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SOME EXPERIMENTS WITH COUPLED HIGH FREQUENCY CIRCUITS

By L. W. Austin

1. INTRODUCTION

Very little experimental data has been given on the relative magnitudes of the currents in coupled circuits under different conditions of coupling. Fischer [1] has shown that, when a circuit containing a spark gap is coupled to a second oscillatory circuit and this second circuit in turn very loosely coupled to a third circuit containing a thermoelement, the current in the third circuit shows a well-marked maximum for a given degree of coupling between the first and second circuits, the current in the third circuit decreasing when the coupling between the first and second is either increased or decreased from this most favorable value. A very remarkable fact brought out in this paper is that for small degrees of damping the best results are to be obtained when the mutual inductance between the first and second circuits is extremely small. The reason for this behavior of high-frequency transformers with damped oscillations can be easily qualitatively explained by considering the reaction of the circuit receiving the energy on the circuit from which the energy is received. As the coupling between the two is increased the receiving circuit tends to draw a greater amount of energy out of the sending circuit, and hence acts as an increasing resistance introduced into the sending circuit, increasing its damping and decreasing the amplitude of the oscillations. It appears desirable that further quantitative data on this subject should be given and it is with this object that the present work has been taken up.

[1] C. Fischer, Ann. d. Phys., vol. **22**, p. 265, 1907.

2. THE SOURCE OF THE OSCILLATIONS

For convenience in experimentation it was desired to set up the apparatus in a moderately small space, and this precluded the use of powerful spark apparatus on account of the direct action of the spark circuit on the detecting devices. Experiment showed that when feeble sparks carrying only a few milliamperes were employed undesirably large damping was introduced into the sending circuit. The buzzer method of exciting feebly damped oscillations by the whip-crack discharge,[2] it was found, did not give sufficient energy for the present purpose. Finally a satisfactory form of buzzer circuit[3] was determined on, which is shown in Fig. 1. In this B is a United States Signal

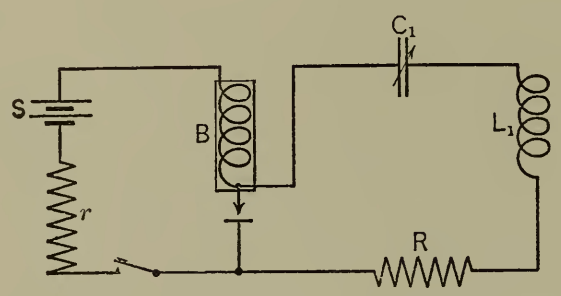

Fig. 1

Corps buzzer of the 1905 type excited by two storage cells with a regulating resistance and key in series. The oscillatory circuit which is connected around the break of the buzzer consisted of a variable air condenser C_1, having a maximum capacity of 0.005 microfarads and an inductance L_1 of 20 turns of No. 20 wire wound in a coil of approximately 10 cm diameter.[4] The value of this inductance was 0.062 millihenrys.

This circuit, when the buzzer was properly adjusted, gave out very feebly damped oscillations, the logarithmic decrement, when no extra resistance was introduced, being between 1 and 2 percent.

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[2] M. Wien, Ann. d. Phys., **25**, p. 625, 1908, and L. W. Austin, this Bulletin, **6**, p. 149; 1908.

[3] L. W. Austin, this Bulletin, **6**, p. 528; 1910.

[4] It is to be understood that all the inductances employed in the work were wound in single layers.

With a proper adjustment of the buzzer, the direct effect of the spark on the thermoelements or other detectors used in the current measurements can be made negligible; sometimes, when the adjustment is most perfect, amounting to less than 0.0001 of the total deflection.

A second form of buzzer[5] circuit which, while it gives less energetic oscillations and involves the use of stronger coupling between the circuits, at the same time is easier of adjustment, especially for very long wave lengths, is shown in Fig. 2.

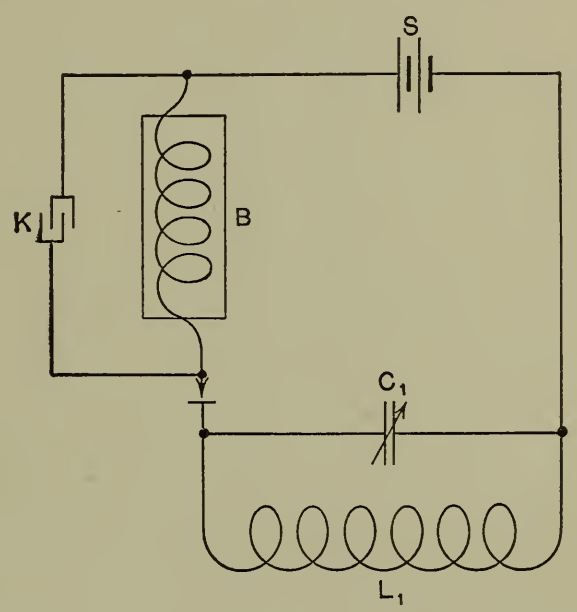

Fig. 2

Here B is the buzzer driven by one or more storage or dry cells with a regulating resistance in series. L_1 is an inductance, C_1 a variable tuning condenser, K a fixed condenser large enough to prevent sparks at the buzzer contact, which would produce a disturbance in the receiving apparatus. When the current is broken, the inertia of the current in L_1 charges the condenser C_1 and feebly damped oscillations are produced in the circuit L_1C_1. The damping may be increased by introducing resistance in this circuit.

[5] Zenneck, Leitfaden der drahtlosen Telegraphie, p. 3.

3. THE THERMOELEMENTS

For a considerable portion of the current measurements thermoelements were required. These were constructed as follows: Two copper wires were placed side by side about 3 mm apart and embedded in insulating material with their ends protruding (Fig. 3). To the end of one of these was soldered about 5 mm of 0.02 mm platinum or constantan wire. To the other was soldered a short bit of No. 20 platinum wire, to the end of which a bead of tellu-

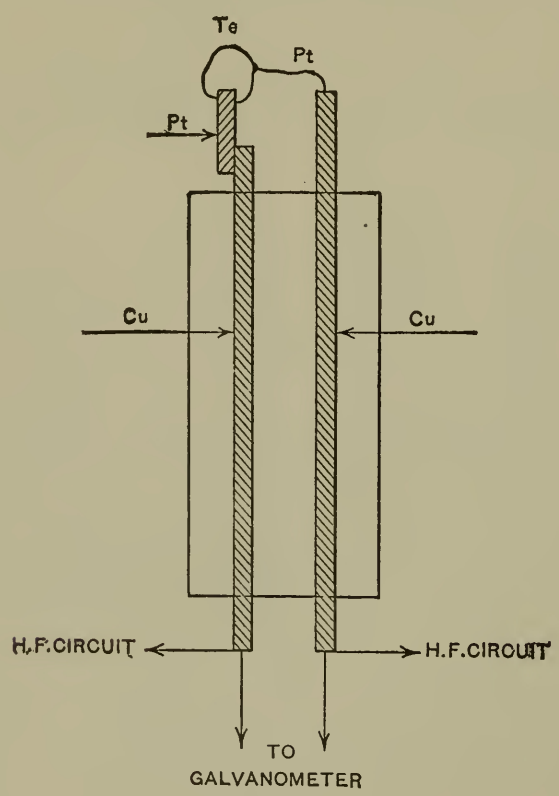

Fig. 3

rium had previously been attached when the platinum was white hot.[6] The end of the fine wire was next allowed to rest against the tellurium and the two were welded together electrically by means of a small induction coil with a high resistance in series with the secondary. The contact will be less fragile if the welding is done in an oxygen-free atmosphere. The resistance of a thermoelement prepared in this way may be anywhere from 5 to

[6] White-hot platinum wire when inserted in tellurium forms practically a resistance-free contact.

50 ohms, according to the conditions of welding and the resistance of the fine wire, the lower resistance being somewhat more difficult to obtain. The thermoelement is next inclosed in a test tube, and, if likely to be handled roughly, the whole may be inclosed in a larger test tube with cotton or felt between the two.

TABLE I

Platinum-Constantan and Tellurium-Platinum Thermoelements in Series

Galvanometer Deflections		Ratio
Platinum-constantan	Tellurium-platinum	
2.2	62	28
4.0	108	27
6.2	176	28.5
9.1	255	28
18.5	510	27.5
20.3	560	27.5
24.6	700	28.5
29.1	810	28

Thermoelements prepared in this way, if carefully handled, are extremely stable and perfectly constant in their electrical properties over long periods. One thermoelement of 11 ohms resistance has now been in constant use in the laboratory for nearly two years and has shown no appreciable variation during the whole time. These thermoelements, on account of the nature of their construction, can not be calibrated by means of direct currents, but may be compared at least over the range of the larger high-frequency currents with a sensitive hot-wire meter which has already been calibrated, arranged for mirror and scale reading.[7] Comparison can, of course, be made also with wire thermoelements of ordinary types. Table I shows the admirable pro-

[7] The hot-wire instrument used was a General Electric Company's voltmeter employing a wire of 15 ohms resistance and giving full scale deflection for 240 milliamperes. By means of a mirror attached to the pointer or, less preferably, if the pointer itself be observed by a microscope, a current of 1 milliampere is readily readable. The constancy is all that could be desired. See Electrical World, Vol. XLIX, 1907, p. 308.

portionality between the galvanometer deflections of a constantan platinum thermoelement already calibrated and those of the tellurium-platinum element.

The 32-ohm thermoelement with the most sensitive galvanometer gave a deflection of about 1 mm for 120 microamperes.

4. THE CONTACT RECTIFIER

For measuring still smaller oscillatory currents, a contact rectifier was used, in which the contact was formed between a crystal of zinkite and one of chalco-pyrite. This combination goes under the trade name of the perikon detector. In its properties it resembles very closely the silicon-steel rectifier described in a former article [8] but is more easily adjusted and is somewhat more constant in its action. When used with a galvanometer as shown in Fig. 6 the galvanometer deflection is proportional to

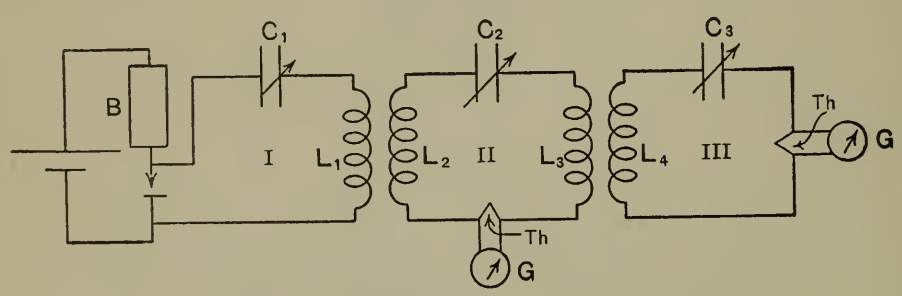

Fig. 4

the square of the high frequency oscillations passing through the rectifier.[9]

5. METHOD OF OBSERVATION

The general scheme of the circuits is shown in Figs. 4 and 6. Here circuit I is the buzzer exciter circuit, already shown in detail in Fig. 1, circuit II a closed oscillatory circuit consisting of a coupling inductance L_2 of 0.03 millihenry, an inductance L_3 of 0.425 millihenry, and a variable air condenser C_2 having a maximum capacity of 0.001 microfarad. The circuit contains also a thermoelement Th of the type already described, across the terminals of which a galvanometer is connected. In Fig. 4,

[8] This Bulletin, **5**, p. 133, 1908.

[9] This Bulletin, **6**, p. 530; 1910.

circuit III is a tuned circuit consisting of an inductance L_4 of 0.42 millihenry, a variable air condenser C_3 of 0.001 microfarad, and a thermoelement.

In Fig. 6, circuit III is an untuned circuit consisting of an inductance L_4 of 0.42 millihenry, a fixed stopping condenser K of about 0.04 microfarad and a perikon detector D which can be connected to the galvanometer. On account of the high resistance of the perikon detector and the large capacity of the condenser, circuit III may be considered as strictly aperiodic.

The wave length used in all the experiments was 900 m and the sending decrement δ_1 was varied between 0.02 and 0.8 by inserting resistance in the oscillatory portion of the buzzer exciter circuit. The decrement of the exciter circuit was determined from the resonance curve, observed in a standard wave meter of known damping, when loosely coupled to the exciter, using the well known formula

$$\delta_1 + \delta_2 = \pi \frac{C_m - C}{C_m} \sqrt{\frac{I^2}{I^2_m - I^2}}$$

which expression becomes simplified to

$$\delta_1 + \delta_2 = \pi \frac{C_m - C}{C_m}$$

when the capacity change is just sufficient to make $I^2_m = 2I^2$. Here C_m and I_m represent the values of the capacity and oscillatory current for resonance. The decrements in circuits II and III were determined similarly by exciting them with circuit I, after its decrement had been determined.

6. THE RELATION BETWEEN THE COUPLING AND THE CURRENT DISTRIBUTION IN TWO TUNED RECEIVING CIRCUITS

This case is represented by the circuits of Fig. 4. Here circuit I, very loosely coupled to circuit II, may be taken to represent a sending station adjusted to send out waves of but a single wave length. Circuit II with its 11-ohm thermoelement represents a receiving antenna of moderate dimensions, while circuit III, containing a thermoelement of 32 ohms, represents a tuned, closed receiving circuit coupled to the antenna.

TABLE II

Coupling and Currents in Circuits II and III

$\lambda=900$ m. $\delta_{II}=0.059$. $\delta_{III}=0.0996$. [I in milliamperes]

K	$\delta_1=0.02$		$\delta_1=0.16$		$\delta_1=0.8$	
	I^2_{II} (milliamperes)^2	I^2_{III}	I^2_{II} (milliamperes)^2	I^2_{III}	I^2_{II} (milliamperes)^2	I^2_{III}
0	16.9	....	16.9	....	16.9	....
0.010	.....	....	.....	....	....	....
.014	16.6	0.49	16.5	0.41	16.2	0.39
.020	15	1.08	15.3	.93	14.9	.86
.028	11.6	1.22	13.7	1.95	13.8	1.78
.030	10.7	2.60	12.5	2.56	....	....
.033	.....	....	.....	....	12.4	3.25
.037	7.05	3.67	8.95	4.02	11.0	4.13
.041	4.92	3.81	7.8	4.45	9.4	4.75
.049	2.01	3.56	5.45	4.80	8.4	5.60
.061	1.30	2.71	4.34	4.57	7.5	5.95
.073	.77	1.88	3.34	3.92	6.2	5.95
.099	.....	....	.....	....	5.5	5.75
.126	.....	....	.....	....	4.5	5.3

Table II and Fig. 5 give the results of a series of observations on three different values of sending decrement for various degrees of coupling k between circuits II and III. It is seen that as the coupling is increased the current in circuit II falls rapidly, while that in circuit III increases rapidly up to a given point. In this neighborhood both curves change their direction and both fall together as the coupling is further increased. From these curves it is seen that the current in circuit II falls more abruptly and at a smaller coupling the less the damping of the received wave trains. Similarly, the current in circuit III rises more rapidly and abruptly and with smaller coupling, in the case of the feebly damped trains. It is noticeable also that the maximum in the current of circuit III is much more marked with the feebly damped trains. In the case of a sending decrement $\delta_1 = 0.8$, the maximum is scarcely

to be observed, the magnitude of the current remaining almost unchanged as the coupling is increased in strength beyond the

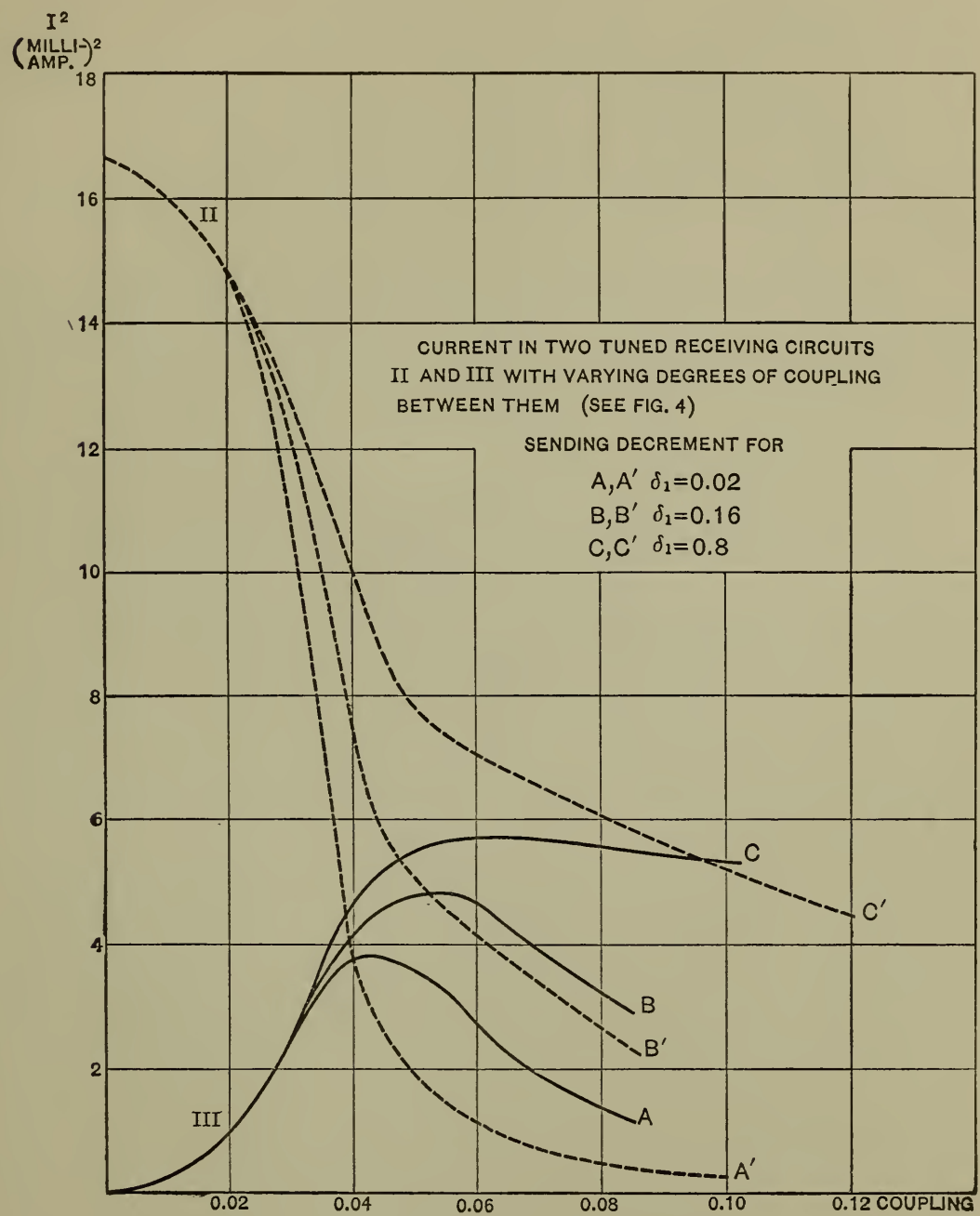

Fig. 5

point at which it has ceased to rise. It is also to be noted that the maximum amount of energy capable of being drawn into circuit III is relatively larger, the greater the sending decrement.

7. COUPLING AND CURRENT DISTRIBUTION BETWEEN A TUNED AND AN UNTUNED RECEIVING CIRCUIT

In several forms of wireless receiving apparatus the detector is contained in an untuned circuit coupled to the antenna. Such a case is represented in Fig. 6. Here, as before, circuit I represents the sending station, circuit II the antenna, which in this case contains a 32-ohm thermoelement, and circuit III, with its perikon detector and fixed condenser K, the untuned detector circuit.

It has been shown in another place that the deflections of a galvanometer attached to a perikon detector are proportional to the square of the current in a circuit to which it is coupled, for any given frequency.[10] It is strictly true, however, only when the

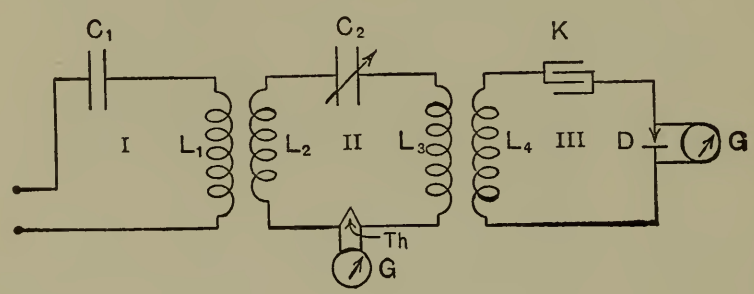

Fig. 6

resistance in the circuit is either larger or very much smaller than the inductive reactance of the circuit.[11]

Table III and Fig. 7 show the relations between the currents in circuits II and III for different degrees of coupling for a sending decrement 0.16. It is seen that the current in circuit III rises rapidly up to a certain degree of coupling, beyond which it falls slightly as the coupling is increased. Comparing Figs. 5 and 7, it appears that the position of the maximum current in circuit III occurs as would be expected, with a much stronger coupling when circuit III is untuned, and that the maximum itself is much less strongly marked. The curves are given for but one value of sending decrement, as it was found that the change in the form of the curve was but very slight, as the sending decrement was varied.

[10] This Bulletin, **6**, p. 530; 1910.

[11] Zenneck, Leitfaden der drahtlosen Telegraphie, p. 78.

TABLE III

Coupling and Currents, Circuit III Untuned

$\lambda = 900$ m. $\delta_I = 0.16$ $\delta_{II} = 0.13$

K	Thermoelement Circuit II I^2_{II}	Perikon Circuit III Deflections
0	1.66	...
0.032	1.62	24
.057	1.51	131
.088	1.44	295
.115	1.38	423
.145	1.21	580
.212	.75	640
.463	.41	520
.570	.23	430
.655	.12	350

8. THE RELATION BETWEEN COUPLING AND SHARPNESS OF RESONANCE

It has already been stated that we may consider the coupling of a circuit containing resistance to another circuit as introducing a certain proportion of its resistance into the latter. This will not only decrease the amplitude of the oscillations in the circuit but will also increase its natural logarithmic decrement and decrease the sharpness of the resonance curve when it is brought into resonance with any circuit from which waves are being sent.

In order to observe this relationship quantitatively the detector circuit III shown in Fig. 6, containing a perikon detector of 2000 ohms resistance [12] connected to a galvanometer, was coupled inductively to circuit II with the thermoelement removed. This latter circuit was excited by the buzzer exciter. Under the conditions used, it was determined experimentally that the natural decrement of the buzzer exciter circuit was approximately 0.02 and that that of circuit II was very nearly the same. The damping of the system was then observed as the coupling between the circuits II and III was increased. The results are given in Table IV and Fig. 8. It is to be seen that the influence of the coupled detector on the damping is practically negligible for K = 0.057

[12] The resistance of rectifiers of this type is a variable quantity depending on the magnitude of the oscillatory current. See this Bulletin, 5, p. 133; 1908.

and nearly so for K = 0.085, and that the values become very large as the coupling is increased to a maximum. If the buzzer exciter has a decrement of 0.12, corresponding to a rather feebly damped wireless sending station, and circuit II has a decrement of 0.13 representing a receiving antenna, Table IV shows that the damping due to the coupled detector remains relatively negligible until

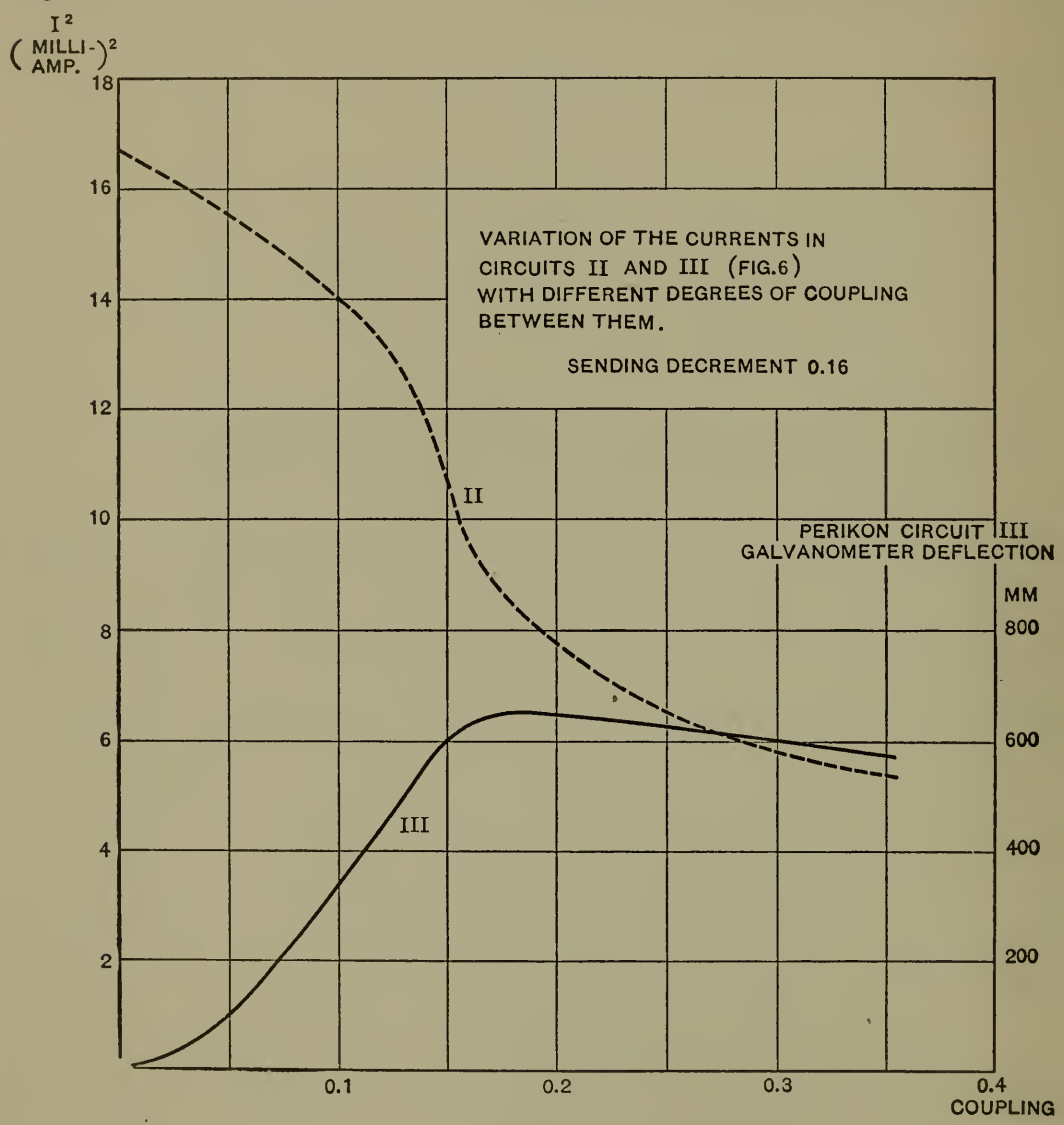

Fig. 7

the coupling has been increased beyond 10 per cent. The form of the curve in Fig. 8 indicates that the coupling damping increases with the mutual inductance until the point is reached where the current curve ceases to rise. (See Fig. 5.) The rise of the damping curve is then for a short distance very slight but with still closer coupling again rises abruptly.

TABLE IV

Coupling and Total Apparent Decrement

$\lambda = 900$ m

K	$\delta_I = 0.02$	$\delta_{II} = 0.02$	$\delta_I = 0.02$	$\delta_{II} = 0.13$	$\delta_I = 0.12$	$\delta_{II} = 0.13$
	Perikon deflections	$\Sigma\delta$	Perikon deflections	$\Sigma\delta$	Perikon deflections	$\Sigma\delta$
0.032	14	0.040	..	....	....	....
.039	54	.042	7	0.149	7.5	0.244
.057	200	.050	28	.151	27.5	.270
.085	410	.060	83	.162	66	.320
.114	450	.072	135	.179	92	.342
.148	430	.111	195	.196	130	.370
.212	340	.150	250	.239	156	.430
.303	280	.180	240	.294	154	.510
.463	230	.250	230	.380	150	.620
.570	185	.372	210	.510	132	.830
.655	115	.705	150	.840	100	1.110

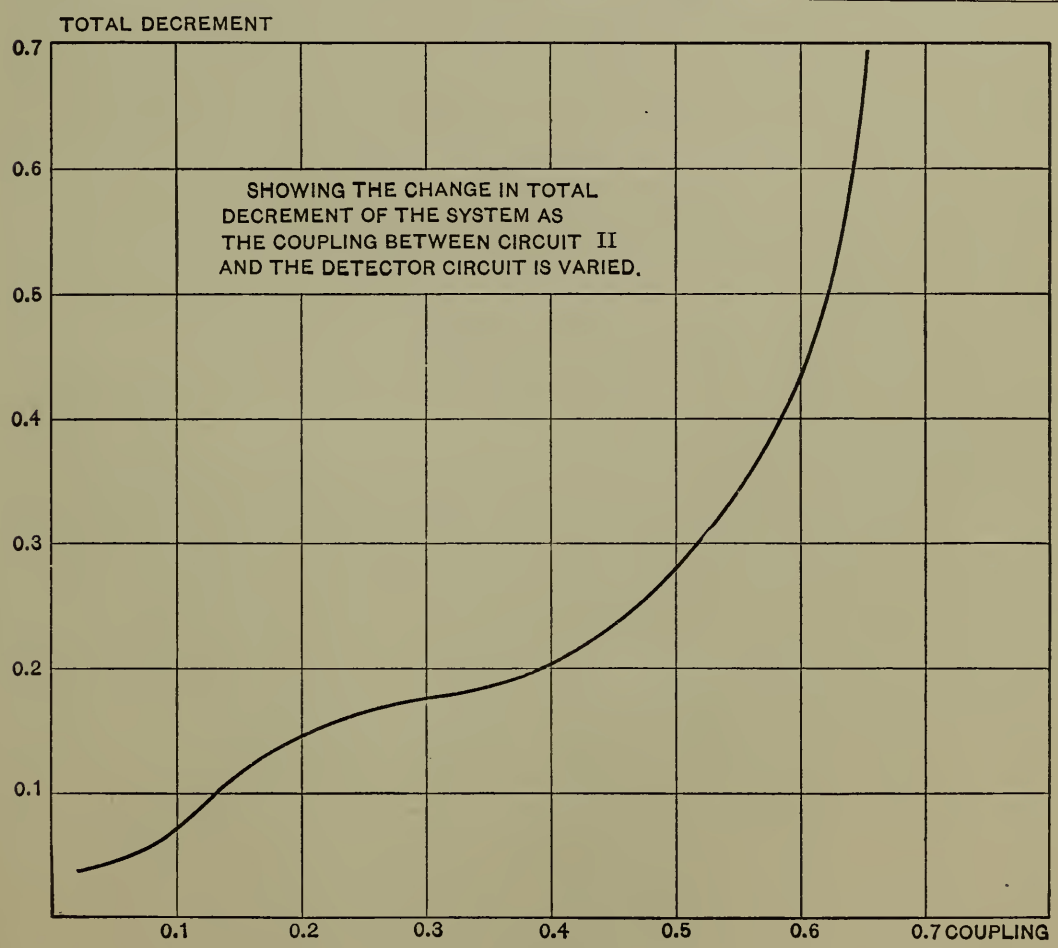

Fig. 8

9. DISCUSSION OF RESULTS

If the tables and curves be examined in regard to the quantitative relationship between the energy in the two circuits under special consideration in each case, it will be found that in the case of the more feebly damped oscillations the maximum of the I_{III}^2 curve in circuit III occurs at that degree of coupling for which the I_{II}^2 curve in circuit II has fallen to approximately one-fourth of its maximum value, while with increasing sending damping, the maximum for I_{III}^2 approaches the point at which I_{II}^2 falls to one-half.

The results obtained have also a practical bearing on the construction and method of use of receiving circuits. They show that for the greatest efficiency in working, the apparatus must be so arranged that the amount of energy withdrawn from the antenna may be varied until the point of maximum effect is obtained. If the detector is connected in shunt across an inductance the number of turns contained between the detector terminals should be variable and independent of the number of turns of the inductance which are used for tuning purposes. If the detector is connected around a condenser, it must have in series with it a small variable condenser which can be used to regulate the amount of energy flowing into the detector. By far the simplest and best method, however, is the inductive coupling of the untuned detector circuit to the antenna or to an intermediate tuned circuit, the coupling coils being arranged so as to be easily moved toward or away from each other by means of a rack and pinion or some similar device.

The portion of the work on the relation between coupling and sharpness of resonance also shows the importance of having means of varying the amount of energy drawn from the antenna circuit. The results show that if the coupling be made stronger than is required for the maximum effect in the detector, the damping is largely increased, resulting in an enormous loss in sharpness of tuning, while at a point a little before the maximum is reached the detector produces a comparatively feeble influence on the receiving damping and at the same time the intensity of the current in the detector is but little below its maximum value.

U. S. Naval Wireless Telegraphic Laboratory,
Washington, D. C., May 1, 1910.