" high by 28" wide, by 23" deep.
WEIGHT:	Amplifier Rack: 448 lb. Transformer: 448 lb.

NOTE: This model KLF amplifier is ideally suited for use with the V1000 vibrator and D.C. Field Supply Type 1000 to provide a ± 550 lb. thrust, 6 to 5000 cps vibration system.

When (2) Model KLF amplifiers are series/parallel connected, they are ideally suited for use with the V1000B vibrator and D.C. Field Supply Type 1000 to provide a ± 750 lb. thrust, 6 to 5000 cps vibration system.

Although the amplifier output attenuates beyond 2000 cps, full rated thrust of the V1000 or V1000B vibrators may still be obtained due to the increasing sensitivity of the machines above this frequency range. See the Genisco-Savage Technical Data Sheets and performance curves for the V1000 and V1000B vibrators.

(From specifications published by Genisco, Incorporated, Los Angeles, California.)

VITA

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Candidate for the Degree of

Master of Science

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