THE EFFECT OF MAGNETIC AND ELECTRIC FIELDS ON THE DIELECTRIC CONSTANTS OF LIQUIDS

By

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B.S. in Electrical Engineering

University of Kansas

1925

A Thesis submitted to the Department of Physics
and the Faculty of the Graduate School of
the University of Kansas, in partial
fulfillment of the requirements
for the degree of
Master of Arts.

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June 30, 1926.

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NOTE - Reference numbers as they appear in the manuscript refer to the numbers appearing before the separate works included in this bibliography.

TABLE OF CONTENTS

INTRODUCTION

ABSTRACT

The heterodyne zero beat method of measurement was used to detect a possible change in the dielectric constant of several liquid dielectrics, first, when a magnetic field was impressed across the dielectric, and second, when an electric field was impressed across it. The dielectrics were chosen of both polar and non-polar compounds. Carbon disulfide, carbon tetrachloride, benzine, turpentine, and olive oil were tested with the magnetic field, and all of these with the addition of denatured alcohol with the electric field. For the tests giving the most conclusive results, the magnetic field strength was 2840 gauss, and the electric field for similar results was over 700 volts per cm. An actually measured sensitivity of change of dielectric constant ranging from 1 part in 265,000 to 1 part in 2,800, depending upon the constants of the apparatus, was the limit of this method, at an oscillation frequency of 1,000,000 cycles per second. In none of these tests was there any effect apparent.

PURPOSE OF RESEARCH

According to the most modern theory of dielectric media, it is no more than reasonable to expect that an external field should affect the molecular activity within a dielectric. It is the purpose of this research to test several dielectrics for a possible effect, both due to the presence of a magnetic field, and due to the presence of an electric field. The dielectrics chosen are liquids. Although gases are the ideal substances to exhibit such an effect, it was thought that on account of the practical difficulties involved in such measurements, an investigation with liquids would be the most satisfactory all around. The tests with the magnetic field were of primary interest to the writer and were expected to yield particularly interesting results.

THEORY OF DIELECTRIC MEDIA

The theory of dielectrics is relatively old. Probably the earliest theory explaining the phenomena exhibited by a charged body is the well-known "fluid" theory. A later hypothesis connected with the name of Mossotti suggested that a substance having a dielectric constant greater than unity consists of conducting molecules immersed in a perfectly insulating medium. [1] But these theories were incapable of explaining many of the observed characteristics of matter such as the relationship between the dielectric constant and the refractive index, the distinction between conductor and insulator, etc.

In 1878, H. A. Lorentz, the great Dutch physicist, published a memoir containing a hypothesis which has led to the modern theory of dielectrics, and one which explained many of the observations which had hitherto not been understood. He assumed that electricity of opposite sign is concentrated on large numbers of distributed particles scattered throughout the body. These particles of electricity were referred to by him as "atoms of electricity".

This theory explains very definitely the distinction between a conductor and an insulator, or for general purposes, a dielectric. In a conductor, the electrons may be thought of as free to move about. In a dielectric, it is thought that the electrons are contained within the molecule and cannot be dragged out of these molecules by any external field. They may, however, be displaced in position relative to each other, until the force exerted on them by the external field is just balanced by the restraining force of mutual attraction.

This may be thought of in another way.[2] If the molecules may be most simply considered as consisting of only two opposite charges which determine the direction of the molecular axis, when an external field is impressed upon the dielectric, these molecular doublets may be thought of as rotating around until their axes allign themselves with the direction of the field. When they are alligned in this way, all the end to end charges neutralize each other excepting those on the extreme ends. This explains the transfer of a charge through the dielectric. When the direction of the field is reversed, the doublets rotate and the charge is also reversed. It is to be expected, then, that an external field of constant direction might greatly influence the ease with which this transfer can take place due to an alternating field as in the ordinary condenser; in other words, it might have an effect on the dielectric constant, and that effect should be to decrease the normal value, especially when the constant field is perpendicular to the alternating field.

There is no direct indication, however, that a magnetic field should influence this function of the dielectric. From experiments carried along on other lines it is found that a magnetic field often exerts an effect upon electronic phenomena, and the possibilities in this direction have not been fully explored. If the orbits of orientation of the electron were to assume definite angles upon the impression of magnetic fields, as they are supposed to do in the modern interpretation of the spectral lines of some materials, some effect might be expected to be present in the dielectric constant.

DISCUSSION OF METHOD AND APPARATUS

There are two ways in which the change in dielectric constant might be measured. According to the electromagnetic theory of light, and upheld by numerous measurements, the dielectric constant is proportional to the square of the refractive index within certain frequency limits. A change in the refractive index could easily be noted by the use of an interferometer upon application of either a magnetic or an electric field, if such a change were present. But it was thought that the direct measurement of a change in the capacity of a condenser of which this medium was used as the dielectric would be the more direct and most convenient to make, and certainly the results would be more generally acceptable.

Since it was expected that the effect to be observed would be small, the most sensitive type of apparatus yet devised for such measurements was set up for use. This apparatus uses the well known high frequency heterodyne beat method which was first developed and successfully used about 1919. J. Herweg [3] described such a scheme at that time and very soon afterward Whiddington [4] developed it in his apparatus, the "ultramicrometer", with which he achieved astounding results in accurate measurements of small distances.

The circuit from which the present one is modeled taken from Zahn.[5] The frequency used is approximately 1,000,000 cycles per second. The sensitivity depends upon the frequency used; but, as the frequency is increased, the apparatus becomes more unstable, and until better equipment is available, this appears to be the upper practicable frequency limit. Weatherby and Wolf [6] in a recent test used a similar method, but their determinations are based upon a comparison of counted beat notes. The zero beat method of Zahn, however, and the one used in the present test, is thought to be more accurate since it precludes the possibility of errors in timing the beats.

The circuit is shown in Fig. 1. Essentially it consists of two high frequency vacuum tube oscillators tuned to a frequency of about 1,000,000 cycles per second. One frequency differs from the other, however, by an audio-frequency of approximately 1,000 cycles per second, and has as its determining factor the test condenser containing the dielectric under test. This heterodyne beat note is picked up by a third detecting tube. At the same time, the output of this tube, by means of a transformer coupling to a fourth audio-frequency oscillator, has impressed upon it a note of constant audible frequency. The result is a second heterodyne beat note which may be adjusted to zero without fear of any interfering coupling.

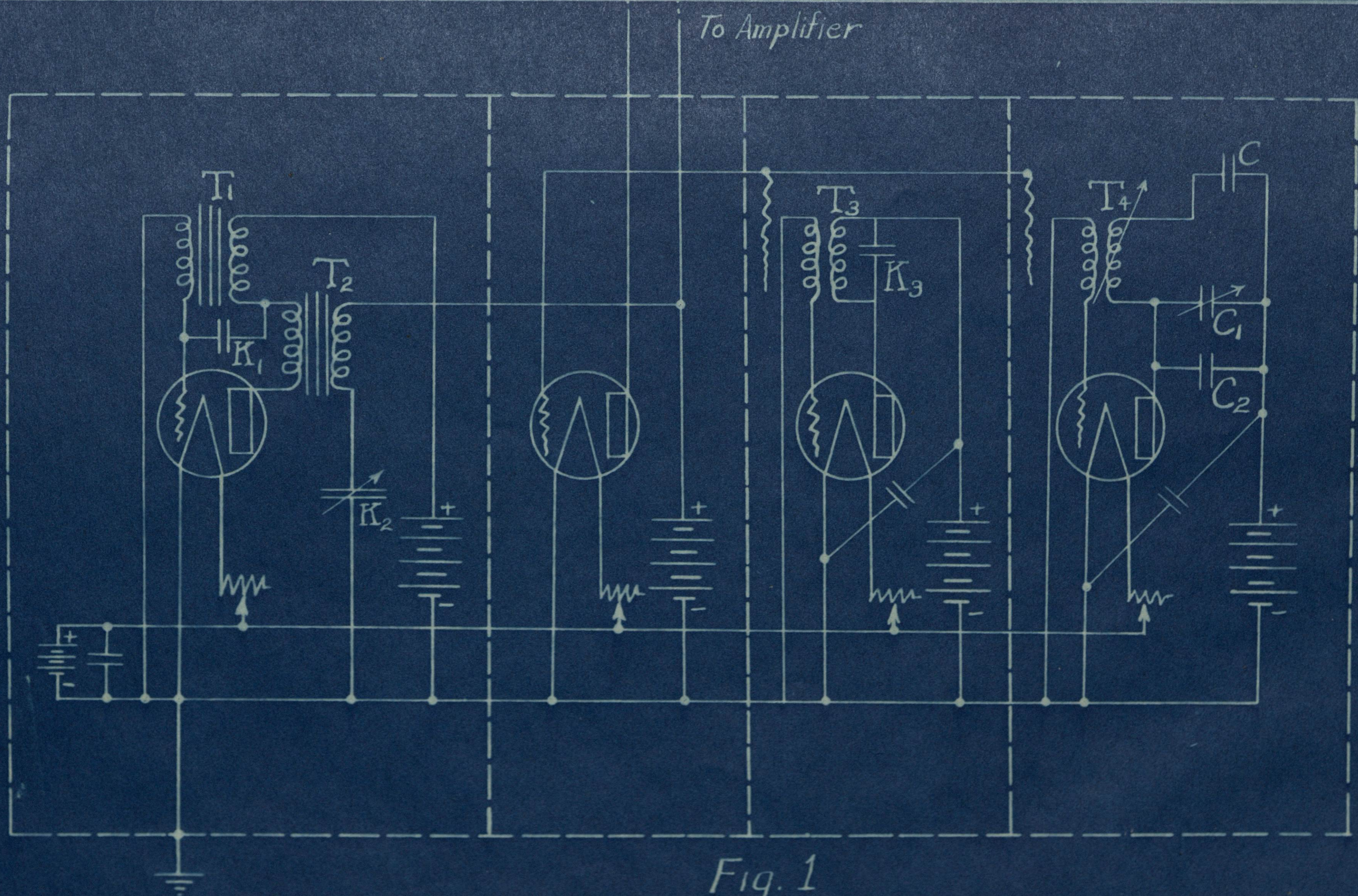


Fig. 1

Oscillator Circuit

The tubes used are standard 5-volt radio tubes of the 201-A type. A single 6-volt lead storage battery of the automobile type is used as the "A" battery, supplying the four tubes in parallel. The "B" battery supply consists of four separate 45-volt heavy duty radio batteries, each one of which is connected to a single tube.

The dotted lines in the diagram represent the shielding which in this case is of heavy screen wire; it is made to completely enclose each section, above as well as below. The first compartment on the left contains the audio-frequency oscillator tuned to a frequency of approximately 1000 cycles per second. T_1 is a standard laboratory iron-core mutual inductance. It was found to tune to a satisfactory audio-frequency when the shunting condenser K_1 was made .025 mf. T_2 is a standard audio-frequency amplifying transformer of the ratio 3:1. It was found entirely satisfactory to connect the single lead from the secondary of this transformer to the output of the next tube as is shown, but the variable condenser K_2 (.003 mf.) was added to regulate the volume of the constant-frequency tone to compensate for the change in volume of the beat note from the other oscillators when testing different dielectrics.

The second compartment contains a detecting unit which picks up the beat frequency of the two high frequency oscillators. To avoid unnecessary coupling between these two oscillators, a "floating grid" is used. This consists of nothing more than a short wire projecting a few inches into each of the high frequency compartments, and picking up energy from each by electric induction and delivering it to the grid of the detecting tube. This results in a beat note of audible frequency being delivered to the output, where at the same time, the constant frequency of the first oscillator is also impressed upon it. The result in the output circuit then is a heterodyne beat note having as a frequency the difference between these two. This note was then delivered to a two-stage audio-frequency amplifier supplying a loud speaker. This scheme proved very satisfactory.

The third and fourth compartments contain the high frequency oscillators. The coupling transformers T_3 and T_4 each consist of two coils of # 20 copper wire 10 cm. in diameter wound separately and taped together with two narrow pieces of friction tape. The coil in the plate circuit of the first oscillator is shunted by the condenser K_3, which has a capacity of .00025 mf. A wave meter used to test the frequency of this oscillatory circuit indicated a wave length of 300 meters.

The oscillatory circuit in the fourth compartment consists of this plate circuit coil shunted by a system of condensers, including the test condenser C. C_1 is a precision condenser of capacity .0005 mf. Since it was expected that a very small effect would have to be measured, C_2 was made large in comparison to C_1, and the total of $C_1 + C_2$ was also lafge in comparison to C. To make the first tests, C_2 was made .01 mf. Provision was made for changing this value as C was changed in order that the readings of C_1 might represent values of reasonable magnitudes.

The test condenser C was made of 20 plates of sheet brass approximately 9 cm. square. The plates were spaced .4 cm. apart on an average. The unit was inserted into a small glass battery jar, and was fitted with the plates in a vertical plane in such a way that proper spacing was maintained without the necessity of any solid dielectric. The total capacity of this condenser with an air dielectric was found by measurement to be .000365 mf. Another condenser which was used as the test condenser for impressed electric fields consisted of two brass plates 8 cm. by 13 cm. in area, and spaced 7 cm. apart. Its calculated capacity was found to be .0000013. mf.

It was found both necessary and convenient to have some device with which to tune one of the high frequency oscillators to give approximately zero beat note in the loud speaker before beginning any tests. This was made possible by the addition of a variable inductance in the oscillatory circuit of the second high frequency oscillator.

The usual precautions were observed in assembling and operating this apparatus. Any electrostatic coupling between oscillators was guarded against by the thorough electrostatic shielding which was all grounded. Resistance coupling was minimized by the use of separate "B" batteries for each oscillator, each battery being shunted by a 1 mf. condenser. The "A" battery was also shunted by a 1 mf. condenser. The entire unit was placed upon a stone pier in the basement of the laboratory to eliminate any unstable condition arising from building jars and vibrations. Variations in temperature and humidity did not affect the operation of the apparatus, for no great time interval elapsed between readings made after the unit was once adjusted.

All adjusting controls were made accessible to the exterior of the shield by extension rods in order that there would be no body capacity effect upon making adjustments of the apparatus. It was found that the "B" batteries must be new ones in good condition to minimize the residual drift in the frequency of the oscillators. It was also found necessary to charge the storage "A" battery frequently to maintain a constant filament current supply. Even with all of these precautions, there remained a drifting effect of the audible beat note to the extent of less than one per second, but readings for comparison could be taken so quickly that this source of error was not serious.

For tests of the effect of a magnetic field on the dielectric constant, a large electro-magnet was used. The test condenser was placed directly between the pole pieces and provision made for turning the unit through 90 degrees with respect to the direction of the magnetic field. A grounded electrostatic shield was carefully placed over the condenser and lead wires to protect them from the changing potential of the wires on the magnet cores when the current was switched on. Every precaution was taken to prevent small movements of the pole pieces upon switching on the field, as any small movement might have affected the capacity of the test condenser. The core and iron parts of the magnet were carefully grounded.

The electric field was supplied in three ways. A vacuum tube rectifier was connected to plates outside the jar of condenser C, first parallel to those within, and then perpendicular to them, as shown in Fig. 2. For a second method, a block of radio "B" batteries was connected directly through an auxiliary condenser to the plates of C as shown in Fig. 3. By means of the mercury switch S, one-half of the batteries was reversed in polarity and a zero field thrown across the plates, or vice-versa, with no resultant change in the capacity of the system in parallel with the condenser C. In using

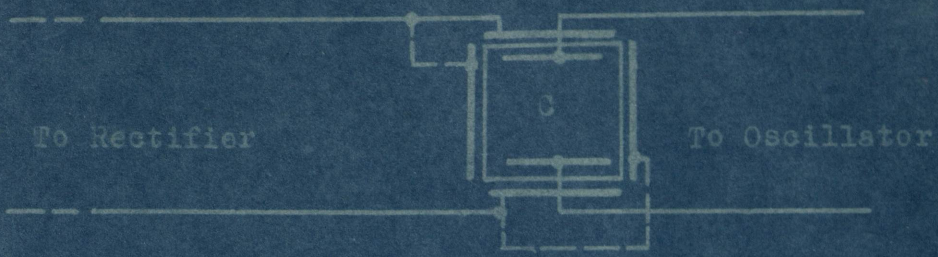


Fig. 2

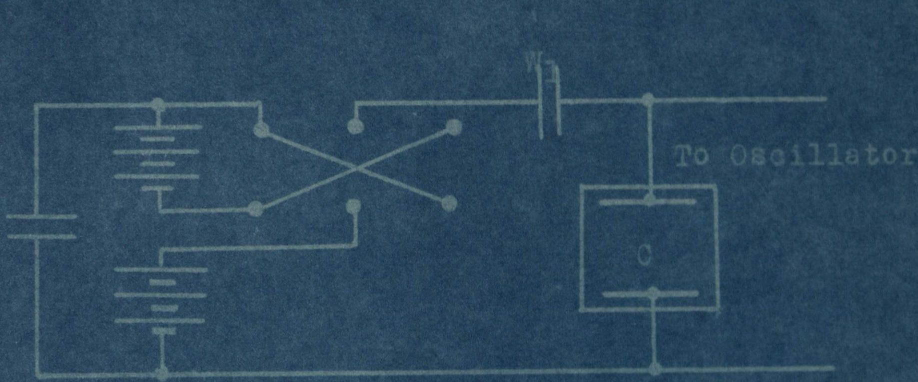


Fig. 3

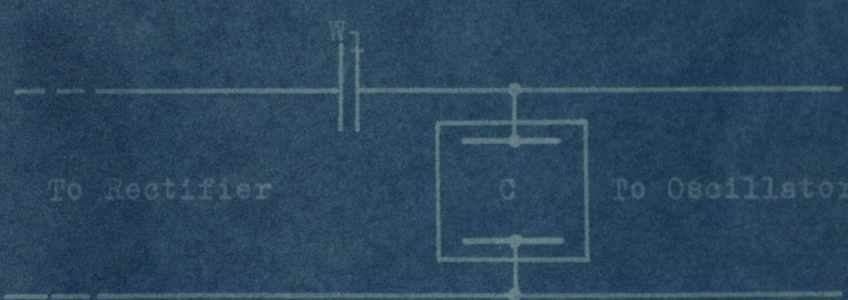


Fig. 4

this scheme, it was necessary to shield the batteries, switch, and lead wires by a grounded wire cage, and operate the switch by means of a long wooden rod extending through a small hole in the cage. The batteries were shunted by a 1 mf. by-pass condenser as is shown in the diagram. The condenser W_1 was necessary to prevent a direct short across the test condenser, and was made of the same order of magnitude as C; it was not made larger because the test condenser C would thereby be made a much smaller part of the oscillator capacity and as a result the apparatus would be less sensitive; it was not made smaller because the drop in potential across it would become larger in comparison to that across the test condenser.

A third method followed the same scheme except that the rectifier was used instead of the batteries to supply the electric field. The diagram of Fig. 4 shows the circuit. No reversal of potential for zero field was necessary, but instead a switch in the primary of the high potential transformer served to throw the field on and off. It was found necessary, however, to use a condenser in place of C_1 and C_2 which would withstand much higher potentials than ordinary ones are built for. Its capacity at the same time was lowered to permit a reasonably large potential drop across C (for C_1 + C_2 in series with the plate circuit coil of T_4 are shunted across the test condenser). This necessarily reduced the sensitivity of the test condenser somewhat for it reduced the total capacity shunted across T_4. When it was necessary to use these condensers of small capacity, more turns were added to the transformer T_4 to maintain a constant oscillation frequency. This helped to decrease the sensitivity of the test condenser again, for it added more distributed capacity and made the test condenser a smaller part of the whole governing capacity.

EXPERIMENTAL PROCEDURE AND RESULTS

It was found necessary to operate the vacuum tubes for about two hours before the apparatus became stable enough to made any accürate determinations. A residual drift and variation in the beat notes remained even then to an inappreciable extent. Weatherby and Wolf [6] account for such a change in a similar apparatus as being due to three causes: (1) charges collecting on the inner walls of the vacuum tubes; (2) motion of the shielding plates due to humidity and temperature changes in the room; (3) imperfect insulation. It seems to the writer that a more probable source of this variation lies in the constantly changing chemical structure of the "A" and "B" batteries and its effect on the potential and resistance values of these batteries.

MAGNETIC FIELD

For tests with a magnetic field impressed across the dielectric, the procedure was as follows:

With an air dielectric in the condenser C (20 plate condenser of capacity .000365 mf.), the oscillator system was adjusted to zero beat by means of the variable inductance in T_4 and variable capacity C_1 (C_1 was originally intended for use in indicating the change in capacity of C, but was found to be ideal as a fine adjustment for obtaining zero beat). The magnetic field was then impressed upon the dielectric, and after proper adjustments had been made, it was found that switching the field on and off caused no change in the zero beat note. Without disturbing the condenser, its lead wires, or shielding, the dielectric to be tested was poured into the jar. The zero beat note was brought back by a compensating adjustment of the variable inductance T_4 and condenser C_1, and the field again switched on, noting whether a change from zero beat note occured. The same procedure was followed again for the same dielectric, this time with the condenser turned at right angles to its former position with respect to the magnetic field. The dielectrics used were carbon disulfide, carbon tetrachloride, benzine, turpentine, and olive oil. An attempt was made to use water solutions of various substances, but it was found that with this apparatus, the conductivity of the material was too great to permit oscillation. Denatured alsohol could not be tested for the same reason.

Although there was always present the drifting effect of the beat note, its magnitude was less than one beat per second, and after many trials in which this drift was taken into account, it appears very definite that either any affect on the dielectric constant does not exist, or it is smaller than this apparatus is capable of detecting. The electric field present during these tests (alternating field) is estimated as less than 100 volts per cm.

Theoretically, apparatus such as this with which a change of one beat note per second can easily be detected, should detect a change in the dielectric constant of 1 part in 500,000 when operating at a frequency of 1,000,000 cycles per second; this is on the assumption that the test condenser constitutes the whole of the oscillator capacity. A test was made to determine the actual sensitivity of the apparatus. A scheme such as shown in Fig. 5 was used.

P and P_1 were chosen very large compared to C, and the resulting capacity differed from the original C by an inappreciable amount. A comparatively large change might be made in P without changing the total capacity of the system very much. The procedure for finding the sensitivity was as follows:

With the oscillators adjusted for zero beat, the capacity P was changed a definite amount. The resulting frequency note was counted and timed by the use of a stop watch. To correct for the effect of the drifting beat note, the measurements were made once for an increase of the capacity P, and once for a decrease of P. The average percentage change in the capacity of the system (C) was then determined on the basis of an observable change in the beat note frequency of one per

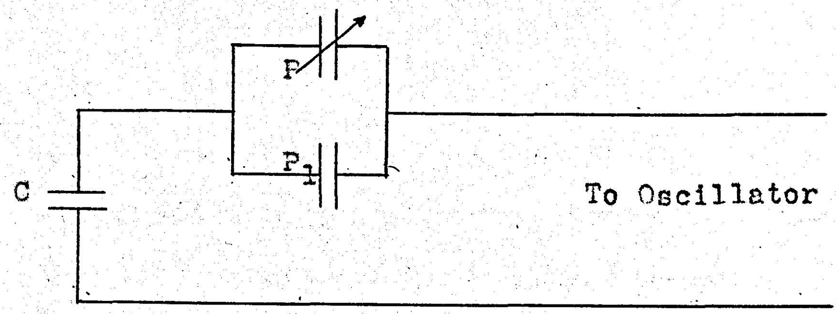


Fig. 5

C = .000365 mf.
P = .0005 mf. (Federal Air # 83)
P_1 = .05 mf.

Readings P	Capacity change	Beats	Seconds
96.5 - 58.5	.0002 mf.	30	4.8
58.5 - 96.5			3.9
96.5 - 58.5			3.9
58.5 - 96.5	(constant)	(constant)	3.9
96.5 - 58.5			4.0
58.5 - 96.5			3.7
96.5 - 58.5			4.3
58.5 - 96.5			4.0

Average change of beat notes per sec. = 7.4

Change of capacity P per beat note = .000027

* Percentage change of capacity of system

$$= \frac{(.000027)(.000365)}{(.0505)\ (.0505)} = 1 \text{ part in } 265{,}000.$$

* This approximate calculation assumes two conditions: (1) that the series capacity P and P_1 is large enough in comparison to C to make inappreciable its effect on the total (C); and (2) that the change in P from one setting to another is small enough in comparison to the total $P_1 + P_2$ to be neglected without appreciable error. It may be noted that the maximum value for P is always used. This is done because the effect expected is a decrease in the effective C.

second, and as the calculation shows, was one part in 265,000.

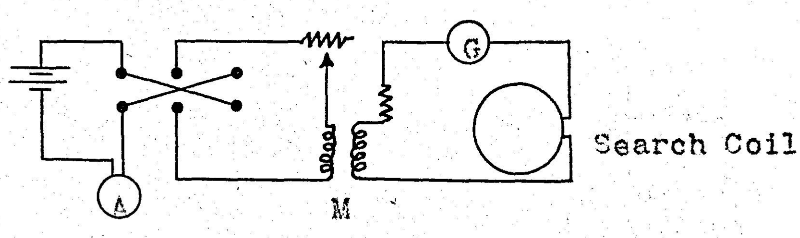
The discrepancy between the theoretical and the actual sensitivity is due to the fact that quite a large fraction of the governing capacity of the system lies in the distributed capacity between turns of the inductance coils, etc.

The strength of the magnetic field impressed across the dielectric was determined by the use of a search coil and ballistic galvanometer. The galvanometer was calibrated by the use of a mutual inductance of known value. The field strength was found to be 2840 gauss.

ELECTRIC FIELD

Essentially the same procedure was followed in tests for the effect of the electric field on the dielectric constant as was followed when a magnetic field was used. For the method of which a diagram is shown in Fig. 2, a potential of 30,000 volts was applied both parallel to the plates and then perpendicular to them, without noting any effect when following the procedure outlined for the magnetic field. This field strength corresponds to one of 3000 volts per cm. For this test, the two plate condenser previously described was used for C. In order to determine the relative

TEST FOR STRENGTH OF MAGNETIC FIELD



I = reading of ammeter A.
d_1 = deflection of galvanometer through M.
d_2 = deflection of galvanometer by use of search coil.
n = turns in search coil.
Ar = area of pole face.

M = 16 M. H.
Ar = 38.4 sq. cm.

I	d_1	d_2
.25	10.1	9.9
	9.9	10.2
(constant)	10.0	10.2
	10.0	10.0
	10.0	10.2
Average	10.0	10.1

$$\phi = \frac{2(M)(I)(10^8)(d_2)}{(n)(Ar)(d_1)}$$

$$= \frac{2(.016)(.25)(10^8)(10.1)}{(8)(38.4)(10.0)}$$

$$= 2{,}840 \text{ (gauss)}$$

strength and direction of the field within the test jar when an external field was applied, a charged pith ball was suspended between the condenser plates. The reaction of the pith ball showed a strong field to be present, but indicated that it was not at all uniform. A similar indication was secured when the field was applied at right angles to its former direction. Because of the non-uniformity of the applied field by the use of this method, the results are not regarded particularly conclusive. A test of the sensitivity of the apparatus set up in this way, as shown in Fig. 6, shows that a change in the dielectric constant of one part in 20,000 or more may be observed by a change of frequency of one beat note per second.

The next method as it is diagrammed in Fig. 3 was more of an experiment than a test for results; it was followed chiefly to see if the oscillator would continue to function under such conditions. The potential supplied by the battery was 360 volts. But when it is considered that C_1 and C_2 are in parallel with C, which in turn is in series with W_1, the potential drop across the test condenser is about 2 volts. This corresponds to a field strength of only 0.28 volts per cm. The observations in this test were very definite in their conclusiveness to the effect that no change existed, for the sensitivity remained as before; but

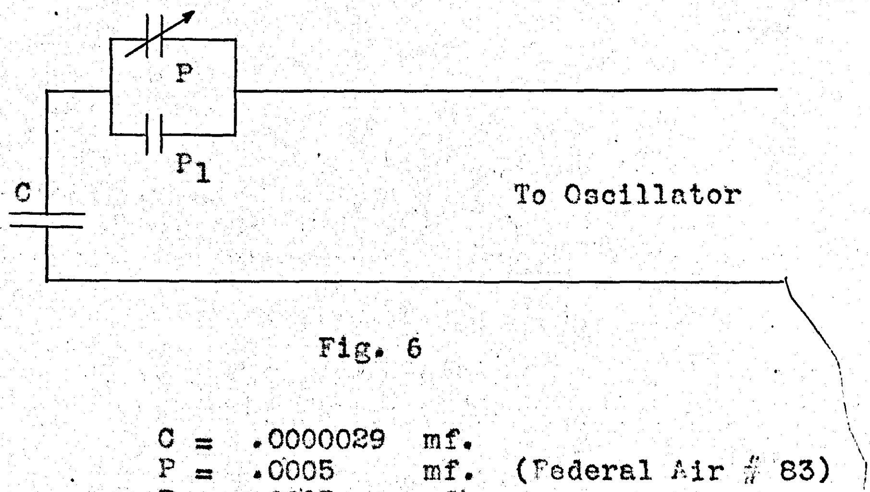


Fig. 6

$C =$	.0000029	mf.	
$P =$	.0005	mf.	(Federal Air # 83)
$P_1 =$	.0005	mf.	
$C_1 + C_2 =$	.0055	mf.	

Readings P	Capacity change	Beats	Seconds
96.5 - 78	.0001	60	8.1
78 - 96.5		60	10.0
96.5 - 78		60	10.0
78 - 96.5		20	4.2
96.5 - 78	(constant)	40	6.5
78 - 96.5		40	7.5
96.5 - 78		40	7.5
78 - 96.5		40	7.9

Average change of beat notes per second = 5.85

Change of capacity P per beat note = .0000169

* Percentage change of capacity of system

$$= \frac{(.0000169)(.0000029)}{(.001)\quad(.001)} = 1 \text{ part in } 20{,}200.$$

* This approximate calculation is subject to the same assumptions as that for Fig. 5.

with such a weak field, the results are not very convincing.

The third method, as it is shown in Fig. 4, allowed the use of relatively high potentials directly across the test condenser. The condensers C_1 and C_2 had to be replaced with one of higher insulating qualities, and at the same time one of smaller capacity to allow a larger potential drop across C. With such a one in place, the potential was tested across C with a high potential electrostatic voltmeter. A reading of 5000 volts was the highest obtained for which any tests were made. But since the capacity of the voltmeter itself was large compared to that of the system (C), the actual drop with the meter disconnected, as it was when the test was run, was much higher. The 5000 volt drop represents a field strength of 714 volts per cm. The sensitivity test showed, on the same basis as before, that this set-up (Fig. 7) recorded a change of 1 part in 2860. This enormus decrease in sensitivity is explained by the fact that the condensers used to shunt the coil of T_4 are so small that they form only a small part of the governing capacity of the oscillator; the remaining capacity is distributed capacity.

It was found impossible to get a potential drop across the alcohol with the latter method; the electrostatic voltmeter placed across the condenser having this substance as the dielectric registered a zero reading.

This is explained by the fact that the conductivity of alcohol is comparatively high. With the external field supplied by the two auxiliary plates outside the test condenser jar, the dielectrics tested were carbon disulfide, carbon tetrachloride, benzine, denatured alcohol, turpentine, and olive oil. With the external field supplied directly from the test condenser plates, only carbon disulfide, carbon tetrachloride, and benzine were used. In all of these tests the alternating field was estimated to be less than 15 volts per cm.

On each of these dielectrics, for each method used, enough trials were taken to make the negative result obtained in each case appear to be very definite and conclusive.

SUMMARY AND CONCLUSION

The results of this research are conclusive only within the limits of the sensitivity of the apparatus. A problem of this type resolves itself into one of the successful construction and operation of an ultra-sensitive measuring device.

The nature of the results, however, are upheld by those of two similar tests as published in recent articles. Fraser [7] tests for the effect of a magnetic field upon the index of refraction of several gases by the very accurate interferometer method, and obtains very definite negative results. Weatherby and Wolf [6], by a method very similar to the one employed in this research, fail to note any effect of the presence of a magnetic field upon the dielectric constant of helium and several other gases, to a computed accuracy of 1 part in 500,000. It may be noted, however, that this value appears to be exaggerated somewhat for an actual test using a test condenser of similar dimensions yields a value for sensitivity of only slightly better than 1 part in 200,000.

In closing, the writer wishes particularly to thank Mr. James D. Stranathan under whose direction this research was carried out, for his many suggestions in regard to, and his ready assistance in helping to avoid the numerous difficulties with which the completion of this test was accompanied.

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June 30, 1926