Design and testing of a downhole continuous wave generator

Cole L. Smith

Follow this and additional works at: http://scholarsmine.mst.edu/masters_theses

Recommended Citation
DESIGN AND TESTING OF A DOWNHOLE CONTINUOUS
WAVE GENERATOR

BY

COLE L. SMITH.

A
THESIS
submitted to the faculty of
THE UNIVERSITY OF MISSOURI - ROLLA
in partial fulfillment of the requirements for the
Degree of
MASTER OF SCIENCE IN GEOLOGY - GEOPHYSICS OPTION

Rolla, Missouri

1968

Approved by

[Signatures]

[Advisor's Name]

[Affiliate's Name]
ABSTRACT

The continuous shear wave generator was designed to be the first instrument capable of producing a continuous high frequency signal below the weathered layer of the earth. This is to be accomplished by placing the instrument in a bore hole and lowering it below the weathered layer where the higher frequencies are severely attenuated. The generator produced a measurable signal output with the output force being approximately 11 pounds force. Testing of the generator showed the necessity of using a spring system with a low natural frequency. The testing also indicated several improvements which should be made in the generator in order to obtain a greater force output.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABSTRACT</td>
<td>ii</td>
</tr>
<tr>
<td>LIST OF FIGURES</td>
<td>iv</td>
</tr>
<tr>
<td>LIST OF PLATES</td>
<td>v</td>
</tr>
<tr>
<td>Chapter I. INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>Chapter II. DESIGN AND TESTING OF THE WAVE GENERATOR........</td>
<td>4</td>
</tr>
<tr>
<td>A. Coil Design</td>
<td>4</td>
</tr>
<tr>
<td>B. Coil Housing</td>
<td>5</td>
</tr>
<tr>
<td>C. Shaft Guides</td>
<td>7</td>
</tr>
<tr>
<td>D. Shaft</td>
<td>7</td>
</tr>
<tr>
<td>E. Springs</td>
<td>8</td>
</tr>
<tr>
<td>F. Method of Testing</td>
<td>9</td>
</tr>
<tr>
<td>G. Results of Testing</td>
<td>10</td>
</tr>
<tr>
<td>Chapter III. CONCLUSION</td>
<td>27</td>
</tr>
<tr>
<td>BIBLIOGRAPHY</td>
<td>30</td>
</tr>
<tr>
<td>APPENDICIES</td>
<td></td>
</tr>
<tr>
<td>A. Explanation of the Formula Used to Find the Force Between Two Circular Coils</td>
<td>31</td>
</tr>
<tr>
<td>B. List of Equipment</td>
<td>35</td>
</tr>
<tr>
<td>C. Plates</td>
<td>37</td>
</tr>
<tr>
<td>VITA</td>
<td>45</td>
</tr>
</tbody>
</table>
# LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Permeability and saturation curves for cast steel and transformer iron</td>
<td>6</td>
</tr>
<tr>
<td>2</td>
<td>A.C. impedance versus A.C. voltage</td>
<td>11</td>
</tr>
<tr>
<td>3</td>
<td>Frequency versus A.C. impedance</td>
<td>14</td>
</tr>
<tr>
<td>4</td>
<td>A.C. voltage versus acceleration</td>
<td>16</td>
</tr>
<tr>
<td>5</td>
<td>Response of the 0.07 and 0.07 inch spring set</td>
<td>17</td>
</tr>
<tr>
<td>6</td>
<td>Response of the 0.21 and 0.07 inch spring set</td>
<td>18</td>
</tr>
<tr>
<td>7</td>
<td>Response of the 0.33 and 0.07 inch spring set</td>
<td>19</td>
</tr>
<tr>
<td>8</td>
<td>Response of the 0.21 and 0.21 inch spring set</td>
<td>20</td>
</tr>
<tr>
<td>9</td>
<td>Response of the 0.33 and 0.21 inch spring set</td>
<td>21</td>
</tr>
<tr>
<td>10</td>
<td>Response of the 0.33 and 0.33 inch spring set</td>
<td>22</td>
</tr>
<tr>
<td>11</td>
<td>Computation of damping at resonance</td>
<td>24</td>
</tr>
</tbody>
</table>
# LIST OF PLATES

<table>
<thead>
<tr>
<th>Plate</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>I.</td>
<td>Electrodynamic Vibrator</td>
<td>38</td>
</tr>
<tr>
<td>II.</td>
<td>Schematic of Vibrator</td>
<td>39</td>
</tr>
<tr>
<td>III.</td>
<td>Coil Housing</td>
<td>40</td>
</tr>
<tr>
<td>IV.</td>
<td>Shaft Guide</td>
<td>41</td>
</tr>
<tr>
<td>V.</td>
<td>Shaft</td>
<td>42</td>
</tr>
<tr>
<td>VI.</td>
<td>Spring</td>
<td>43</td>
</tr>
<tr>
<td>VII.</td>
<td>Test Setup</td>
<td>44</td>
</tr>
</tbody>
</table>
Chapter I
INTRODUCTION

There has been little work done on the seismic transmission characteristics of undisturbed sediments at high frequencies. This is for two reasons. 1) When a controlled frequency energy source is used on the surface, the high frequencies are severely attenuated in the over-burdened or weathered layer. 2) When an impulse or explosive source is used either on the surface or under the weathered layer, a great thickness of homogeneous material containing no reflecting boundaries is required. This is necessary so a pure wave form, one susceptible to analysis, is obtained. If there are reflecting boundaries present, the wave form will be modified by reflections from the boundaries.

There have been some attempts to avoid the problems of high frequency attenuation in the weathered layer and contamination of the signal by reflections from boundaries. One of the first attempts to avoid these problems was made by Howell, Kean and Thompson. They used an electrodynamic vibrator connected by an aluminum shaft to a plate resting on the bottom of a borehole. With this arrangement they could record frequencies up to 1400 Hz at 1000 feet from the borehole. They attempted to avoid contamination of the signal by using wave trains a few hundredths of a second long. Despite some significant results, they were forced to conclude that they could not achieve accurate determination of attenuation factors.

Another attempt to overcome the problems encountered in transmission studies was made by McDonal, Angona, Mills, Sengbush,
van Nostrand, and White.\(^2\) They exploded dynamite below the weathered layer of the Pierre shale. The Pierre is a shale several thousand feet thick with no reflecting boundaries. Although good results were obtained from this attenuation study, it should be pointed out that the Pierre is almost unique in being a homogeneous bed with a great enough thickness for this type of study to take place.

A different solution to the problems involved in high frequency attenuation studies must be used. A signal can be induced below the weathered layer to avoid the high frequency attenuation there. In addition, by use of Statistical Communication Theory one may negate the boundary effects provided a continuous, wide-band random signal may be generated within the layer under investigation.

By use of a continuous wide-band random signal and correlation analysis, that signal that travels the direct path between any two points of measurement may be separated from those signals that were reflected or refracted from boundaries. This correlation technique would thus yield the statistical characteristics of the direct traveling wave form, from which the transmission characteristic of this medium may be obtained.

A seismic source capable of solving the transmission study problems by the methods mentioned above must have several characteristics:

1) It must be capable of transmitting a wide frequency range into the surrounding rock.

2) It must be able to operate at various depths.

3) It must produce a continuous signal.

4) It must produce enough force so the signal is discernible at some distances from the instrument.
A suggested design for an instrument meeting the requirements listed above is shown in Plates I and II. Such an instrument, which is described here as a downhole continuous wave generator, consists of three basic parts: a coil system with associated magnetic circuit, a mass spring system, and a downhole suspension system. The arrangement of these systems is shown on Plate II.

The generator was designed to move a shaft wound with a coil which will carry an alternating current. The A.C., or moving, coil was positioned between two D.C., or field, coils in a double-end magnetic structure. When current was passed through the coils, a force was generated between the A.C. coil and the two D.C. coils by the change in mutual inductance with position of the A.C. coil. The force produced was the driving force of the shaft. The shaft was held in place by two plate springs. The force was then transferred to the down-hole suspension system by the mass-spring system and into the surrounding rocks through the pistons and gripper plates of the suspension system.

The design and testing of the generator was divided into two parts. The design and testing of the suspension system and some of the design and testing of the mass-spring system is discussed in the Master's thesis entitled, "The Downhole Suspension and Testing of an Electrodynamic Shear Wave Exciter", by Mr. Robert F. Kehrman (University of Missouri-Rolla, 1968), co-worker on the project.

The design and testing of the coil system and some of the mass-spring system is the subject of my research. The results of this research are contained herein.
Chapter II
DESIGN AND TESTING OF THE WAVE GENERATOR

A. Coil Design

The coils were designed to allow the wave generator to be placed in an eight-inch-diameter borehole with a half-inch clearance on both sides of the generator. The coil sizes were further limited by the necessity of there being sufficient metal surrounding them to avoid saturation of the magnetic circuit.

The D.C. coils were composed of ten layers of ten gauge copper wire with seventeen turns per layer, which were capable of forty amperes with no undue heating. The A.C. coils were composed of twelve layers of twenty gauge copper wire, which were capable of carrying two amperes with no undue heating.

An analysis was performed to determine the geometry of the coils which would give the maximum amount of force within the space limitations set by the diameter of the borehole. The analysis yielded a theoretical calculation of the optimum geometry for the coils. The calculations were based on the following formula used by Scott to find the force between two circular filaments:

\[ F_m = i_{ac} i_{dc} \mu_{mr} \frac{d M_{ac}}{dz} M_{ac} M_{dc} \]  

(1)

Where \( i_{ac} \) is the current in the moving coils, \( i_{dc} \) is the current in the driving coils, \( \mu_{mr} \) is the mean relative permeability of the magnetic circuit, \( \frac{d M_{ac}}{dz} \) is the first derivative of the mutual inductance between the moving coil and the driving coils with respect to the axis of the coils, \( M_{ac} \) is the number of turns of
wire in the moving coil, and \( M_{dc} \) is the number of turns of wire in the driving coil. The computations were done on a computer using a modified form of equation (1) as given by Curtis and Curtis\(^4\) to find the force between two circular coils. The formula is explained in Appendix A.

\[
F_m = i_{ac} i_{dc} \mu_{ac} M_{ac} M_{dc} \frac{1}{2} \left( 1 + D_2 + D_4 + \frac{(x D_2^2)}{2} \right) \quad (2)
\]

By varying the distance between the D.C. and A.C. coils, the mean radii and length of the coils, the best geometry of the coils was found. The coil configuration which gave the maximum amount of force with the space limitations set on the coil size was found to have D.C. coils two inches in length with a mean radius of one and three-fourths inches, an A.C. coil three inches in length with a mean radius of three-fourths of an inch, and a distance of two inches between the centers of the D.C. and A.C. coil.

The field coils were connected to the power supply in such a way that their fields were opposing. This caused a high flux density through the intermediate plate of the coil housing (Shown in Plate II) and the adjacent air gap. The high flux density through the air gap interacting with the current in the moving coil generated an alternating force.

B. Coil Housing

The coil housing, made of cast steel, is shown on Plates II and III. Cast steel was chosen because it was easily machined and, as shown in Figure 1, it will not become saturated at even relatively
Figure 1. Permeability and saturation curves for cast steel and transformer iron.
high intensities. Cast steel also has a good permeability at high magnetic intensities, as shown in Figure 1. As designed the minimum thickness of the magnetic circuit in the coil housing is one inch with the intermediate plate having a thickness of two inches. This was designed to help avoid saturation of the coil housing. Access to the coils is attained by removing the shaft guide and they may be easily lifted out of the housing.

C. Shaft Guides

The shaft guides, shown in Plates II and IV, were also made of cast steel. They served the purpose of sealing the moving shaft from the air chamber and served as a guide for the shaft to insure that movement was in a vertical direction. The shaft guides were also used to complete the magnetic circuit by providing an inch-thick path where the magnetic flux lines could flow.

Set inside the shaft guide was a tube of teflon, shown on Plate II, which served as an air seal at the top of the shaft guide. It was also used to cut down on friction and protect the shaft from being nicked and scratched by metal to metal contact with the shaft guide.

D. Shaft

The shaft, shown on Plates II and V, was made in four parts and was composed of three different types of metal. The portion of the shaft labeled A on Plate V is made of cold rolled steel which was selected for its strength. Even though the cold rolled steel became permanently magnetized, it did not have hysteresis losses, because it was located beyond the magnetic circuit. The part of the shaft labeled B was made of cast steel, and the central
portion of the shaft labeled C was made of disks of transformer iron in a cast steel sheath. This type of construction helped to avoid the eddy current losses due to the alternating current of the moving coil. The moving coil was wound directly onto the shaft and the force moving the coil also moved the shaft. The bolt labeled D was screwed into the shaft with the spring in between. The shaft transmitted the force directly to the spring. The bolt could be adapted in such a manner that extra weight could be added to the weight of the shaft in order to change the frequency response of the machine.

E. Springs

The springs were made of tempered steel and were designed as shown in Plate VI. The desired natural frequency of the system determined the thickness of the springs. The springs were designed to produce natural frequencies of approximately 30 Hz, 100 Hz, 500 Hz, and 1000 Hz. Other natural frequencies could be obtained by various combinations of these springs. Since there were two springs on the generator at one time, there were ten combinations that were possible with each combination producing a different natural frequency of the system.

The spring constant for the first mode of vibration of the plate-type spring could be computed by considering the spring as a disk clamped at all points of its circumference. The formula for computing the spring constant for a single spring was derived from the expressions found in Harris and Crede⁵:
\[ \omega_n = 4.09 \sqrt{\frac{Et^3}{ma^2(1-r^2)}} \]  \hspace{1cm} (3)

\[ \omega_n = (f_n)(2\pi) \]  \hspace{1cm} (4)

\( E = 28.6 \times 10^6 \) pounds/inch\(^2\), which is Young's Modulus for steel.

\( A \) is the diameter of the disk.

\( r \) is Poisson's Ratio for steel.

\( m \) is the mass of the shaft to be suspended from the spring.

\( \omega_n \) is the angular natural frequency.

\( t \) is the thickness of the disk.

\( f_n \) is the natural frequency in cycles per second.

By solving equation (e) for \( t \) we have

\[ t = \frac{(2\pi f_n)^2 ma^2(1-r^2)^{1/3}}{(4.09)^2 E} \]  \hspace{1cm} (5)

When the equation is solved, we find that

\[ t_{30} = 0.03 \text{ in.} \]

\[ t_{100} = 0.067 \text{ in.} \]

\[ t_{500} = 0.2 \text{ in.} \]

\[ t_{1000} = 0.31 \text{ in.} \]

where the subscript indicates the first natural frequency of the system for a given spring thickness.

F. Method of Testing

A complete list of the equipment used in testing the generator is found in Appendix B.

The generator was tested by lowering it into a hole in a 700 pound concrete block and activating the suspension system shown
on Plate VII. The pistons and gripper plates, shown on Plate II, were extended under a pressure of 350 PSI and the cable, shown on Plate VII, was allowed to go slack. Current was passed through the coils and the force generated was picked up by the accelerometer mounted where shown in Plate VII. The amplifier used to drive the A.C. coil had a power output of 200 W and a frequency response of 21 to 50,000 Hz at full power with only 2 percent distortion. The quartz accelerometer had a sensitivity of 0.986 picocoulombs/g, a frequency response from near D.C. to 7,000 Hz, and a linearity of ±1 percent. The output of the accelerometer was monitored on an oscilloscope and the results recorded.

G. Results of Testing

The change of A.C. impedance* with respect to A.C. voltage at 195 Hz is plotted in Figure 2. It should be pointed out that when the D.C. current was 20 amps and 40 amps, the ammeter which was used to measure the alternating current went off scale. Where a change of scale in the ammeter readings was necessary, there was a sudden change in the slope of the curve. This seemed to be the fault of the instrument and does not reflect a change in the A.C. current. Only when the D.C. current was 30 amps was a complete series of readings taken with no change in scale necessary. An observation which may be made is that the impedance increased to a certain

* When impedance is spoken of in this paper, the ratio V/I is being referred to, where V is the A.C. voltage as read for an A.C. voltmeter and I is the A.C. current as read from an A.C. ammeter.
Figure 2. A.C. impedance versus A.C. voltage.

\[ Z = \frac{V}{I} = \frac{1}{I} \cdot V \]

\[ \phi = \frac{1}{2} \cdot x \]
value which is different for different D.C. currents and then leveled off to a constant value. This was most probably due to saturation of the laminated core of the moving coil.

The circuit impedance of a coil with a laminated iron core is shown by Welsby to be proportional to $Z^-$, where $Z^-$ is the field impedance relating to conditions existing on the negatively defined side of a current sheet. Then

$$Z^- = j w \mu n a \left(\frac{\text{TANH} \frac{Pa}{Pa}}{Pa}\right)$$

where

- $j = (-1)^{1/2}$
- $w =$ angular frequency
- $\mu =$ permeability
- $n =$ universal magnetic constant
- $a =$ inside radius of the coil
- $P =$ field propagation coefficient

It can be seen in Figure 1 that up to the point of saturation $\mu$ is a function of $H$

$$\mu = B/Hn$$

where $H$ is the magnetic intensity and $B$ is the magnetic induction.

As can be seen in Figure 1, once the metal becomes saturated, $B$ approaches a constant value. As this figure shows, the transformer iron becomes saturated at a much lower $H$ than the cast steel does. This indicates that saturation probably occurs in the laminated iron core and not in the rest of the magnetic circuit since the increase of $H$ after the saturation of transformer iron is probably
not enough to saturate the cast steel. Another way of writing equation (6) is

\[ Z^- = j \omega \frac{B}{H} a \left( \frac{\text{TANH} Pa}{Pa} \right) \]

up to the point of saturation and

\[ Z^- = j \omega \mu n a \left( \frac{\text{Tanh} Pa}{Pa} \right) \]

after saturation. As can be seen from the figure, saturation occurs at different A.C. voltages for different D.C. currents. Saturation always occurs when the A.C. current is about 0.47 amps, as is to be expected.

When saturation of a material becomes noticeable, there will still be a slight increase of B with a large increase of H until complete saturation of the metal is accomplished. This is noticeable in Figure 3, where Z is plotted against frequency. At a given frequency, when the D.C. current is changed from 0 to 20 amps, there is a fairly large drop in Z. When the saturation begins to occur, there is a less noticeable drop in Z at a given frequency. When the D.C. current is changed from 30 amps to 40 amps and complete saturation is being approached and \( \mu \) is becoming constant, there is a much smaller decrease in Z at a given frequency. This figure also demonstrates another situation which can be expected to occur in A.C. coils of this type. At very low frequencies the D.C. resistance and hysteresis losses of the coil provide the only large power losses. At higher frequencies additional power is dissipated by the effect of eddy currents in the core, the winding, and the
Figure 3. Frequency versus A.C. impedance

A.C. Voltage = 40 volts
conducting material. According to Welsby, at high frequencies the losses become proportional to $\sqrt{f}$, where $f$ is the frequency in cycles per second.

Another test was run in which the frequency was held constant with the D.C. current set at three different values to see if an increase in A.C. voltage would produce a linear increase in acceleration. The acceleration measured on the air chamber was actually the acceleration of the particles at the boundary between the gripper plates and the cement back, as was concluded by Mr. Kehrmann in his thesis. The results of the test are given in Figure 4. The effect of the saturation of the core is apparent in this figure also. The lower portion of the curves are a function of two quantities, $\mu$ and the increasing A.C. current. The upper portion of the curves were becoming linear because, as saturation took place and $\mu$ became constant, the acceleration had a linear relationship with the A.C. current up to an A.C. voltage of 40 V. When the A.C. voltage was 50 V, there seemed to be a high value when the D.C. current was 40 A and 20 A. The cause for the variance in these values from the expected values is unknown.

A group of tests was run to determine the frequency response of the generator with different sets of springs. A D.C. current of 33 A and an A.C. voltage of 50 V was passed through the coils. The frequency input was varied and the acceleration of the generator was measured. The results were plotted in Figures 5 through 10. The different combinations of springs which were used are: the 0.21 and 0.07-inch spring set, the 0.33 and 0.07-inch spring set,
Figure 4. A.C. voltage versus Acceleration.
Figure 5. Response of 0.07-0.07 inch spring set.

D.C. = 33 A
A.C. = 50 V
Figure 6. Response of the 0.21 and 0.07 inch spring set.

D.C. = 33 A
A.C. = 50 V
Figure 7. Response of the 0.33 and 0.07 inch spring set.

D.C. = 33 A
A.C. = 50 V
Figure 8. Response of the 0.21 and 0.21 inch spring set.

D.C. = 33 A
A.C. = 50 V
Figure 9. Response of 0.33 and 0.21 inch spring set.
Figure 10. Response of the 0.33 and 0.33 inch spring set.
the 0.21 and 0.21-inch spring set, the 0.33 and 0.21-inch spring set, the 0.33 and 0.33-inch spring set, and the 0.07 and 0.07-inch spring set.

When these figures were compared, it was found that the first natural frequency of the system could be identified with certainty with only two sets of the springs. The 0.07 and 0.07-inch spring combination had a first natural frequency of 195 Hz and the 0.07 and 0.21-inch spring combination had a first natural frequency at 525 Hz. There are two peaks which seemed to appear in approximately the same position regardless of which combination of springs were used. These peaks occurred at about 2400 Hz and 4300 Hz and seemed to indicate the existence of secondary spring-mass systems, probably in the suspension system. The other peaks present with different combinations of springs were believed by Mr. Kehrman to represent harmonics of the primary spring-mass system.

Using the 0.07 and 0.07-inch spring combination, the damping of the system was determined. The frequencies around the natural frequency were varied over very small intervals and the acceleration measured. The results are given in Figure 11. According to Thomas, the damping could be found by measuring the width of the resonance curve at the half-power points by using the following formula:

\[ \xi = \frac{1}{2} \left( \frac{f_2 - f_1}{f_{n}} \right) \]  

(8)

\( \xi \) is the ratio of the damping of the system \( C \) to the critical damping \( C_c \); \( f_n \) is the natural frequency; and \( f_1 \) and \( f_2 \) are frequencies at the half-power points. The critical damping is
Figure 11. Computation of damping a resonance.
given by

\[ C_c = 4\pi f_m \] (9)

where \( m \) is the mass of the shaft and springs. By using equations 8 and 9, it is found that \( \xi \) is 0.021 and \( c \) is 14.22 slugs per second.

The maximum force produced by the coils was found by measuring the acceleration of the generator using the 0.07 and 0.07-inch spring set. The generator was driven at its first natural frequency of 195 Hz using a D.C. current of 40 amp and an A.C. voltage of 50 V. The force was found by the following formulas found in Thomas:

\[ X = \frac{F_o / k}{\sqrt{\left(1 - \frac{m\omega^2}{k}\right) + \left(\frac{c\omega}{k}\right)^2}} \] (10)

\[ \omega_m = \sqrt{k/m} \] (11)

\[ x = x_0 e^{i\omega t} \] (12)

Where

\( F_o \) is the driving force
\( k \) is the spring constant
\( m \) is the mass of generator without the shaft
\( \omega \) is the angular frequency
\( x \) is the complex amplitude
\( c \) is the damping of the system.
\( t \) is the time, and
\( x \) is the displacement.
By taking the second derivative of \( x \) with respect to time, we find that:

\[
\dddot{x} = -i\omega^2 x
\]  

(13)

or

\[
a = \omega^2 x
\]  

(14)

where \( a \) is the acceleration. By putting equation 10 in terms of the natural frequency, we have:

\[
F = \frac{a}{2} k \left[ \frac{\omega_n^2}{\omega_n^2} - \left( \frac{\omega}{\omega_n} \right)^2 \right] \left[ \frac{2\xi}{\omega_n^2} \right]^2
\]  

(15)

or

\[
F = \frac{a}{\omega_n^2} k 2\xi
\]  

(16)

when the system is driven at its first natural frequency. Using equation (11)

\[
F = 2a m \xi
\]  

(17)

From this equation it is found that the force provided by the coils at the natural frequency of the system is 10.3 pounds force.
Chapter III

CONCLUSION

The generator will produce a measurable signal over a wide frequency range. The problem of transmitting the signal from the generator to the wall rock is a coupling problem and will not be discussed here. The amount of damping in the system should be reduced as much as possible in order to increase the acceleration output of the system. It was found that carelessness in attaching the springs to the shaft would produce a large increase in the damping of the system. The shaft, being out of alignment, would rub against the teflon and produce near critical damping.

A mass-spring system with a low natural frequency should be used. An amplifier should be used which will provide an increasing A.C. voltage input with increasing frequency causing a constant A.C. current to flow through the A.C. coil. If the system has a low natural frequency and a constant current through its A.C. coil, then there should be a constant force output considering the generator as a single degree of freedom system, at frequencies greater than the natural frequency. Additional spikes will appear in the response curve at frequency beyond the first natural frequency resulting from response of the system to higher modes of the plate-type spring.

There is saturation of the laminated transformer iron core of the A.C. coil, but no saturation is indicated elsewhere in the magnetic circuit. To improve the generator a material with a higher
permeability at higher flux densities should be used for the core of the A.C. coil. Eddy current losses are present in the core, although they are not too severe as evidenced by the lack of overheating at high frequencies. According to Thomas these losses can be cut down by decreasing the size of the laminations from 1/16 of an inch to 0.01 of an inch. This will be sufficient for frequencies up to 10,000 Hz. When testing a coil, it is difficult to tell hysteresis loss from eddy current losses. The hysteresis losses have their greatest effect at lower frequencies and are inversely proportional to the square root of the core volume.

Another loss factor is the presence of an air gap of over 1/2 inch between the laminated iron core and the intermediate plate. An amplifier capable of an output of 20 amps or more should be used so the diameter of the wire used in winding the A.C. coil may be increased. By increasing the diameter of the wire so it will carry more current, the number of layers on the A.C. coil will be reduced and will allow a decrease in coil radius without a corresponding decrease in amp turns. This will allow a bigger core which will serve two purposes: 1) It will allow a reduction in air gap and 2) as pointed out above, it will lower the hysteresis losses.

Since the D.C. power supply cannot output as much current as the D.C. coils are capable of carrying without overheating, the diameter of the wire of the D.C. coils should be decreased so they have the maximum number of amp turns which can be used with the available equipment.
All the improvements suggested above are an attempt to increase the force the coils are producing.
BIBLIOGRAPHY


APPENDIX A

Explanation of the Formula Used to Find the Force Between Two Circular Coils
EXPLANATION OF THE FORMULA USED TO FIND THE FORCE BETWEEN TWO CIRCULAR COILS

Curtis and Curtis gave the following formula for finding the force between two circular coils:

\[ f_m = \frac{i_{AC} i_{DC}}{N_1 N_2} \left\{ \frac{1}{2} \left[ D_2 + \frac{(xD)^2}{2\lambda_2} \right] \right\} \]  \hspace{2cm} (1)

where when dealing with two circular filaments

\[ f_m = \frac{\pi^2 \gamma_m \kappa}{\mu \alpha (1-\kappa^2)^{\gamma/\alpha}} \left\{ \kappa^4 - 2(2\kappa^2) (C_2^2 + 2C_2^2 + 4C_3^2 + \cdots ) \right\} \]  \hspace{2cm} (2)

and in formula (2)

\[ a_1 = \text{radius of the filament at the circumference of the large circle} \]
\[ a_2 = \text{radius of the filament at the circumference of the smaller circle} \]
\[ \alpha = \frac{a_2}{a_1} \]
\[ z_m = \text{the axial distance between the circular filaments when the force is a maximum} \]
\[ y_m = \frac{z_m}{a_1} \]
\[ f_m = \text{force in dynes between the filaments carrying unit current in the cgs electromagnetic system} \]
\[ \kappa^2 = 4\alpha/[(1+\alpha)^2 + y_m^2] \]

It will be noted that the an in formula (2) refers to the a's in the following table and not to the radii of the coils.
\[ a_0 = 1 \quad b_0 = \sqrt{1-k^2} \quad c_0 = k \]
\[ a_1 = \frac{1}{2}(a_0 + b_0) \quad b_1 = \sqrt{a_0 b_0} \quad c_1 = \frac{1}{2}(a_0 - b_0) \]
\[ a_2 = \frac{1}{2}(a_1 + b_1) \quad b_2 = \sqrt{a_1 b_1} \quad c_2 = \frac{1}{2}(a_1 - b_1) \]
\[ a_3 = \frac{1}{2}(a_2 + b_2) \quad b_3 = \sqrt{a_2 b_2} \quad c_3 = \frac{1}{2}(a_2 - b_2) \]
\[ \vdots \]
\[ a_m = \frac{1}{2}(a_{m-1} + b_{m-1}) \quad b_m = \sqrt{a_{m-1} b_{m-1}} \quad c_m = \frac{1}{2}(a_{m-1} - b_{m-1}) \]

When dealing with two circular coils in formula (1):

- \( f_m \) = the maximum force for unit current in two filaments located at the centers of the cross sections of the coils.

- \( a_1 \) and \( a_2 \) = the mean radii of the larger coil and the smaller coil respectively,

- \( N_1 \) and \( N_2 \) = number of turns of wire in the larger coil and the smaller coil, respectively,

- \( b_1 \) and \( b_2 \) = one-half the axial width of the larger coil and the smaller coil respectively,

- \( c_1 \) and \( c_2 \) = one-half the radial depth of the larger coil and the smaller coil, respectively,

\[ \alpha = \frac{a_2}{a_1} \]
\[ A^2 = a_0^2 + a_2^2 \]
\[ \beta = \frac{(1-\alpha^2)}{(1+\alpha^2)} \]
\[ y_m = 0.5 - \frac{9}{20} \alpha^2 - \frac{1}{16} \alpha^4 \quad \text{if} \quad 0 < \alpha < 0.75 \]
\[ x = y_m / \sqrt{1+2x^2} \]
\[ \lambda_1 = 0.0 \]
\[ \lambda_2 = \frac{3\beta^2 - 2x^2}{\beta^2 + 2x^2 + x^4} \]
\[
\lambda_3 = \frac{4x^2 + \lambda_2(11x^4 + 10x^2 - \beta^2)}{\beta^2 + 2x^2 + x^4} \\
\lambda_4 = \frac{16x^2 \lambda_3 (x^2 + 1) - 3x^2 \lambda_2 (23x^2 + 8)}{\beta^2 + 2x^2 + x^4}
\]

\[
B_1 = \frac{c_1^2}{a_1^2} \left[ 5(b_1^2 + b_2^2 - c_2) - 3c_1^2 \right] - \frac{c_2^2}{a_2^2} \left[ 5(b_1^2 + b_2^2 - c_2) - 3c_2^2 \right]
\]

\[
B_2 = \frac{c_1^2}{a_1^2} \left[ 5(b_1^2 + b_2^2 - c_2) - 3c_1^2 \right] + \frac{c_2^2}{a_2^2} \left[ 5(b_1^2 + b_2^2 - c_2) - 3c_2^2 \right]
\]

\[
B_3 = \frac{c_1^2}{a_1^2} \left[ 9c_1^2 + 15c_2^2 - 10(b_1^2 + b_2^2) \right] + \frac{c_2^2}{a_2^2} \left[ 9c_2^2 + 15c_1^2 - 10(b_1^2 + b_2^2) \right]
\]

\[
B_4 = \frac{1}{A^2} \left[ 10(b_1^2 c_1^2 + b_2^2 c_2^2) - 10(b_1^2 - c_1^2)(b_2^2 - c_2^2) \right]
\]

\[ - 3(b_1^4 + c_1^4 + b_2^4 + c_2^4) \]

\[
D_2 = \frac{1}{12x^2} \left( \frac{c_2^2}{a_2^2} - \frac{c_1^2}{a_1^2} \right) + \frac{2[c_1^2 - b_1^2 + c_2^2 - b_2^2]}{A^2} \lambda_2
\]

\[
D_4 = \frac{1}{360A^2} \left( B_4 \lambda_4 + (\beta B_1 - x^2 B_2) \lambda_3 \right) + \frac{3}{A^2} \left( B_1 x^2 B_3 - 5x^4 \left( \frac{c_1 c_2 A^2}{a_1 a_2} \right) \right) \lambda_2 - 6\beta B_1
\]

\[
x_b^2 = \frac{1}{12x^2} \left( 2\beta \left( \frac{c_1^2}{a_1^2} - \frac{c_2^2}{a_2^2} \right) + \frac{(x^2 - \beta) c_1^2}{a_1^2} + \frac{(x^2 + \beta) c_2^2}{a_2^2} \right) \lambda_2
\]

\[ + \frac{2[b_1^2 - c_1^2 + b_2^2 - c_2^2]}{A^2} \lambda_3 \]
APPENDIX B

List of Equipment
LIST OF EQUIPMENT

1. Harrison model 6269A D.C. power supply.
2. Bogen model M0200A amplifier.
3. Beckman model 9010 function generator.
4. Textronix model 502 and 547 oscilloscope.
5. Simpson model 260 voltmeter.
7. Magitran solid state power supply.
8. Kistler model 566 multi-range electrostatic charge amplifier.
9. Two scale ammeter.
APPENDIX C

Plates
Plate I. Electrodynamic Vibrator.
Plate II. Schematic of Vibrator.
Plate III. Coil Housing.
Plate IV. Shaft Guide.

SIDE VIEW

TOLERANCES ARE ± .005" UNLESS OTHERWISE SPECIFIED
NOTE - ALL TOLERANCES ARE ± .005"
UNLESS OTHERWISE SPECIFIED

COLD ROLLED STEEL

CAST STEEL
Plate VI. Spring
Plate VII. Test Setup.
A. Air line
B. Suspension devices
C. Test block
D. Coil chamber
E. Cable
F. Accelerometer mount
VITA

The author was born on May 19, 1944 in Harlingen, Texas. He received his elementary and junior high education in the public schools of Richland, Washington and Fort Worth, Texas. His high school years were begun at Carrollton, Texas and terminated at Paschal High School in Fort Worth, Texas.

After completing his secondary education in June, 1962, he enrolled at Texas Christian University in Fort Worth, Texas with the aid of a scholarship. In June, 1966, he completed his Bachelor of Science Degree in Geology.

Upon receiving a N.A.S.A. Graduate Fellowship, he enrolled at the University of Missouri-Rolla and has been working for two years toward the completion of a Master of Science Degree in Geophysics.