A COURSE IN RADIO FUNDAMENTALS

Study Assignments, Experiments and Examination Questions

BASED ON

THE RADIO AMATEUR'S HANDBOOK

By

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☆ CONTENTS ☆

Introduction

THE content of a course of study in a technical subject must be determined by the objectives to be realized. The radio amateur of peacetime has always been noted for his ability to secure results, in the way of effective communication, far beyond what might reasonably be expected from the equipment he uses. This practical "know-how" has not, however, always been accompanied by an equivalent understanding of underlying principles. In a time when technical knowledge is an invaluable asset both to the individual and the nation, it is only natural that those who already have some skill in the art of radio communication should wish to supplement that skill with a foundation of theoretical knowledge — realizing that a good technician becomes a better one by knowing the "why" as well as the "how." Our objective in preparing this course, therefore, was to accent, for the amateur, those principles most frequently applied in actual radio communication.

This volume is a study guide, examination book and laboratory manual. The basic text is *The Radio Amateur's Handbook*, Chapters Two to Ten, inclusive, in the 1942 and subsequent editions. Either the standard edition or the special edition for war training purposes may be used equally well; in both editions the identical section numbers are used for the same subject matter. In the course, the *Handbook* material is divided into thirty-six study assignments; each assignment should represent approximately a week's work, on the assumption that six to eight hours will be available. Certain assignments may call for more time and others for less; those which have no accompanying experiments obviously can be completed more rapidly than those which have a considerable amount of experimental work. With each assignment there is a series of questions designed to bring out the important points in the text. Problems of a numerical nature are included wherever possible, with answers given at the end of the book; in a few cases where more than routine methods are required, the complete solution is given. Also accompanying each assignment, when feasible, are one or more experiments of a nature which, we believe, will not only illustrate the principles being studied but will in many cases throw additional light on the subject under consideration. Information supplementary to that contained in the *Handbook* is frequently contained in the descriptions of the experiments.

As a home-study course, this material was prepared principally for radio amateurs who have already had some practical experience in building and operating radio apparatus. This experience is probably essential for the construction of the various pieces of equipment used. In view of such pre-training a number of elementary experiments, such as the construction of simple oscillators and receivers, have not been included in the series. The desirability of such experiments for classes which have had no previous radio experience is pointed out at appropriate points in the text.

Experiments and Apparatus

An important part of any technical course of study is experimental work. Outlining a suitable series of experiments for the home worker is always a problem of considerable difficulty, because the cost of the equipment necessarily must be kept to a minimum. To that must be added the fact that very little laboratory apparatus of any kind is presently available, even when cost is no consideration. Insofar as possible, therefore, the apparatus used in the experiments described herein uses components which can be found in the average amateur station or which can be salvaged from discarded broadcast receivers. While this inevitably puts some limitation on the scope of the experimental work, it is not a question of choice but of necessity, a necessity which frequently now faces those conducting formal courses as well as those studying at home.

The experiments outlined all have actually been performed with the equipment recommended, with the results given in the description of each experiment. These descriptions are for the most part fully detailed, with emphasis on those factors which tend to cause departures from the theoretically ideal conditions and, as a consequence, frequently confuse the student who is working without the benefit of personal instruction. It will be apparent to anyone familiar with the subject that many obviously desirable experiments have had to be omitted because of unavoidable limitations of equipment. Our purpose here is to do as much as possible with as little as possible; in formal courses, where more elaborate laboratory apparatus may be available, the devising of suitable experiments utilizing it can safely be left to the individual instructor.

The construction of the various pieces of experimental gear is described as the need for it arises in the course. Simple breadboard-style construction is used throughout, since it is economical and convenient, but more elaborate and durable construction may be desirable for equipment which is to have a great deal of use. In addition to these units, it will be necessary to have at least one multi-purpose test instrument of the volt-ohm-milliammeter type. All of the experiments have been planned on the basis of using only one such instrument, but the work will be facilitated considerably if voltmeters and milliammeters of various ranges are available so that readings of several quantities can be taken simultaneously. Another necessary adjunct is a communications-type receiver, of any make or model so long as it is provided with the frequency calibration which is usually a feature of these sets. A number of miscellaneous small parts — fixed condensers and resistors, chiefly — also will be needed. They are specified with each experiment as required.

Home Study

Those studying alone usually are inclined to move more rapidly than circumstances warrant. There is frequently a tendency, also, to slight those points about which the student already feels himself fairly well informed. It is a mistake to do either; the only sure way is to omit nothing and to pay as much attention to seemingly simple material as though the work were being done in a formal class.

It is recommended that the set of questions accompanying each assignment be treated as though it were a class-room examination, and that the answers be *written* just as though the paper were going to be marked by an instructor. After answering all questions as completely as possible, the answers should be compared with the *Handbook* text for errors and omissions. This is the only practicable way to check what has been learned, and the whole process promotes the clear thinking which is so essential when there is no instructor at hand to criticize and correct. Reducing a statement to writing spotlights those points about which there is uncertainty, and forces the student to formulate his ideas in such a way that doubt about what is meant is reduced to a minimum. To say "I know the answer but can't express it" is simply a confession that the answer is *not* known. Continual self-criticism is an essential ingredient of successful home study.

Observations taken in the course of the experimental work should be recorded in a notebook kept especially for the purpose. The laboratory notebook should be kept as carefully and neatly as would be required in a regular class, and the observations should be as complete and detailed as possible. It will be helpful, too, to include with the data a written explanation of the phenomena observed and the results secured, including reasons why (when necessary) there is a difference between experiment and theory. Such written notes are invaluable as a means of fixing the principles and practice firmly in mind. Should the subject matter under study suggest further experimental possibilities within the scope of the equipment, the exploration of such possibilities cannot help but be beneficial, if the work is carried out in a methodical way and an attempt is made to provide a logical interpretation of the results.

It is possible to learn, and learn thoroughly, at home — by adopting and preserving the attitude of seriousness toward the work which it deserves.

Part One

ELECTRICITY AND MAGNETISM

THE fundamental facts of electricity and magnetism form the foundation upon which the whole structure of electrical communication rests. The connection between such things as frictional electricity and a radio circuit may frequently seem somewhat obscure, but the concepts of charge and field are basic in both.

Many of the essential ideas can be demonstrated by experiments using apparatus constructed from odds and ends of metal and wood. There is no better way to grasp the principles involved than to perform such experiments, simple though they are.

ASSIGNMENT 1

Study *Handbook* Sections 2–2 and 2–3. Perform Exps. Nos. 1, 2 and 3.

Questions

1) What is meant by the electrostatic field, and how is its strength described?

2) Define capacity.

3) From Sec. 2–3 and the remarks under Experiments 2 and 3, in what way would you expect the following factors to affect the capacity of a condenser? Give the reason in each case:

- a) area of plates;
- b) separation between plates;
- c) dielectric material between plates;
- d) number of plates, when the condenser consists of a set of interleaved plates with alternate ones connected together.

4) What is meant by the resistance of a conductor?

5) What is the nature of the force between two electrostatic charges if

- a) both are positive;
- b) one is positive and one is negative;
- c) both are negative.

6) What is the meaning of potential difference?

7) Name five conductors and five insulators.

8) What is the fundamental particle of electricity?

9) What is the nature of positive and negative electric charges?

10) Name the units for each of the following, giving a suitable definition in each case:

- a) difference of potential;
- b) quantity of electricity;
- c) capacity;
- d) electromotive force.

11) Explain (a) how an insulated conductor can be charged by contact with a charged body; (b) how such a conductor can be charged by induction.

12) Is capacity necessarily associated only with a condenser?

ASSIGNMENT 2

Study *Handbook* Section 2–4.

Questions

1) What is meant by an electric current?

2) How does conduction take place in metals?

3) Describe briefly the fundamental difference between the two general types of batteries as exemplified by the dry cell and the lead storage battery. One type is called a primary battery or cell and the other a secondary battery or cell. Which term do you believe should be applied to which type?

4) What is meant by ionization?

5) Name four types of electrical conduction.

6) How can current flow be established in a vacuum?

7) What is the convention with respect to direction of current flow?

8) In a metal the flow of current is proportional to the applied electromotive force. Is this same proportionality true of current flowing in a gas? Would you expect it to be true in a vacuum, when the current is formed of electrons emitted by a hot cathode?

9) What is the unit of electric current?

ASSIGNMENT 3

Study *Handbook* Section 2–5 and perform Exps. Nos. 4, 5 and 6.

Questions

1) Describe self-induction.

2) The laws of forces existing between magnetic poles are similar to those governing forces between electrostatically-charged bodies. What, then, will be the nature of the force between:

- a) a north pole and south pole;
- b) two north poles;
- c) two south poles.

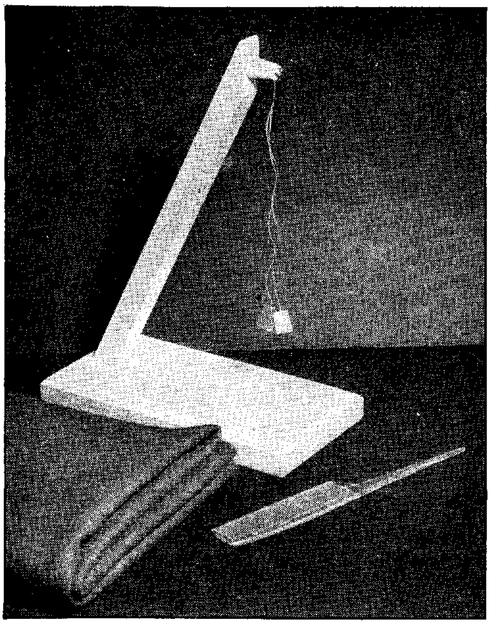


Fig. 1

3) Calculate, from the diameter of each coil and the length of wire, the approximate number of turns on each winding of the electromagnet used in Exp. 4. Using first one battery and then the two in series, measure the corresponding currents through Coil 1 alone, Coil 2 alone, and Coils 1 and 2 connected in series as described in the experiment. Calculate the ampere turns for each of the six cases. Which of the six should show the strongest magnetic effect? Check experimentally.

4) Using the equipment of Exp. 4, connect the two coils in series as described in the experiment and apply the 3 volts from the battery. Observe the magnetizing effect by the attraction for a piece of soft iron. Disconnect the two coils and connect the two "starting" ends of the windings together, applying the battery to the other two ends. How does the magnetizing effect now compare with the original strength? Explain why there is a difference.

5) Under what conditions can a voltage be induced in a conductor?

6) Is inductance necessarily associated only with wire wound in a coil?

7) How is the intensity of a magnetic field described?

8) Name the various units of inductance, and describe their relationship.

9) What is meant by the term permeability?

10) What factors determine the inductance of a coil?

11) What is the direction of flow of an induced current compared to the direction of flow of the current causing the induction?

12) When the current through a coil is broken, is the induced voltage larger or smaller than the voltage induced when the current is started? Why?

13) How is an unmagnetized piece of iron attracted by a magnet?

14) Upon what factors does the strength of the magnetic field set up about an electromagnet depend?

EXPERIMENT 1

Electrostatic Induction

Apparatus: This experiment requires only very simple equipment: a few bits of metal foil, a little thread (preferably silk, which is a better insulator than cotton), a celluloid comb, and a piece of felt on which to rub the comb to work up an electrical charge by friction. Many materials can be substituted for the celluloid and felt; hard rubber (a fountain pen or comb) or glass rods will do very well in place of the celluloid, for instance, and wool cloth in place of the felt.

It is convenient to have a simple mounting for the suspended pieces of foil, as shown in Fig. 1. (The same mounting can be used for the subsequent experiment.) A wooden base about 4 × 8 inches will be adequate. The support is a piece of 1 × 1 wood fastened to the base at an angle of about 60 degrees. A stand-off insulator is mounted horizontally at the top of the support, and the threads holding the foil pieces are held under the top screw of the insulator. The insulation should be as good as possible, since even a little leakage will greatly affect the way in which the apparatus responds in the experiment. The insulator should be kept clean and dry, as should also the threads and the wooden support. In humid weather it may be almost impossible to build up a sufficient charge or to retain it for any length of time.

The foil pieces should be about ½ × ½ inch in size, and should be quite thin. The lighter the weight the better, so aluminum foil is to be preferred to tin or lead foil. Although thin aluminum foil is still to be found on some kinds of candy, probably the best source is an old tubular paper by-pass condenser (a blown-out unit will provide plenty of foil). Cut two pieces to size, smooth them out, punch a hole with a needle at one end, and tie on lengths of thread. A seven-inch length is about right. When mounting the foil pieces, make sure that both hang at the same height.

Procedure: Only one foil piece is required for the first step in the experiment. The other may be hung over the wooden support to keep it out of the way. Rub the comb briskly on the felt and bring it near the suspended foil. As the comb is brought nearer the foil will be attracted and will approach the comb edge on. If it is allowed to touch the comb or to approach near enough for a spark to jump, it will immediately be repelled by the comb, and will continue to be repelled so long as both foil and comb retain their charges.

The explanation for this is as follows: When the comb is rubbed on the felt it acquires electrons from the latter and thus becomes negatively charged. When brought near the foil so that the latter is in the electrostatic field of the comb, free electrons on the foil are repelled by the field and collect on the end of the foil farthest from the comb. The foil turns edge on because the forces acting tend to keep the collection of electrons as far from the comb as possible. The movement of electrons on the foil away from the comb causes the far side of the foil to be negatively charged, and since the foil is insulated and no new electrons can enter it, there is a deficiency of electrons on the edge nearest the comb. Thus the near edge is positively charged, and since this charge is opposite in sign to the charge on the comb the near edge is attracted to the comb. The positively charged end, being nearest the comb, is in a stronger part of the comb's field than the far edge, hence the force of attraction is greater than the force of repulsion. Therefore the foil moves toward the comb.

When the foil touches the comb or comes near enough for a spark to jump, a portion of the charge on the comb is imparted to the foil. That is, some of the excess electrons on the comb flow into the foil so that the latter then has an excess of electrons. It has thus acquired a negative charge and is immediately repelled from the comb since both comb and foil now have the same kind of charge. The charges on both will gradually leak off with time, or they may be discharged intentionally by touching them with a grounded conductor or semi-conductor. A touch with the finger is usually sufficient, since the human body is large enough to accommodate the excess electrons on the charged objects, and has enough conductivity to allow the charge to be dissipated instantly.

Besides the contact method of charging the foil just described, a charge (and generally a stronger one) may also be imparted to the foil purely by induction. Touch the uncharged foil with the end of a piece of stiff wire several inches long held in the hand. Use the wire to hold the foil so that it cannot move when the charged comb is brought near it. Under these conditions the repelled electrons will flow down the wire to the body, leaving a positive charge on the foil. Now take away the wire and as quickly as possible (but *after* the wire is removed) move the comb away from the foil so that the latter cannot touch it. Removing the wire leaves the foil with an insulated positive charge, and since the foil is then charged oppositely to the comb, the two will attract each other. Should they touch, the foil will again be charged by contact and repulsion will occur. Thus charging by contact gives a charge of the *same* sign as the charge on the comb, while charging by induction gives a charge of *opposite* sign.

In charging by contact the charge imparted depends upon the surface leakage on the comb, and since celluloid is a good insulator only a limited number of electrons can flow into the foil. When charging by induction the field set up by the accumulation of electrons on the comb is used, and electron movement on the comb is not essential. Hence it is frequently possible to impart a stronger charge by induction than by contact under these conditions, particularly when the area of the conductor to be charged is appreciable compared to that of the comb (or other insulator) which has the original charge.

Now let both pieces of foil hang freely and bring the charged comb in the vicinity. Observe the sequence of happenings. Explain.

Give both pieces of foil the same kind of charge so they repel each other. Write an explanation for what is observed to happen.

EXPERIMENT 2

Capacity

Apparatus: The equipment and set-up for this experiment are shown in Fig. 2. The stand used in Exp. 1 supports a 5- or 6-inch length of stiff copper wire (No. 12 or 14) to the lower end of which has been soldered a small piece of very fine bare wire (No. 38 if available) rounded in the form of a hook. Two triangular pieces of thin aluminum foil about 3/8 inch on a side hang on the hook. The holes through which the hook passes can be punched through the foil with a needle, and should be as close as possible to one apex of the triangle. The two "leaves" should be free to move on the hook without interfering with each other. This forms a simple electroscope, or instrument for measuring the intensity of a charge.

On a block of wood about 4 × 6 inches mount a flat metal plate 2½ × 3½ inches, using two stand-off insulators as supports. This plate must be well insulated from the wooden base. Attach a length of wire to the plate.

Procedure: First charge the electroscope as strongly as possible by induction, using the procedure outlined in Exp. 1. The best charge can be obtained by holding the charged comb close to and lengthwise with the wire support so that the wire is in the strongest possible field. On removing the grounding wire and comb, the two leaves should spring apart. Since the tops of the leaves are not free to move very far, the leaves will take the position of an inverted V; with a good charge the angle of the V should be about 90 degrees.

Now take the wire from the insulated plate and, handling it with an insulated rod (the comb will serve), touch it on the wire support for the leaves. The leaves will drop toward each other, but will not completely lose their charge. Now remove the wire and the leaves will not change their position. The wire from the plate may be touched on the electroscope again but the position

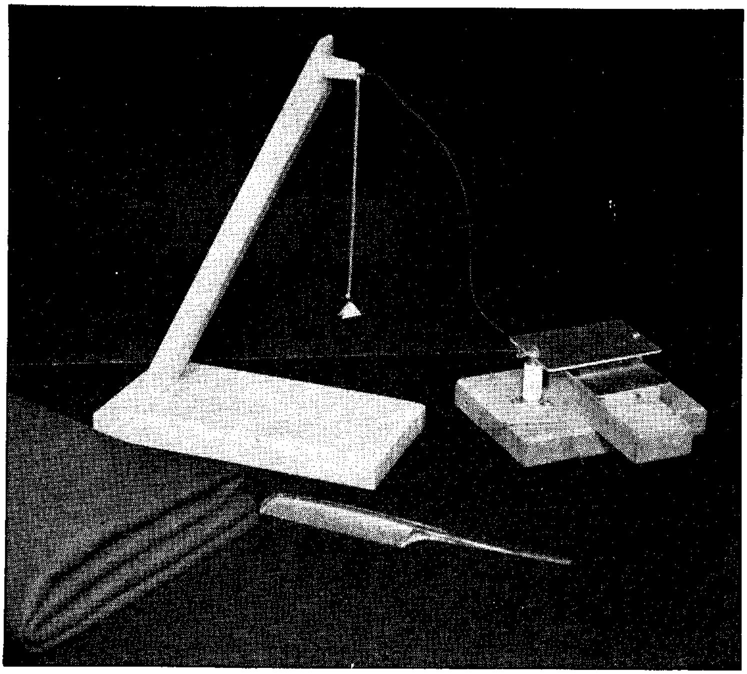


Fig. 2

drained off the electroscope by discharging it now having disappeared.

The conclusion to be drawn from this experiment is that the system with the larger surface — i.e., the electroscope and plate connected together as compared to the electroscope alone — will have a lower potential, for a given quantity of electricity, than that with the smaller surface — i.e., the electroscope alone. The ratio of quantity to potential is called the capacity of the system; that is,

$$C = \frac{Q}{E}$$

where C is capacity, Q quantity and E potential. In practical units C is expressed in farads, Q in coulombs, and E in volts. A given quantity of electricity on a high-capacity conductor will give a smaller potential than the same quantity on a low capacity conductor. Or if two conductors of different capacities are charged to the same potential, the one with the higher capacity will take the larger quantity of electricity. Under these conditions the quantity of the charge, or amount of electricity stored, will be directly proportional to the capacity of the conductor.

As a variation, the insulated metal plate alone may be charged and then connected to the electroscope. The leaves will spring apart, the extent of the repulsion being an indication of the potential of the plate.

of the leaves will not change. With the wire off, discharge the electroscope with the finger, then touch the wire from the plate to the wire support again. The leaves will once more repel each other, but to a lesser extent than in either of the previous two cases.

In the first case a certain quantity of electricity is placed on the electroscope, the intensity or potential being indicated by the extent to which the leaves repel each other. On connecting the plate to the electroscope some of the charge flows into the plate, distributing itself over the surface of the plate as well as over the surface of the electroscope. Although the total quantity of electricity involved remains the same, the intensity or potential is lowered, as indicated by lesser repulsion between the electroscope leaves, because it is now spread over a larger area. The quantity of electricity distributes itself so that the whole system has the same potential (or voltage), so that reconnecting the plate wire after once removing it causes no further redistribution of charge; both the electroscope and the plate are then at the same potential and hence current will not flow from either one to the other.

With the wire removed and the electroscope discharged, the plate is left with its acquired charge. On connecting the wire once more, some of the electricity on the plate flows back into the electroscope, recharging it — but this time at a lower potential because there is less electricity available than formerly, that part which was

EXPERIMENT 3

Condensers

Apparatus: The same equipment is needed as in Exp. 2, with the addition of a 2 × 3 inch metal plate mounted flat on one end of a piece of wood 2 inches wide and 5 or 6 inches long. Add a wooden shim, if necessary, so that when the second plate is slid under the first, as shown in Fig. 2, the two plates will be separated by about ¼ inch. Attach a length of wire to the plate. Provide a piece of clean glass about 2 × 3 inches in size. Ordinary window glass is satisfactory.

Procedure: Connect the insulated fixed metal plate to the electroscope and charge the system by induction. Connect the wire from the movable plate to ground. (In many cases an actual ground will not be necessary because there will be sufficient leakage through the wood to give the same effect.) Slide the movable plate under the fixed plate, being careful to get no metal-to-metal contact, which will discharge the system. The electroscope leaves will drop toward each other. Raise the movable plate until it is as close as possible to the fixed plate, taking care not to touch the latter and discharge it. The closer the two are to each other, the more the electroscope leaves will drop. Finally, take away the movable plate and the leaves will move apart to their original position.

The fact that the electroscope leaves indicate a lower potential when the movable plate is inserted shows that the capacity of the system has been increased ($E = Q/C$) since none of the stored electricity can have escaped from the system. Since the cause of the lowered potential is the presence of the second plate near the first, the two-plate arrangement evidently has larger capacity than one plate alone. Such a combination is called a condenser. The further decrease in potential which results when the separation between the two plates is decreased shows that the capacity of the condenser increases as the plates are brought closer together. The decrease in potential is the result of the fact that the second plate becomes charged by induction, and since the charge is opposite in polarity to that on the fixed plate, the electrostatic field from the induced charge lowers the potential at the fixed plate. The effect is more marked when the two plates are close together because the fields become more nearly equal in intensity under these conditions. When the movable plate is taken out, the potential of the fixed plate returns to its original value, since the opposing field is no longer present. The electroscope leaves therefore return to their original positions.

Now charge the fixed plate and electroscope once more and insert the movable plate. Slide the piece of glass between the two plates. The electroscope leaves will drop still more when the glass partially replaces the air between the plates, indicating that the potential is lowered more with glass than it is with air. The presence of the glass therefore has increased the capacity of the condenser. Evidently there is less drop in electrostatic field strength through glass than through air, since the capacity can be increased only by lowering the potential, and inserting the glass has the same effect as moving the plates closer together when the medium between them is simply air. The medium is called the *dielectric*, and the ratio of the condenser capacity with a given dielectric to its capacity with air dielectric, all dimensions remaining the same, is called the *specific inductive capacity* of the dielectric or, more frequently (in the practical system of units), the *dielectric constant.*

EXPERIMENT 4

Electromagnetism

Apparatus: This experiment requires the apparatus shown in Fig. 3. A homemade electromagnet having two windings is needed, arranged with a removable core. The core should be soft iron, cylindrical and about 3½ inches long. A suitable core can be made from a ⅜-inch diameter bolt having an unthreaded section of the required length, by sawing off the head and threaded portion. Procure or make a cardboard tube of the same length as the core and having an inside diameter such that the core will fit in it fairly snugly, but loose enough so that the core can easily be slid in and out. Cut out pieces of thin wood or masonite and drill them to fit over the ends as mountings, as shown in Fig. 3. Then wind on about 100 feet of No. 28 enamelled wire, leaving ends for terminals, cover the winding with tape or paper, and put on a second winding of about 200 feet of wire of the same size. Wind both coils in the same direction (that is, same direction of rotation in winding; the layers can travel back and forth along the coil) and label the terminals so that the "start" and "finish" ends are readily identifiable. The wire should be wound fairly evenly, but perfect layers are not at all essential. Considerable time and effort can be saved by using a hand drill for the winding, mounting the drill in a vise and running a bolt of appropriate size through the cardboard tube and into the chuck so that the tube will turn when the drill handle is turned. A small piece of wood with four machine screw terminals mounted on it makes a suitable base for the coil.

Current can be furnished by a pair of ordinary dry cells connected in series. The current-measur-

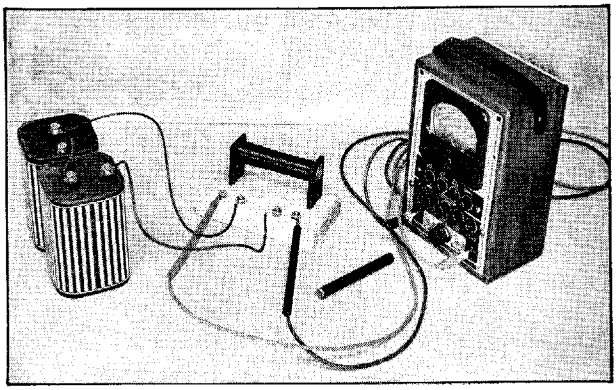


Fig. 3

ing instrument can be a 0–500 milliammeter or a multi-range test set of the general type shown in the photograph. A permanent magnet, either bar or horseshoe, should be provided.

Procedure: Connect one wire from the battery to the smaller coil (Coil No. 1) and insert the iron core in the coil. Hold one end of the permanent magnet near the core, close enough to feel the magnetic pull but not close enough to make the core piece move. Now touch the other battery wire to the remaining terminal of the coil. The permanent magnet will be either attracted or repelled, depending upon the polarity. Repeat, holding the other end of the magnet near the core. If the magnet was repelled in the first place, it will now be attracted, and vice versa. Using either end of the magnet, note whether attraction or repulsion takes place when current flows through the coil. Now present the same end of the magnet to the other end of the core. The opposite effect will take place at opposite ends of the core with the same magnet pole. Note that when the current is cut off these effects disappear, and that either end of the core will be attracted equally well by either end of the magnet.

Since the same effects can be observed by going through the same procedure with a permanent bar magnet substituted for the coil and soft-iron core, it is evident that the current flowing through the coil makes the coil and core equivalent to a bar magnet. That is, the current has caused a magnetic field to be set up. Some of the properties of electromagnetism can be demonstrated by continuing the experiment as follows:

Connect one dry cell, the smaller coil (Coil No. 1) and the test set in series, selecting the proper current scale on the latter to read the current in the circuit (the 500-ma. scale, or nearest to that value, will be suitable). Insert the iron core in the coil. Note the current and bring a piece of soft iron (the remainder of the bolt will do) near the core. When the iron is brought close it will be attracted to the core. Open the circuit and the iron is no longer attracted. (If any attraction still exists, the bolt probably is steel instead of soft iron and has retained some of the magnetism imparted to it when attracted to the core. This property is called *magnetic retentivity,* and since it tends to obscure the principles involved in these experiments, soft iron, which has little or no retentivity, is to be preferred.) Now use the two cells in series, which should double the current, approximately, and repeat. The attraction will be noticeably stronger.

Connect the two coils in series, running a wire from the "finish" terminal of Coil 1 to the "start" terminal of Coil 2, and connect the dry cells and meter in series with the remaining terminals. Again bring the iron near the core and note the attraction. Compare this attraction with that which occurs when Coil 1 alone is used with a single dry cell.

The iron is attracted for reasons quite similar to those given to explain the attraction of an electrically charged body for one without charge (Exp. 1). In the molecular theory of magnetism the iron molecules are miniature magnets which, in a piece of iron showing no magnetism, are assumed to be in random positions so that on the whole their individual fields cancel out, so far as external effects are concerned. When such a piece of iron is brought near a magnet, the molecules tend to align themselves so that they lie parallel with the lines of force. If the field is from an N pole, the S poles of the molecules will turn toward the magnet and the N poles away from it, since unlike poles attract and like poles repel. Hence the iron becomes a magnet itself, with its S pole (in this example) facing the N-pole source of the field. The two magnets therefore attract each other, and if the field is strong enough and at least one of the magnets is free to move the two will be pulled together. The same mechanism explains how the iron core becomes magnetized under the influence of the magnetic field set up by the current flowing through the coil. (The coil itself will attract iron and exhibit all the properties of a bar magnet, without the iron core, if the current through it is large enough. With the apparatus described the field without the core is rather weak, so that only small and therefore light pieces of iron will be attracted, but the effect can be clearly observed if a battery of 6 volts or more is used.)

The force of attraction is naturally greater the stronger the field, hence increasing the current through the coil, as is done in the second part of the experiment by increasing the battery voltage applied to Coil 1, must cause a stronger field to be set up, since the attraction is greater with greater current. That the field strength also depends upon the number of turns is shown by connecting the two coils in series. Although the current through the two in series with 3 volts applied is somewhat less than the current through Coil 1 with the single dry cell, the attraction is nevertheless stronger (hence the magnetic field is stronger) with the greater number of turns despite the smaller current. If other dimensions remain the same, the field strength will be proportional to the current for a given number of turns and proportional to turns for a given current. This dual proportionality can be combined in the single expression *ampere-turns*, or product of amperes through the coil times number of turns in it. The number of ampere-turns thus is a measure of the magnetizing force.

EXPERIMENT 5

Electromagnetic Induction

Apparatus: Same as in Exp. 4, with the exception that the permanent magnet is not needed. Set the scale of the test set to use the instrument as a milliammeter having a maximum deflection of 1 milliampere (or the nearest range to 1 ma. provided on the particular test set used).

Procedure: With the core out of the magnet assembly, connect the milliammeter across the terminals of the larger coil (No. 2). Connect one side of the battery to one terminal of the smaller coil (No. 1). Connect a wire to the other side of the battery and touch its free end to the remaining terminal of Coil 1. When the contact is made the milliammeter needle will show a small instantaneous deflection but will quickly return to the zero position. Now remove the wire from the terminal and the needle will deflect in the opposite direction, again returning quickly to zero. The deflections probably will be quite small — less than 0.1 milliampere. Repeat the experiment with only one dry cell instead of two, when it will be found that the deflections are of the same type, but smaller. Note the direction of the deflection on *making* contact and if it is not the same as the normal direction of needle movement, reverse the meter terminals.

Now insert the iron core and close the circuit through Coil 1. The deflection should be of the order of 0.5 milliampere. While the circuit is still closed, reverse the meter terminals. Now open the circuit and the needle will deflect again, this time in the same direction since the meter has been reversed. The purpose of reversing the terminals is to avoid a large deflection in the direction opposite to normal; although this probably will do no harm to the instrument, the needle does not travel very far before hitting the stop and frequently will bounce in the opposite direction (that is, the normal direction of motion) giving the impression that the deflection is in the same direction both on closing and opening the circuit. That this is not the case is easily demonstrated by reversing the meter terminals while current is still flowing through Coil 1.

The observed phenomena can be explained as follows: On closing the circuit a magnetic field is set up by the current flowing through Coil 1. While the field is changing — that is, growing from zero to its final intensity — electrons in Coil 2, which is in the field, are forced to move, causing the current indicated by the milliammeter. Since current can flow only when there is a voltage present to force it to flow, it is evident that the changing magnetic field has caused a voltage to be induced in Coil 2, even though there is no direct connection between this coil and the battery. When the field becomes steady the milliammeter shows no deflection, hence the phenomenon of induced voltage must be associated only with a *changing* field. On opening the battery circuit the field disappears and, in the process of changing from its steady value to zero, again causes a voltage to be induced in Coil 2, as shown by the milliammeter deflection. Since the deflection on opening the circuit is in the opposite direction to that on closing the circuit, the induced voltage must have one polarity when the field is increasing in intensity, and the opposite polarity when the field is decreasing.

Changing the battery voltage, and hence the amount of current through Coil 1, showed that the induced voltage depends upon the strength of the magnetic field, since the field is stronger with greater current, other things being equal. In the last part of the experiment the current remained the same, but much larger deflections were obtained by inserting the iron core. Hence the core must have greatly increased the intensity of the field or, stated another way, many more lines of magnetic force must be set up in iron than in air for the same magnetomotive force (represented by the current flowing in the coil). The ratio of the number of lines of magnetic force which will be set up in a given material to those in air, the dimensions and magnetizing force being the same, is called the *permeability* of the material. The experiment demonstrates that iron has many times the permeability of air.

EXPERIMENT 6

Electromagnetic Induction — (Cont.)

Apparatus: Same equipment as in Exp. 5.

Procedure: Repeat Exp. 5 with the iron core in the coil. Note the direction of current flow in Coil 1. (Use the conventional direction; that is, assume that the current flows from the positive terminal of the battery through the coil and back to the negative terminal.) Close the circuit and note the direction of current flow through Coil 2. Remember that the meter indicates normally (pointer deflection to the right) when its positive terminal is connected toward the positive side of the circuit, hence current normally flows from positive terminal to negative terminal through the meter. On opening the circuit the current through Coil 2 reverses, as shown by Exp. 5.

What is the relationship between direction of current flow in Coil 1 and that in Coil 2 on closing the circuit? Trace the current through the coils, both having been wound in the same direction. What is the relationship between the two currents on opening the circuit? On closing the circuit the induced current flowed in the opposite direction to the current in Coil 1 while the latter current was increasing from zero to its steady value. On opening the circuit the current in Coil 2 reversed its direction, the current in Coil 1 now being decreased from its maximum value to zero. The direction of flow of the induced current is such as to oppose the change in current which caused it. If the original current increases, the induced current will oppose the increase. If the original current decreases, the induced current will oppose the decrease — that is, it will tend to keep the current flowing.

These same effects take place in Coil 1 alone, but cannot be shown conveniently with simple apparatus. However, since both coils are in the same magnetic field it is easy to see that the same effects would be exhibited in both. On closing the circuit a current will be induced in Coil 1 which flows in the opposite direction to the battery current and exists only until the battery current reaches its steady value. The accompanying induced voltage is maximum at the instant of closing the circuit and is practically equal to but opposite in polarity to the battery voltage. It cannot exceed the battery voltage, of course, since a higher induced than applied voltage would mean that electrical energy was being supplied from the coil to the battery, which is obviously impossible. The amplitude of the induced voltage is greatest when the magnetic field is changing most rapidly, which is at the instant the circuit is closed, and decreases as the field builds up until finally it becomes zero when the field is no longer changing. On opening the circuit a voltage of opposite polarity is induced in the coil, and the current accompanying this induced voltage flows in the same direction as the battery current. Under these conditions the polarity of the induced voltage and that of the battery are the same, so that the bucking effect which exists on closing the circuit no longer is present. If the circuit is broken quickly the magnetic field will disappear very rapidly, and since the amplitude of the induced voltage increases with the rapidity of change in the magnetic field, the induced voltage may be very high — hundreds or thousands of times the battery voltage. The energy in the field likewise will have to be dissipated very rapidly, and it is used up in the spark which accompanies the breaking of the circuit. The property of storing energy in a magnetic field on closing the circuit and releasing it when the circuit is opened is called *inductance*. Since for a given current the field is stronger — that is, the more energy is stored — with a larger number of turns, as shown in Exp. 4, and also with a core of high permeability, as shown by Exp. 5, the inductance is greater the greater the number of turns and the greater the permeability of the medium in which the field is set up.

If Coil 2 is in the same field, the voltage induced in it will be proportional to the voltage induced in Coil 1, to the ratio of its turns to the turns in Coil 1, and to the proportion of the total field set up by Coil 1 which bathes the turns of Coil 2. In the present case the coils are quite close together, hence are practically in the same field. Since Coil 2 has approximately twice the number of turns of Coil 1, the voltages induced in Coil 2 will be approximately twice those induced in Coil 1. These relationships can be shown in a qualitative way by the "finger test," even though measurement is impossible with this equipment. Disconnect the milliammeter, place two fingers of one hand across the terminals of Coil 2, and close the battery circuit through Coil 1. Since the induced voltage on "make" is quite small, the fingers feel no shock. On opening the circuit, however, there will be a distinct although quite harmless shock, showing that the induced voltage on "break" is quite high. Repeat with the fingers across the terminals of Coil 1; again nothing will be felt on "make," but a small shock will occur on "break." Since part of the energy is dissipated in the spark, it may be necessary to moisten the fingers to feel any effect at all in this second case. A better indication can be secured by holding one finger on the terminal at which the switching is done and keeping the battery wire in contact with the same finger while closing and opening the circuit. The induced voltage on "break" is obviously much larger than the battery voltage, which can give no shock itself, but is not as large as in Coil 2, which has a greater number of turns.

Part Two

OHM'S LAW FOR D.C. AND A.C.

THIS second part of the course deals mainly with the relationships between current and voltage which are included under the general heading of Ohm's Law for both direct and alternating currents. The experimental work largely consists in the measurement of typical simple circuits and the comparison of the measurements with calculations. The experimenter, if he is to get the most from his experimental work, should appreciate the reasons why observed measurements sometimes differ considerably from those calculated for ideal conditions. A coil, for example, has not only inductance but resistance as well, and the presence of the resistance may make the observed measurements differ considerably from the values calculated on the assumption that only inductance is present. And frequently the power consumed in the measuring device may be of the same order of magnitude as that in the circuit being measured.

Results will be affected by inaccuracies in calibration of measuring instruments, and also by lack of precision in reading the instruments. This latter "human factor" can be minimized by taking not one reading but a whole series of them for the given set of operating conditions, then averaging the set of readings to find a "mean" which probably will be nearer the proper value than any one reading alone. For example, the voltage across a circuit element may be read five different times, with the following results:

No. 1 — 24.5 volts
No. 2 — 24.3 "
No. 3 — 25.1 "
No. 4 — 24.4 "
No. 5 — 24.8 "

Unless some extenuating conditions make it possible to say without doubt that one or more of these readings is definitely wrong, the *average* of the five — in this example, 24.6 volts — should be used as the true reading.

ASSIGNMENT 4

Study *Handbook* Section 2–6. Perform Exps. 7–11, inclusive.

Questions

1) Write Ohm's Law in the three forms to solve for E, I, and R when the other two quantities are known.

2) Define milliampere, microampere.

3) A resistance of 50,000 ohms is connected in parallel with one of 25,000 ohms. What is the resultant resistance?

4) An inductance of 10 henrys is connected in series with one of 15 henrys. What is the total inductance if the fields of the two inductances do not interact?

5) What is the total inductance if the two inductances of Question 4 are connected in parallel?

6) Define time constant.

7) How does a voltmeter differ from a milliammeter?

8) Write the formulas for power dissipated in a d.c. circuit when any two of the three quantities, voltage, current and resistance, are known.

9) What is the unit of power?

10) Compare ohm and megohm.

11) Three resistances, 5, 14 and 22 ohms, are connected in parallel. What is the resulting resistance? If 6 volts is applied to the combination, what is the total current, the current through each resistor, and the power dissipated in each?

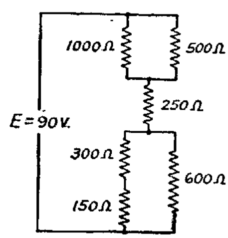
12) How may a single 0–1 milliammeter be used to measure several ranges of currents and voltages?

13) If a current of 350 microamperes flows through a circuit with an applied voltage of 40, what is the resistance of the circuit?

14) What is the time constant of a circuit consisting of a condenser having a capacity of 4 μfd. and a resistance of 150,000 ohms?

15) If two 8-μfd. condensers are connected in series, what is the resulting capacity?

16) In the following circuit, find the current through each resistor and the voltage across it:



17) A d.c. supply of 250 volts is available, and it is desired to provide voltages of 75 and 125

volts with respect to one terminal of the supply by means of a voltage divider. The current drain at the taps will be negligible. What must be the resistance of each section of the voltage divider if the current through the divider is to be limited to 10 milliamperes?

18) A load taking 5 milliamperes is connected across the 75-volt section of the voltage divider of Question 17, and a load taking 8 milliamperes across the 125-volt section. What will be the actual value of the voltage at each tap with these loads?

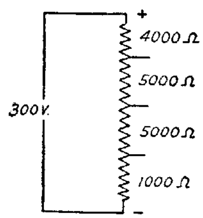
19) If the current through the voltage divider of Question 17 is permitted to be 25 milliamperes, calculate the resistance of each section. If the loads specified in Question 18 are applied, what will be the actual voltage at each tap under load? Is the drop in tap voltage with load as great in this case as with the 10-milliampere divider?

20) Calculate the power lost in the two voltage dividers of Questions 17–19, with and without the load circuits connected.

21) If three resistors, 10,000, 40,000 and 12,000 ohms, are available, how can they be connected to give a total resistance of 20,000 ohms?

22) If the power consumed in a 50,000-ohm resistor is 2 watts, what is the applied voltage? What is the current through the resistor?

23) What are the voltages between the negative terminal and the tap points in the following circuit?



24) What is the unit of electrical energy?

25) What factors determine the resistance of a conductor?

ASSIGNMENT 5

Study *Handbook* Section 2–7.

Questions

1) Define frequency, cycle, alternation.

2) What is a harmonic?

3) What are the relationships between cycle, kilocycle and megacycle?

4) What is meant by phase?

5) What is meant by the peak value of an a.c. wave?

6) Define effective value. What is the relationship to the peak value in a sine wave?

7) What range of frequencies is considered to be in the audio-frequency spectrum?

8) What is the phase relationship between current and voltage in an inductance?

9) What is meant by the term "sine wave"?

10) What is the average value of an a.c. wave? What is its relationship to the peak value of a sine wave?

11) Write the expression for angular velocity.

12) Is the current through a capacity leading or lagging the applied voltage? By how many degrees?

13) What is the phase relationship of current and voltage in a resistance?

14) A frequency of 15 megacycles corresponds to how many cycles per second?

15) Convert 1960 kc. to megacycles; cycles.

ASSIGNMENT 6

Study *Handbook* Section 2–8.[1] Perform Exps. 12–14, inclusive.

Questions

1) What is the reactance of a 250-$\mu\mu$fd. condenser at 14 Mc.? At 3.8 Mc.?

2) Write Ohm's Law for alternating current flowing through a resistance.

3) Find the impedance of a circuit consisting of a 2-μfd. condenser in series with a resistance of 40 ohms at a frequency of 60 cycles.

4) What is the impedance at 60 cycles of a 1-μfd. condenser in series with a 1200-ohm resistor?

5) What will be the currents through the two circuits of Questions 3 and 4 if the applied voltage is 115? In each case, what is the voltage across the resistor and the voltage across the condenser? What is the power factor of each circuit?

6) Find the reactance of an inductance of 15 henrys at 120 cycles. What will be the capacity of a condenser having the same reactance at the same frequency?

7) An inductance of ½ henry and a capacity of 0.05 μfd. are connected in series. What is the total reactance of the circuit at a frequency of 1000 cycles?

8) If a 200-ohm resistor is connected in series with the inductance and capacity of Question 7, what is the impedance of the circuit? What current will flow if 10 volts is applied to the circuit? What will the current be if the condenser is short-circuited? If the inductance is short-circuited? If the resistor is short-circuited? Calculate the voltage across the inductance, capacity and resistance in each case, and also find the power factor in each case.

9) Is power dissipated in a pure reactance?

10) Can a d.c. milliammeter be used for measuring alternating current?

11) What is meant by the distributed capacity of a coil?

[1] In the first printing of the 1942 Standard Edition, the second formula in the right-hand column on page 31 was incorrectly given with a × instead of a + sign. The formula should read $Z = \sqrt{R^2 + X^2}$.

12) What is the distinction between the impedance in an a.c. circuit and the resistance in a d.c. circuit?

13) If the same current flows through an inductance and a capacity in series, what is the phase relationship between the voltages across them? What will be the voltage measured across the two in series?

14) If the same voltage is applied to an inductance and a capacity in parallel, what is the phase relationship between the currents flowing through them? What will be the current measured in the common lead between the source of voltage and the parallel combination?

15) What are the reactances of the choke coil and fixed condensers used in Exps. 12 and 13? (L = 30 henrys, C = 0.1, 0.25 and 1 μfd., f = 60 cycles.)

16) What is the reactance of a 0.01-μfd. condenser at 30 cycles? If it is in series with a 0.5-megohm resistor across a voltage of 15 at the same frequency, what is the voltage across the resistor? What voltage will appear across the resistor if the frequency is 10,000 cycles?

17) A 5-henry choke and 1000-ohm resistor are connected in series across 115 volts, 60 cycles. What is the power factor of the circuit?

18) In a circuit containing resistance and reactance, how much of the power supplied is dissipated in the resistance and how much in the reactance?

19) Write the formulas for inductive and capacitive reactance. What units must be used in these formulas?

20) If you know only the applied voltage and the current flowing in an a.c. circuit, is it possible to determine the impedance? The power factor? The resistance and reactance present?

ASSIGNMENT 7

Study *Handbook* Section 2–9.

Questions

1) If the primary of a filament transformer designed for 115-volt operation has 350 turns, how many turns should be wound on the secondary to give a terminal voltage of 6.3?

2) Assuming that the secondary load on the transformer of Question 1 is to operate at unity power factor and that transformer losses are small enough to be neglected, what size wire should be used for the secondary if the secondary is to deliver 5 amp., allowing 1000 circular mils per ampere? What size wire on the primary?

3) If the transformer of Question 1 is also to have a high-voltage secondary to give 350 volts each side of a center tap (or 700 volts overall), how many turns will be needed on this winding?

4) Describe the operating principles of the transformer.

5) The secondary load on a transformer having a 5-to-1 primary-to-secondary turn ratio is 300 ohms. What is the impedance looking into the primary from the source of power?

6) How does an autotransformer differ from an ordinary transformer?

7) What are the relationships between turn ratio, voltage ratio, current ratio and impedance ratio in a transformer?

8) If the impedance looking into a transformer primary is 5000 ohms when the secondary load is 7500 ohms, what is the primary-to-secondary turn ratio?

9) A transformer is delivering a current of 10 amperes into a resistance load at a voltage of 10. If the transformer efficiency is 85 per cent, what

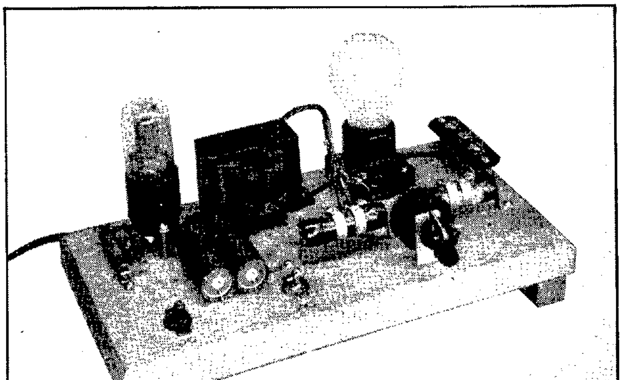


Fig. 1 — Transformerless power supply for use in experiments. The circuit diagram of this supply is given in Fig. 2. The baseboard is 5½ × 11 inches, with the rectifier tube and the filament dropping resistor, R_1, mounted in the rear left corner. The filter condensers, C_1 and C_2, and the filter choke, L_1, are near the rectifier tube. The variable resistor in the foreground is R_4, with the two bleeder resistors, R_2 and R_3, just behind it.

The supply delivers an adjustable voltage from 0 to about 100 volts d.c. and provision also is made for 115-volt a.c. output. Switches, S_1 and S_2, in the a.c. and d.c. lines provide a convenient means for cutting off the voltage when changes or adjustments are made in the associated circuits. The lamp is used for determining the grounded side of the power line. Before plugging into a power socket the open side of the lamp should be connected to ground (water pipe or radiator), then the plug should be tried both ways in the socket. In one position the lamp will light, showing that the common lead is the ungrounded side of the line. When this occurs, reverse the plug so that the common side of the supply will be connected to the grounded side of the line.

The common terminal is the positive terminal of the d.c. supply, this arrangement being used because the supply will be used for bias in later experiments involving vacuum tubes.

power is taken from the line? If the primary voltage is 115, what is the primary current, assuming a power factor of 1?

10) A transformer has a primary-to-secondary turn ratio of 1.8 to 1. What will be the impedance looking into the primary when the secondary load is a resistance of 6000 ohms? When the secondary load is 4000 ohms? 12,000 ohms? 200 ohms? 10 ohms?

11) A speaker output transformer is designed to couple a 5-ohm voice coil to a pentode output tube which requires a load of 7000 ohms. What turn ratio is required? If the power delivered to the voice coil is 2 watts, what is the voltage across the voice coil, the current through it, and the voltage applied to the primary?

12) Can transformers properly be specified in terms of "primary impedance" when the secondary load is not specified?

13) If the secondary load on a transformer has a power factor of 30 per cent, what percentage of the rated power-handling capability of the transformer can be realized? Which is more descriptive of the actual capability of the transformer, a "volt-ampere" or "watt" rating?

14) On dismantling the five-volt secondary winding of a transformer it is found that the winding has 10 turns. If it is desired to put on a winding delivering 7.5 volts, how many turns should the winding have? If the old secondary was rated at 8 amperes, what current can be taken from the new winding without overloading the primary?

15) An autotransformer designed for 115-volt circuits has a 250-turn winding. How many turns should there be between one end and a tap which is to deliver 80 volts?

EXPERIMENT 7

Ohm's Law, Voltage Drops

Apparatus: A source of d.c. voltage variable from zero to about 100 volts is needed for this experiment. The circuit shown in Fig. 2 is convenient, since it provides for continuous adjustment of the voltage to any value within the range. It is a "transformerless" supply also adaptable to subsequent experiments.

Procedure: The initial adjustment of the taps on the power supply output resistor or "bleeder," consisting of R_2, R_3 and R_4 in series, illustrates the principle of Ohm's Law. Before making the permanent connection between L_1 and the top end of R_2, insert the milliammeter between these two points, using the 100-ma. scale (or the nearest to it provided by the instrument used), close S_2 and measure the current. Take readings with R_4 set at zero and at maximum. Remove the milliammeter and make the permanent connection between L_1 and R_2. Now read the output voltage (across the whole bleeder) at the two settings of

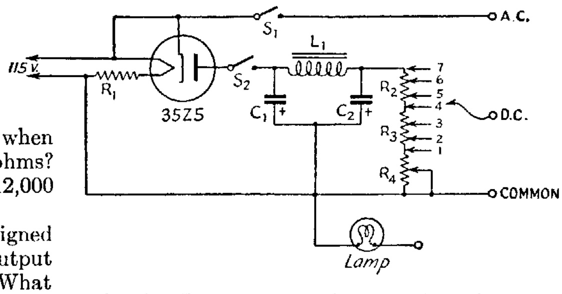


Fig. 2— Circuit diagram of the transformerless power supply.
C_1, C_2 — 40-μfd., electrolytic, 150 volts.
R_1 — 500 ohms, 10 watts.
R_2 — 800 ohms, 25 watts, with two sliders.
R_3 — 300 ohms, 25 watts, with two sliders.
R_4 — 100-ohm wire-wound potentiometer.
L_1 — 100-ma. filter choke, app. 20 henrys.
S_1, S_2 — S.p.s.t. toggle (preferably with long shank for convenience in mounting).
Lamp — 10-watt lamp.

R_4. With the constants given in Fig. 2, the following readings will be typical:

	I	*E*
R_4 at zero	90 ma.	95 volts
R_4 at maximum	95.5 ma	97 volts

With the voltmeter between the common lead and point 1, measure the voltage with R_4 at zero and maximum. Note the maximum voltage, turn R_4 to zero and set the first slider on R_3 (point 2) to give the same voltage. Then turn R_4 to maximum, note the new voltage, turn R_4 to zero and set the second slider (point 3) to this voltage. With R_4 at zero, set the first slider on R_2 (point 5) to about 45 volts and the second slider (point 6) to about 75 volts. When this is done a typical tabulation of voltage readings will be as follows:

Between *C* and	R_4 *Zero*	R_4 *Maximum*
1	0 volts	9 volts
2	9 "	17 "
3	17 "	25 "
4	25 "	33 "
5	43 "	48 "
6	75 "	80 "
7	95 "	97 "

The voltages appearing across the individual resistances constitute voltage drops between points of the complete bleeder circuit, and the sum of these voltage drops must equal the total voltage applied to the bleeder, since the total current flows through each resistor. Thus with R_4 at maximum the drop across it is 9 volts; the drop across R_2 (between points 1 and 4) is 24 volts, and the drop across R_2 (points 4 and 7) is 64 volts. The sum of these three voltages is 97, which is the applied voltage. With R_4 at zero, the voltage across R_3 is 25, and across R_2, 70, totalling 95. These values can be checked by measurement between the appropriate points. The bleeder resistances are very small compared to the voltmeter resistance, so that the current flowing through the latter is small compared to the current through the bleeder and no appreciable error is introduced by the fact that the voltmeter current does not flow through all of the bleeder.

By Ohm's Law

$$R = \frac{E}{I}$$

and the values of the resistances can be calculated from the observed currents and voltages. In the case of the total bleeder, with R_4 at zero

$$R = \frac{95 \text{ volts}}{0.090 \text{ amp.}} = 1056 \text{ ohms}$$

and with R_4 at maximum

$$R = \frac{97 \text{ volts}}{0.0855 \text{ amp.}} = 1133 \text{ ohms.}$$

The current must be expressed in amperes when R is in ohms and E in volts, hence the milliampere readings of the meter must be converted to amperes.

Determine the values of the three resistors separately by the same method, using the voltage drops across each for E in the formula, and the values of current corresponding to R_4 at zero and R_4 at maximum. Thus two sets of voltages and currents are available for checking each resistor, and if the measurements are completely accurate the value of resistance found should be identical. The chances are that the two values so found will not be identical, indicating errors in readings and/or the instrument itself. If the differences are more than a few percent, repeat the measurements of both current and voltage, taking a series of observations and finding averages. Compare the results of this method with the results obtained by the original measurements.

By a similar process, determine the resistance between each pair of taps on the voltage divider. Check the sum of these resistances against the total resistance of the divider.

EXPERIMENT 8

Ohm's Law, Series-Parallel Resistances

Apparatus: Same as for Exp. 7, with the addition of three 10-watt resistors, 1000, 2000, and 5000 ohms. The values need not be exactly as specified, but should be of that order.

Procedure: Connect the resistors as shown in Fig. 3, and apply the full voltage from the power supply. Measure the currents and voltages as indicated. A typical set of data would be as follows:

E = 85 volts
E_1 = 35 volts
E_2 = 50 volts
I = 34.5 ma.
I_1 = 25.0 ma.
I_2 = 9.8 ma.

The sum of E_1 and E_2 should equal E, and the sum of I_1 and I_2 should equal I. Within the limits of error this is the case.

The equivalent resistance of the 5000-ohm and 2000-ohm resistors in parallel can be found by Ohm's Law:

$$R = \frac{E}{I} = \frac{50 \text{ volts}}{0.0348 \text{ amp.}} = 1436 \text{ ohms.}$$

This resistance plus 1000 ohms, or 2436 ohms, is the equivalent resistance of the whole circuit. Checking by Ohm's Law:

$$R = \frac{E}{I} = \frac{85 \text{ volts}}{0.0345 \text{ amp.}} = 2460 \text{ ohms.}$$

By using 0.0348 amp. for the current, the resistance found would be nearer 2440 ohms. Alternatively, the resistance of the "1000-ohm" resistor could be checked by substituting the voltage across it and the current through it in Ohm's Law:

$$R = \frac{E}{I} = \frac{35 \text{ volts}}{34.5 \text{ ma.}} = 1014 \text{ ohms}$$

which value added to 1436 gives a total resistance of 2450 ohms. The measured values can be considered satisfactory, but the observations probably could be improved by taking a series of them and averaging the results.

By the formula for combining resistances in parallel, the resultant resistance of the combination of 2000 and 5000 ohms should be

$$R = \frac{1}{\frac{1}{2000} + \frac{1}{5000}} = 1429 \text{ ohms}$$

which is in very good agreement with the results obtained by measurement.

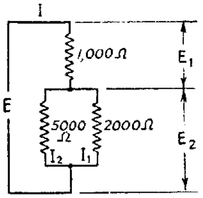


Fig. 3

Rearrangé the circuit so that the 1000- and 2000-ohm resistors are in parallel and the 5000-ohm resistor is in series. Measure the applied voltage and calculate the currents and voltages which should result. The step-by-step calculation should be carried through as follows: (1) Find the equivalent resistance of the two parallel resistors; (2) add the equivalent resistance so found to the series resistance (5000 ohms) to find the total resistance; (3) knowing the applied voltage and the total resistance, use Ohm's Law to find the current flowing; (4) using the current so found, determine the voltage drop across the 5000-ohm resistor and across the 2000- and 1000-ohm resistors in parallel; (5) using the voltage drop across the parallel resistors and their known values of resistance, determine the current through each resistor by Ohm's Law. Check the calculated values by measurement. Repeat with the 200-ohm resistor in series and the 5000- and 1000-ohm resistors in parallel.

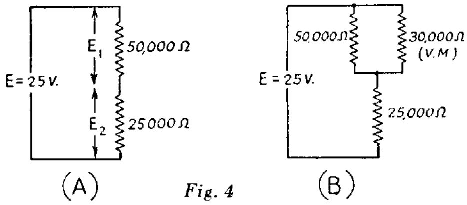


Fig. 4

EXPERIMENT 9

Ohm's Law, Voltage Regulation

Apparatus: Same as for Exp. 8, with the addition of the following fixed resistors: 25,000 ohms, 1 watt; 50,000 ohms, 1 watt.

Procedure: Connect the 25,000- and 50,000-ohm resistors in series as shown in Fig. 4-A and, using the appropriate tap on the power-supply bleeder, adjust the applied voltage to some value just slightly less than the full-scale value on a medium range of the voltmeter. For example, if the instrument has a 30-volt scale a convenient value will be 25 volts. Then by Ohm's Law the current will be

$$I = \frac{E}{R} = \frac{25 \text{ volts}}{75{,}000 \text{ ohms}} = 0.000333 \text{ amp., or } 0.333 \text{ ma.}$$

The voltage drop E_1 across the 50,000-ohm resistor will be

$$E = RI = 0.000333 \times 50{,}000 = 16.67 \text{ volts}$$

and the drop E_2 across the 25,000-ohm resistor

$$E = RI = 0.000333 \times 25{,}000 = 8.33 \text{ volts.}$$

Measure the current, using the lowest current range which does not send the pointer off scale, and then measure the voltage across each resistor. A typical set of readings for the case given would be as follows:

$$I = 0.36 \text{ ma.}$$
$$E_1 = 11.2 \text{ volts}$$
$$E_2 = 5.5 \text{ volts.}$$

The current reading is approximately the theoretical value and the discrepancy is easily accounted for by minor inaccuracies in the instrument, in the rated values of the resistors, and in taking the readings. However, the sum of the voltages across the individual resistors is only 16.7 volts, while the actual applied voltage is 25. The difference is too great to be caused by normal inaccuracies.

The explanation is to be found in the fact that with resistances of this order of value the current flowing through the voltmeter constitutes an appreciable part of the total current flowing through the resistor in series with the meter. Most test instruments have a resistance of 1000 ohms per volt on the voltage ranges, which in the case of the 30-volt scale used in obtaining the above data means that the resistance of the voltmeter is 30,000 ohms. When the meter is connected to measure E_1, the 30,000-ohm voltmeter is in parallel with 50,000 ohms so that the circuit now is a series parallel arrangement, as shown in Fig. 4-B. The resultant resistance of the two in parallel is

$$R = \frac{1}{\frac{1}{50{,}000} + \frac{1}{30{,}000}} = 18{,}750 \text{ ohms.}$$

This resultant resistance is in series with 25,000 ohms, making the total resistance 43,750 ohms. Solving for the current

$$I = \frac{E}{R} = \frac{25 \text{ volts}}{43{,}750 \text{ ohms}} = 0.000572 \text{ amp., or } 0.572 \text{ ma.}$$

The voltage drop across the meter and 50,000-ohm resistor in parallel is therefore

$$E = RI = 18{,}750 \times 0.000572 = 10.7 \text{ volts.}$$

This checks within the limit of error with the value obtained by measurement, 11.2 volts. More accurate results could be secured by determining the value of each resistor separately, using the method given in Exp. 7, and substituting these figures instead of the rated resistances.

Calculate the circuit conditions when the voltmeter is connected to measure E_2, using the method just given. Repeat the experiment using different voltage scales on the instrument, adjusting the applied voltage to an appropriate value each time, and compare the data with the original run, in terms of percentage deviation from the true values. Calculate the circuit conditions for each set of data by the method above.

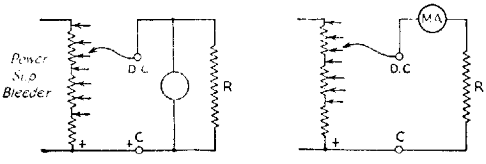


Fig. 5

EXPERIMENT 10

Ohm's Law, E/I Relationships

Apparatus: Same equipment used in Exps. 7, 8 and 9.

Procedure: Set R_4 in the power supply at maximum and measure the output voltages at the various taps. Connect the 5000-ohm resistor to the power-supply output terminals and take readings of current and voltage at each tap on the bleeder. In taking voltage readings, be sure the resistor circuit is closed so that the actual voltage under load is measured. Fig. 5 shows the method. If two instruments are available simultaneous readings can be taken, but equally good results can be secured with only one instrument by shifting from current to voltage ranges. Take similar sets of readings with the 2000- and 1000-ohm resistors, and also with the 10-watt lamp. A typical set of data is given at the bottom of the page. The currents are in milliamperes.

Plot the data so obtained on cross-section paper, as shown in Fig. 6. It is convenient to use half-inch blocks for 10-volt and 10-milliampere intervals. Draw a smooth line through each set of points. Not all the points will lie exactly on the line so drawn, because of slight inaccuracies in measurement, so it is necessary to "average" out the results. If a single measurement is poor, the point obtained from it will lie well out of line with the other points, showing instantly that something is wrong. Such a point should be rechecked by measurement.

In the case of the three resistors, it is obvious that a straight line can be drawn through the plotted points. This indicates that the resistance is constant with varying current; in other words, in such a resistor the ratio between current and voltage is fixed, within the limits of the range of voltages applied. Such a circuit is called "linear" because the plotted curve is a straight line. The *slope* of the line, or the ratio between the number of units covered by the curve in the vertical direction to the number of units moved in the horizontal direction, is constant when the line is straight, and is equal to the resistance. It is expressed in this case in volts per ampere. For example, in the interval between 0 and 10 milliamperes, the curve for the 5000-ohm resistor moves through 50 volts vertically, so that the slope of this curve is

$$\frac{50 \text{ volts}}{0.01 \text{ amp.}}$$

This can be stated as 5000 volts per ampere or as 5 volts per milliampere, and will be recognized as simply another way of expressing Ohm's Law, since $R = E/I$. The more slowly the line rises the lower is the resistance, as illustrated by the lines for 2000 and 1000 ohms.

The curve for the lamp is not a straight line, which means that its resistance is not constant but changes with current. Such a circuit is called "non-linear," and Ohm's Law cannot be applied as simply as in the case of the linear resistors. The increasing amount of power lost in the filament as the current is increased raises the temperature of the filament, and this rise in temperature causes the resistance of the filament to increase.

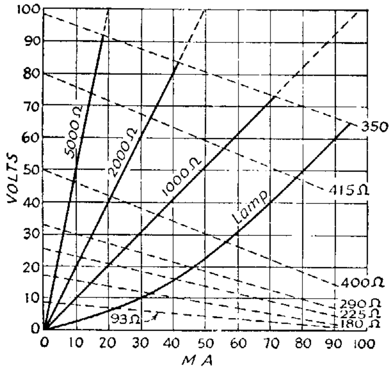


Fig. 6

This effect is present in all metallic conductors, but in the case of the ordinary resistors is too small to be noticed over the current range covered by this experiment. The lamp, however, is intended to work with its filament incandescent, hence the change from room temperature to full operating temperature may be several thousand degrees. The resistance at any current will be given by Ohm's Law, knowing the voltage across the lamp, but that same resistance value cannot be used for any other current.

Other types of circuits may be non-linear for different reasons. The vacuum tube is a familiar example, as is also the gas-conduction tube exemplified by the neon lamp. In general, Ohm's Law can be applied directly only to metallic circuits, and then only when temperature effects are taken into account or are small enough to neglect.

The set of curves in Fig. 6 also shows the effect of internal resistance of the power supply. The current flowing in this resistance causes a voltage drop in the same way as in the external circuit, with the result that the voltage actually applied to the external circuit depends upon the current flowing. The larger the current the greater the internal voltage drop, hence the lower the voltage

Tap	*No-Load Voltage*	*1000-ohm Load*		*2000-ohm Load*		*5000-ohm Load*		*Lamp Load*	
		E	*I*	*E*	*I*	*E*	*I*	*E*	*I*
1	8.7	8	7.7	8.4	4.1	8.6	1.7	6.5	23
2	17.2	14.5	14.5	15.8	7.6	16.7	3.5	11	32.5
3	24.4	20.5	20	22.5	10.9	24	4.6	15.5	40
4	34	25.2	25	28	14.5	31	5.8	19.5	45
5	50	37	35	41	21	46	8.8	27	56
6	80	57	56	66	33	74	14.5	47	78.5
7	97	73	72	83	41.3	92	18	64	94.5

(generally called the "terminal voltage") available for the load. By connecting the series of plotted points which show the voltage at a given tap at no load and with various load resistances, as shown by the dashed lines in Fig. 6, a "regulation" curve is obtained. With this power supply these curves are practically straight lines, indicating that the internal resistance is constant over the range of currents considered. This will not always be true of rectifier-type power supplies, since the internal voltage drop will depend upon the characteristics of the rectifier tube and the filter. However, since the curves in this case are straight, it is possible to determine the effective internal resistance at each tap by taking the slope of the regulation curve at that tap. For example, on the highest tap the voltage changes from 98 at no output current to 63 at a current of 100 milliamperes, approximately. The internal resistance is then

$$R = \frac{E}{I} = \frac{98-63}{0.1} = 350 \text{ ohms.}$$

The approximate values for other taps are indicated in the graph. From this series of curves it is possible to predict the terminal voltage at any tap for any value of external (or load) resistance, simply by drawing a line, from the origin of the graph, having the proper slope to represent the load resistance. The point where this line intersects the regulation curve gives the terminal voltage at that tap.

EXPERIMENT II

Time Constant

Apparatus: For this experiment a d.c. source of about 100 volts (the power supply of Fig. 2) and a 0–1 milliammeter are needed. The nearest range to 1 milliampere on the test instrument will be adequate. Several filter condensers and 1-watt resistors are necessary. Suggested values are 1 μfd. (paper), 8 and 16 μfd. (electrolytic) with at least 100-volt ratings; suitable resistor values are 1, 0.5, 0.25 and 0.1 megohm. An inexpensive bakelite-insulated push-button will be convenient. (These buttons can be obtained at five-and-ten-cent stores.)

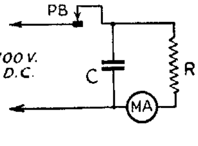


Fig. 7

Procedure: Connect the apparatus as shown in Fig. 7. The time constant of such a circuit is the product of the capacity in microfarads and the resistance in megohms, and represents the time in seconds required for the current from the condenser to drop to 37 per cent of its initial value when discharging. To check time it is necessary to determine one-second intervals, for which purpose any sort of device which makes a tick or other audible indication once each second can be used, such as a clock or metronome. The 5-Mc. standard frequency transmissions from WWV also provide one-second time ticks. In setting up the apparatus be careful to keep the circuit well insulated, since leakage becomes important when the resistance is high.

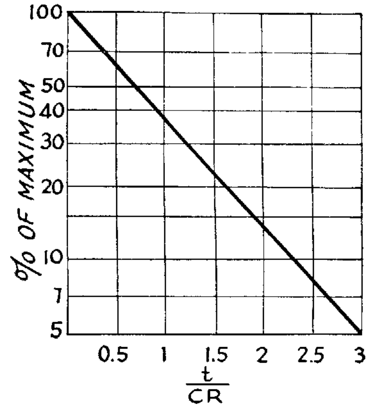


Fig. 8

Using the 1-μfd. condenser and 1-megohm resistor, close the circuit with the push-button and note the current, which should be approximately 0.1 milliampere. Release the push-button on the instant of a time tick and count the time in seconds required for the current to drop to 37 per cent of its value with the push-button closed. The time cannot be measured with a high degree of accuracy, but it should be obvious that with the constants given a time of about one second is required for the instrument pointer to drop to the 37 per cent mark. Repeat with the 8- and 16-μfd. condensers. Then substitute lower values of resistors and follow the same procedure in each case. Tabulate the times required for each set of values.

The way in which the current decreases with time is shown in the graph of Fig. 8. The horizontal values in this graph are plotted in terms of time in seconds and the time constant of the circuit, the numbers representing the factor by which the time constant should be multiplied to obtain the actual time in seconds. If the time constant is 3 seconds (a 6-μfd. condenser and 0.5-megohm resistor, for instance), the value 2 on the abscissa would represent 2×3, or 6 seconds. Therefore at the end of 6 seconds the current from such a combination should have decreased to 14 per cent of its initial value. By choosing integral time intervals the accuracy of time measurement can be increased and the appropriate percentage of maximum current read from the graph.

As an example of experimental use of the graph, suppose that the 16-μfd. condenser and 0.1-megohm resistor are used in the circuit of Fig. 7. On closing the push-button the current should be 1 milliampere with 100 volts applied. Open the push-button and take a reading at the end of exactly five seconds. Say the current at this instant is found to be 0.1 milliampere. Since this is 10 per cent of the maximum current, the quantity t/CR is found from the graph to be 2.3. Since

$$\frac{t}{CR} = 2.3,\ C = \frac{t}{2.3R}$$

and since $t = 5$, $R = 0.1$

$$C = \frac{5}{2.3 \times 0.1} = 21.7\ \mu\text{fd.}$$

The actual capacity of the condenser at this voltage is therefore higher than the rated value of 16 μfd.

By a similar method, check the capacity values of the condensers available.

EXPERIMENT 12

Alternating Current — Reactance and Resistance

Apparatus: This experiment can be performed with the 115-volt line as a source of voltage; provision for connection to the line is made in the power supply of Fig. 2. A multi-range high-resistance a.c. voltmeter is needed. This type is provided in the usual multi-purpose test instrument such as was recommended for this series of experiments. (The moving-iron type of a.c. voltmeter used for tube filament circuits and for ordinary a.c. measurements has too low resistance to be useful.) Since no a.c. current scales are provided on most test instruments, this and the following experiment are based on voltage measurements alone, but if an a.c. milliammeter is available it is helpful to measure current as well as voltage. In addition to the meter there should also be provided paper condensers of 0.1-, 0.25- and 1-μfd. capacity, and a filter choke of the "30-henry" variety, this being the value of inductance *without* direct current flowing through the winding. The 1000-, 2000- and 5000-ohm 10-watt resistors used in the previous experiments will be needed, with the addition of a 10,000-ohm 1-watt resistor.

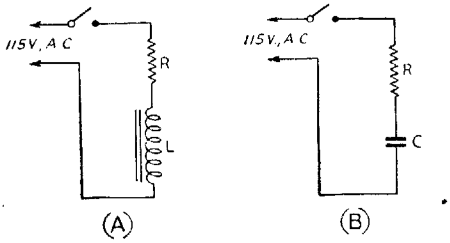


Fig. 9

Procedure: Connect the 1000-ohm resistor in series with the inductance as shown in Fig. 9-A. Measure the voltage across the resistor and that across the inductance. Repeat with the other resistors substituted. A typical tabulation of readings will be as follows:

Resistance	*Voltage Across Resistance*	*Voltage Across Inductance*
1000 ohms	20	120
2000 ohms	22	118
5000 ohms	40	106
10,000 ohms	68	89

The line voltage was 122 when these data were taken.

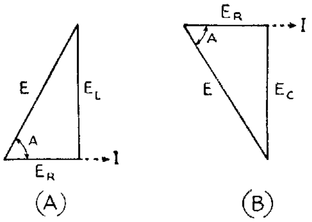


Fig. 10

In no case does the sum of the voltages across the resistor and inductance equal the line voltage. This is because the voltage across the resistor is in phase with the current, while the voltage across the inductance is 90 degrees out of phase with the current. Hence the r.m.s. voltages (which are indicated by the instrument) cannot be added directly, but the phase difference must be taken into account. Because of the 90-degree phase difference the voltages are, so to speak, at right angles to each other and must be combined by the law relating the sides of a triangle. This relationship is shown in Fig. 10-A, where E_R represents the voltage across the resistance, E_L the voltage across the inductance, and E the total or applied voltage, all drawn to scale. Since the length of the hypothenuse of a right triangle is equal to the square root of the sum of the squares of the lengths of the other two sides, the total voltage is given by

$$E = \sqrt{E_R^2 + E_L^2}$$

Solving this equation for E with the observed voltages substituted gives the following results:

Resistance in Circuit	*Calculated Total Voltage*
1000 ohms	122
2000 ohms	120
5000 ohms	113
10,000 ohms	112

with an actual applied voltage of 122. The discrepancy is caused chiefly by the fact that the choke has resistance as well as inductance, so that the voltage across it is not exactly 90 degrees out of phase with the voltage across the resistor. For the present purpose this factor can be neglected and the assumption made that the effects of losses in the choke are negligible.

Take a set of such data, using the highest voltmeter scale which will permit reasonably accurate reading (to keep down the voltmeter current) and calculate the total voltage as described above.

Since in a resistor the current is in phase with the voltage, a line representing the current can be drawn on top of the line E_R representing the resistance voltage. The voltage E_L is 90 degrees out of phase with the current and is drawn upward from the current line to indicate that it leads the current by 90 degrees (which is the same as saying that the current lags the voltage by 90 degrees). The angle A then represents the phase angle between the applied voltage and the current in the circuit. The phase angles for the observations above are 80.6, 79.5, 69.3 and 52.6 degrees, respectively. Construct such triangles to scale, using the observed data, and determine the phase angle between the calculated total voltage and current either by measurement with a protractor or by the use of tables of trigonometric functions.

Using the circuit of Fig. 9-B, take readings of voltage across the resistance and condenser, using the series of resistors with each of the three capacity values. In the case of the 0.1-μfd. condenser it will be difficult to get accurate resistor voltage readings when the resistance is less than 5000 ohms because of the small voltage drop, so the 2000- and 1000-ohm resistors may be omitted in this case. Tabulate the data and compute the applied voltage from the readings. In a condenser the current leads the voltage by 90 degrees, so that the same triangular relationship between resistance voltage, condenser voltage and total voltages applies, and the same formula may be used for computing the total voltage. In this case, however, the triangle is drawn as in Fig. 10-B with the condenser voltage extending downward from the resistance voltage to indicate that the voltage lags behind the current, which is in phase with the resistance voltage. The angle A is the phase angle between the applied voltage and the current when the voltages are drawn to scale. Draw the triangles and measure or compute the phase angle for each of the pairs of readings.

The voltage drops are caused by the resistance in the case of the resistor, by the reactance in the case of the inductance or capacity, and by the impedance, which is the combination of resistance and reactance, in the case of the complete circuit. That is,

$$E_R = IR$$
$$E_X = IX$$
$$E = IZ$$

Since the current is the same in all elements in a series circuit, the voltages in such a circuit will be proportional to R, X and Z. Hence the triangles of Fig. 10 show the relationship between resistance, reactance and impedance in series circuits when Z is substituted for E, X for E_L or E_C and R for E_R, in the drawings. Inductive reactance is indicated by a vertical line drawn upward from the horizontal resistance line and capacitive reactance by a vertical line drawn downward, to indicate the phase relationships. Thus the impedance of a series circuit also can be solved by the triangle formula, or

$$Z = \sqrt{R^2 + X^2}$$

From the triangles previously constructed from voltage measurements, compute the reactance and impedance in each case by taking the length of the resistance voltage line equal to the resistance in ohms and measuring the reactance and impedance to the same scale. This also can be done without measurement by taking the ratio of the voltages and multiplying by the resistance used. For example, with 2000 ohms in the circuit the data above give 118 volts across the inductive reactance and 20 volts across the resistor, with the computed total voltage being 120.

Then

$$\frac{E_L}{E_R} \times 2000 = \frac{118}{20} \times 2000 = 11{,}800 \text{ ohms for } X_L,$$

and

$$\frac{E}{E_R} \times 2000 = \frac{120}{20} \times 2000 = 12{,}000 \text{ ohms for } Z.$$

The value of reactance so computed may vary by several per cent in the different cases because of measurement inaccuracies, but should be approximately the same regardless of the resistance used.

EXPERIMENT 13

Alternating Current — Series Circuits Containing Resistance, Inductance and Capacity

Apparatus: The same equipment is required for this experiment as for Exp. 12.

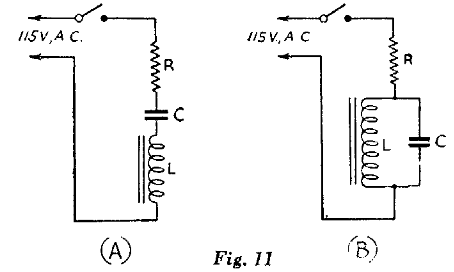


Fig. 11

Procedure: Connect the choke coil, 0.1-μfd. condenser and the 1000-ohm resistor in series as shown in Fig. 11-A. Read the voltages across the resistance, capacity, inductance, and across the condenser and inductance in series. Substitute the 2000, 5000 and 10,000-ohm resistances one at a time in place of the 1000-ohm unit and again take voltage readings. Repeat the same procedure with the 0.25-μfd. condenser replacing the 0.1-μfd. unit, and finally repeat again with the 1-μfd. capacity.

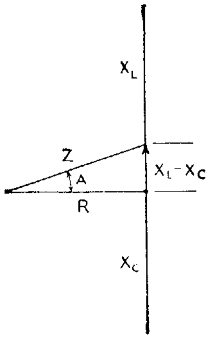
The following tabulation will be typical of the observed data, when the inductance is approximately 30 henrys and the frequency 60 cycles:

	Resistance, Ohms 1000	2000	5000	10,000
When $C = 0.1$ μfd.:				
Voltage across R	7	14	40	67
" " C	218	212	190	153
" " L	115	112	105	90
" " CL	121	119	106	82
When $C = 0.25$ μfd.:				
Voltage across R	52	72	90	97
" " C	443	313	161	92
" " L	428	313	176	115
" " CL	73	51	32	27
When $C = 1.0$ μfd.:				
Voltage across R	10	22	52	78
" " C	38	34	27	18
" " L	153	148	126	97
" " CL	119	116	100	79

The line voltage was 122 when the above data were taken.

Since the voltage across an inductance leads the current by 90 degrees and that across a condenser lags the current by 90 degrees, the voltages across an inductance and capacity in series (where both carry the same current) have a phase difference of 180 degrees. In other words, one voltage reaches its positive maximum at the same instant that the other reaches its negative maximum. At every part of the cycle the polarity of one is opposite to the polarity of the other. Hence the total voltage across the inductance and capacity in series is the *difference* between the voltages appearing across each one. Since the same current flows through all in a series circuit, the same relationships hold between resistance, reactance and impedance. This is shown graphically in Fig. 12, where (as in Fig. 10) the resistance is represented by a horizontal line, the inductive reactance by a vertical line drawn upward to the same scale of ohms, and the capacitive reactance by a vertical line drawn downward. The net reactance in the circuit is the difference between the inductive and capacitive reactances, and is shown as $X_L - X_C$ on the diagram. The impedance is found by using the resistance and net reactance in the triangle relationship. If X_C had been larger than X_L the net reactance would be drawn downward, since the X_C line would be longer than the X_L line and the difference would be in its favor. In such case the phase angle, A, would be leading since the impedance line would be below the resistance line (remembering that the lines can indicate voltage as well as resistance, reactance or impedance and that the current always is in phase with the voltage in a resistance). In the case illustrated in Fig. 12 the phase angle is lagging. Lead or lag is always taken with the voltage as a reference unless otherwise specified, so that a lagging phase angle means that the current is lagging behind the voltage, and a leading phase angle means that the current is leading the voltage.

Fig. 12



When the inductive and capacitive reactances are equal, the net reactance is zero and the impedance is simply equal to the resistance. When this condition exists in a series circuit the circuit is said to be *resonant*, and the current is the same as it would be if only the resistance were present. This current, nevertheless, flows through the inductance and capacity, and because of the reactances of these elements voltages of considerable amplitude can be developed across them. In the above data the circuit is approximately resonant when the 0.25-μfd. condenser is used, and with the lowest value of resistance the voltage across either C or L is several times the line voltage. If the choke coil had no resistance or other losses, the voltage across CL would be zero at resonance. In the actual data the voltage is not zero, and its value is a measure of the effective resistance of the choke. The term "effective" is used to indicate that the resistance operating is not just the d.c. resistance of the winding, but includes power losses in the iron. In this special case the voltage across CL and the voltage across R both represent resistance voltages, hence these voltages are in phase and should add arithmetically to give the applied voltage. That this is so can be checked by adding the voltages for each case, when it will be found that the sum is approximately equal to the applied voltage.

Calculate the applied voltage from the observed data when $C = 0.1$ μfd. and when $C = 1.0$ μfd., using the triangular relationship as shown in Fig. 12. Using the resistance as a reference, calculate the impedances, or find them graphically from scale drawings of the voltages (the method was described in Exp. 12). Neglect choke resistance and assume that the calculated applied voltage is correct. The effective resistance of the condenser is very low and may be neglected without appreciable error.

EXPERIMENT 14

Alternating Current — Inductance and Capacity in Parallel

Apparatus: The same equipment is required as for Exps. 12 and 13.

Procedure: Arrange the circuit as shown in Fig. 11-B. Using the 1000-ohm resistor at R, take voltage readings across R and across the parallel inductance and capacity, using successively the 0.1-, 0.25- and 1-μfd. condensers. Substitute the 2000-, 5000- and 10,000-ohm resistances and repeat the procedure in each case. Following is a typical set of data, taken with the line voltage at 123 volts:

	Capacity, μfd. 0.1	0.25	1.0
When R = 1000 ohms:			
Voltage across R......	6.3	3.5	37
" " LC.....	121	121	118
When R = 2000 ohms:			
Voltage across R......	12	7.5	61
" " LC.....	120	120	105
When R = 5000 ohms:			
Voltage across R......	25	16.5	103
" " LC.....	114	114	66
When R = 10,000 ohms:			
Voltage across R......	43	30	116
" " LC.....	102	103	35

Since L and C are connected together in parallel, only one voltage can appear across them. The current in L may differ considerably from that in C, however, since these currents will depend upon the voltage and the reactance of the particular element considered. That is,

$$I_C = \frac{E_{LC}}{X_C} \text{ and } I_L = \frac{E_{LC}}{X_L}$$

neglecting the effect of resistance and losses in the inductance. These two currents combine to form the current which flows through R and the source of voltage, or "line" current. In the condenser, the current leads the voltage by 90 degrees and in the inductance the current lags the voltage by 90 degrees. Therefore the line current is the difference between the two branch currents, just as in the series case (Exp. 13) the total voltage was the difference between the separate voltages across condenser and inductance. In other words, the impedance of the parallel circuit ($Z = E/I$) is higher than the reactance of either branch alone since the total current is less than the current in either branch. Should I_C and I_I have the same value the line current under ideal conditions would be zero, indicating that the impedance of the parallel circuit is infinite. In practice this is impossible, since the actual phase relationship between current and voltage in the two branches is not exactly 90 degrees because of the internal resistance present, particularly in the inductive branch. Hence complete cancellation of currents, even when the reactances are equal, does not occur, since such cancellation would require a phase difference of exactly 180 degrees between the two currents. The effect of the internal resistance on line current is relatively small if the reactances of the two branches differ considerably (and if the resistance itself is small compared to the reactance) but becomes more and more pronounced when the two reactances approach equality; i.e., when the circuit is near resonance.

With only an a.c. voltmeter available, it is not possible to measure the various currents in such a circuit. The voltage measurements do, however, give a clue to the way in which the impedance of the parallel circuit changes when the condenser reactance is changed. The lowest voltage drop cross the series resistor is obtained when the capacity (0.25 μfd.) which was nearest to series resonance (Exp. 13) is used, showing that the line current is low and hence the impedance of the condenser and inductance is high. This is just the opposite of the case when the inductance and capacity are in series, since in the series circuit (Exp. 13) the current is highest when the reactances are equal. With other values of capacity the resistance voltage increases, which indicates an increase in line current and hence lower impedance in the parallel circuit.

Part Three

RESONANT CIRCUITS

In PERFORMING experiments on resonant circuits, it is necessary to have a source of radio-frequency voltage. For this purpose a combination crystal and self-controlled oscillator is used. This in turn must have a source of power for the heater and plate of the tube. The units shown in the photographs differ only in a few details from similar equipment to be found in practically every amateur station, and if an oscillator and power supply already are available there is nothing to prevent their being adapted to the purpose.

Ordinary voltmeters and milliammeters cannot be used for radio-frequency measurements, so it becomes necessary to devise an instrument which will be suitable. A vacuum-tube voltmeter, useful for r.f. voltage measurements, is relatively simple to build. One which is adequate for the purposes of these experiments can be constructed from a few resistors and condensers, in addition to a small receiving triode. Power for the voltmeter can be taken from the oscillator supply.

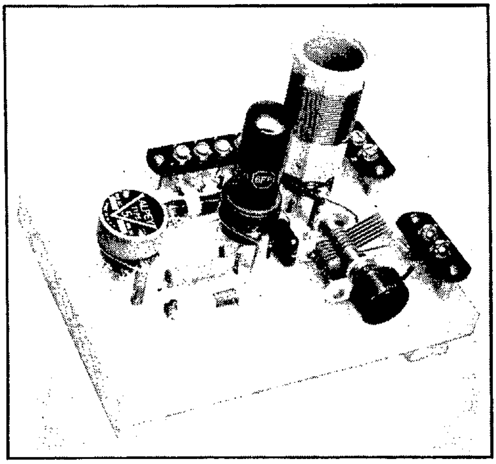


Fig. 1 — **Oscillator for generating r.f. signal used in measurements on resonant circuits. It may be used either with crystal or TNT grid coil, so that either fixed or variable frequency may be obtained. The socket at the left, occupied by the crystal in this photograph, also is used for the grid coil. The breadboard measures 6 × 8½ inches. Power supply connections are brought out to the rear terminal strip. The terminals on the strip in the lower right-hand corner are connected to the ends of the plate tank circuit; the other two-terminal strip is for link output.**

Oscillator

The oscillator shown in the photograph, Fig. 1, is a conventional pentode circuit when crystal is used, and is converted to a TNT by plugging in a grid coil and grid condenser in place of the crystal. The plate tuned circuit of the oscillator is parallel fed, which is advantageous in that no d.c. voltage appears on either the coil or condenser. The plate coil specified in Fig. 2 should be about the right size for most of the experimental work, but in one or two cases shunt capacity of leads may reduce the tuning range to the point where a slightly smaller coil would be desirable. It is therefore suggested that the coil be tapped about 5 turns from one end and provision made for shorting out the 5 turns when required. Alternatively, a separate coil having 25 turns spaced to make the length 1¼ inches may be used. A pair of output terminals is connected directly across the tank for set-ups which require a fairly high r.f. voltage. Provision also is made for link output.

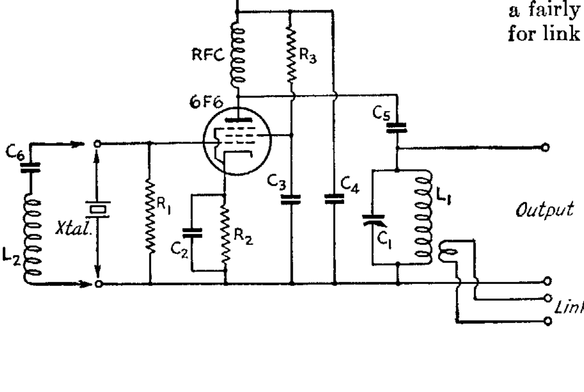


***Fig. 2* — Oscillator circuit.**

C_1 — 100-μμfd. variable.
C_2, C_3, C_4 — 0.01-μfd. paper.
C_5 — 0.002-μfd. mica.
C_6 — 500-μμfd. mica.
R_1 — 0.1 megohm, 1 watt.
R_2 — 400 ohms, 1 watt.
R_3 — 10,000 ohms, 10 watts.
L_1 — 30 turns No. 20 enameled, close-wound on 1½-inch diameter form.
L_2 — 45 turns No. 30 enameled, close-wound on 1½-inch diameter form.
RFC — 2.5-mh.r.f. choke.

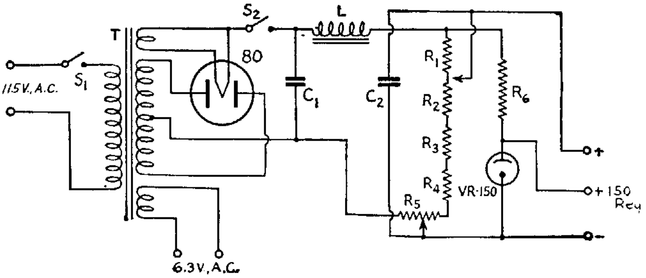


Fig. 3 — Power supply circuit.
C_1, C_2 — 16-μfd. electrolytic, 450 volts.
R_1, R_2, R_3, R_4 — 5000 ohms, 10 watts.
R_5 — 5000-ohm wire-wound potentiometer.
R_6 — 10,000 ohms, 10 watts.
L — 10 to 15 henrys, 100 ma.
T — Replacement or similar transformer to deliver 250 to 300 volts d.c. from filter at 100 ma. (350 volts a.c. each side center tap); with 5-volt and 6.3-volt filament windings.
S_1, S_2 — S.p.s.t. toggle.

For crystal control, any crystal in the 3.5-4-Mc. band can be used. For tuned-circuit frequency control, the "untuned" grid coil, which has a grid blocking condenser incorporated in the coil form, replaces the crystal. The number of turns on this coil should be adjusted so that the oscillator output voltage is substantially uniform (without load) over as much of the 3.5-4-Mc. band as possible. Other wire sizes may be used provided this requirement is met.

Power Supply

The power supply, Figs. 3 and 4, uses an ordinary replacement transformer with an 80 rectifier and condenser-input filter. Any supply which delivers about 250 to 300 volts at 75 to 100 milliamperes will do. The voltage divider incorporated in this supply enables continuous adjustment of the output voltage from zero to the maximum voltage of which the supply is capable. The output filter condenser is connected to the output terminals rather than to the voltage divider so that the condenser can act as a by-pass when the supply is used for audio work. A similar divider can be added to any existing supply, of course. A regulated tap, using a VR-150-30, and delivering 150 volts under loads varying from zero to about 20 milliamperes, is included. A switch is provided in the rectifier output so that the d.c. voltage can be shut off when adjustments are made, while keeping filaments hot.

V.T. Voltmeter

The vacuum-tube voltmeter need not be accurately calibrated, since absolute values of voltage need not be known. However, it is essential to know *relative* voltage values, and a preliminary voltage calibration therefore is necessary. It is desirable to have a voltmeter with a scale as nearly linear as possible, and also one which has high input impedance since the accuracy of measurement of voltages in resonant circuits will be impaired if the voltmeter takes appreciable energy. For these reasons a feedback-type triode voltmeter is used. Selection of the proper cathode resistor sets the voltage range; in the present case approximate ranges of 10, 30 and 100 volts are provided when the plate-circuit milliammeter has a full-scale range of 1 milliampere. The universal test instrument can be used for measuring the plate current.

The circuit of the v.t. voltmeter is shown in Fig. 6. It is simply a tube biased nearly to cutoff so that the positive cycle of an a.c. voltage applied to the input circuit will cause the plate current to increase. Under ideal conditions the increase in plate current will be proportional to the applied voltage, and in practice this linear relationship is very nearly achieved. Some initial fixed bias is applied to the grid by means of the voltage divider consisting of R_5 in series with R_6; R_6 is in the cathode circuit and the drop across it biases the grid negatively. Additional bias is provided by the cathode resistors R_2, R_3 and R_4. The lower the resistance used here the greater the sensitivity — that is, the higher the plate current reading for a given voltage applied to the grid. The higher the resistance, the greater the input

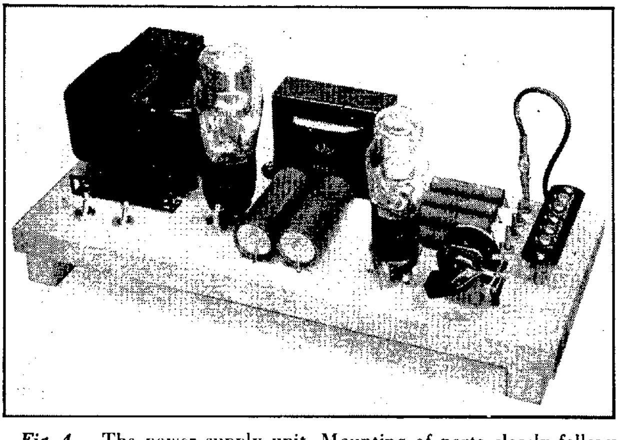


Fig. 4 — The power supply unit. Mounting of parts closely follows the circuit diagram of Fig. 3. The baseboard is 6 × 14 inches. Voltage divider taps are machine screws projecting through the baseboard just to the left of the terminal strip. The variable section of the divider is mounted on a metal bracket at the right front.

voltage range which can be handled; the linearity also is improved with high resistance.

The voltmeter should be calibrated against a d.c. source. The transformerless supply described in Part 2 is quite suitable for this purpose. Connect its negative output terminal to the ground terminal of the v.t. voltmeter input and the positive terminal to the grid side, then vary the output voltage over a suitable range and take readings of the voltmeter tube plate current for each applied voltage. The test instrument can be used to measure both current and voltage by switching it back and forth from the plate of the voltmeter tube (when it should be used as a 0-1 milliammeter) to the input terminals of the v.t. voltmeter (when it should be used as a d.c. voltmeter of appropriate range). When enough data have been taken, plot curves showing plate current against grid voltage for all three values of cathode resistance. A typical chart is shown in Fig. 7. The calibration is linear on the two higher ranges except near the low end of the scale, where there is a small departure from a straight line.

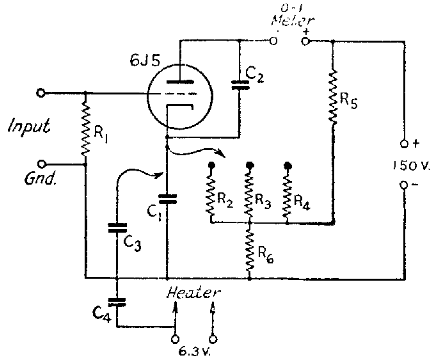


Fig. 6 — V.t. voltmeter circuit.
C_1, C_2 — 0.1-μfd. paper.
C_3 — 1-μfd. paper.
C_4 — 0.01-μfd. paper.
R_1 — 5 megohms.
R_2 — 3000 ohms, 1 watt (10-volt scale).
R_3 — 25,000 ohms, 1 watt (30-volt scale).
R_4 — 0.1 megohm, 1 watt (100-volt scale).
R_5 — 50,000 ohms, 2 watts.
R_6 — 3000 ohms, 1 watt.

The value of the bias resistor R_6 may require some modification for tubes of slightly different characteristics. Its resistance should be high enough to bring the plate current almost, but not quite, to zero when no voltage is applied to the input terminals. Should the plate current be zero at first trial, R_6 should be reduced in resistance until the plate milliammeter shows a small indication — between zero and a few hundredths of a milliampere.

Changing the plate voltage has the effect of shifting the curve up or down on the graph, but if the *increase* — not the actual value — in current with applied input voltage is considered, the calibration is not changed appreciably. However, with higher plate voltage the plate milliammeter may go off scale near the upper end of the range, while lower plate voltage will cut down the maximum grid input voltage which it is possible to handle without overloading. The regulated tap on the power supply of Fig. 4 provides a constant voltage of suitable value.

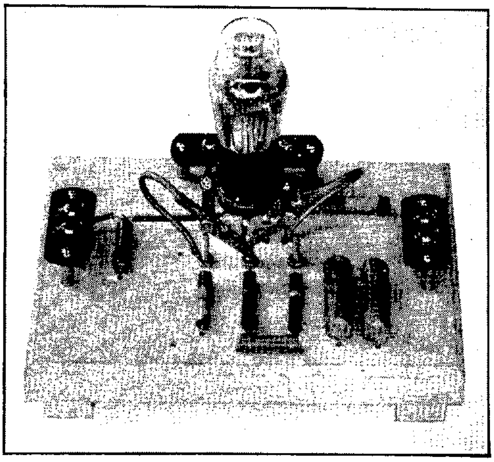


Fig. 5 — Vacuum-tube voltmeter for r.f. measurements. It has three ranges, 10, 30 and 100 volts. Input terminals are at the left, power supply terminals at the rear, and meter terminals at the right. The three cathode resistors are in the front center, with machine-screw terminals projecting through the board to serve as connection posts. The flexible wire at the left connects to the 1-μfd. by-pass condenser (one of the old flat metal-can type) which is mounted underneath the baseboard. The right hand flexible lead connects to the tube cathode. When making r.f. measurements the 1-μfd. condenser is disconnected.

Condensers C_1 and C_2 are r.f. by-passes and tend to build up the plate current to a value which indicates the peak voltage of an applied

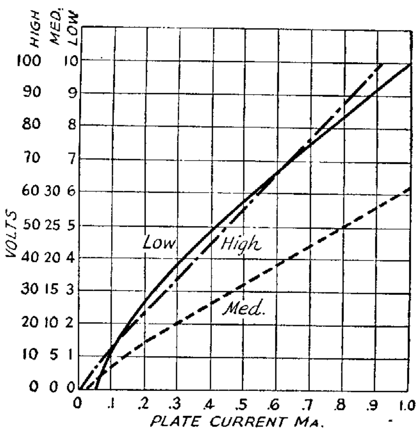


Fig. 7 — Typical d.c. calibration curves for the vacuum-tube voltmeter of Fig. 5.

r.f. wave. C_3 is a similar by-pass for audio frequencies across the cathode circuit. Whether or not the instrument reads peak voltage is not important in the present application, since relative voltages are of chief interest. In making r.f. measurements it will be sufficient to assign the measured voltage a value equal to the d.c. voltage which gives the same plate current reading. C_4 is an r.f. by-pass on the heater circuit.

Circuit Board

It is convenient, although not wholly necessary, to have a "circuit board" arranged somewhat as shown in Fig. 8. Variable condensers can be fastened solidly to it, as can also one coil. The other coil is left free for varying coupling when both are used. In the unit shown in the photograph, the coils are wound on ordinary mailing tubes and are mounted on small pieces of Presdwood or thin wood (so the free coil will sit still and not topple over) by miniature stand-off insulators. The variable condensers should have a maximum capacity of 250 $\mu\mu$fd. or more to give ample experimental range; old broadcast condensers will do quite nicely. The small condenser at the left is for capacity coupling when needed.

A half-dozen or so 6- to 8-inch lengths of flexible wire with alligator clips at each end will be convenient for changing circuits. There is no permanent wiring on the circuit board shown; all connections are made by means of such clips.

Calibrated Receiver

Relatively few tests can be made on r.f. circuits without measurement of frequency. It is assumed that every amateur will have a receiver with 80-meter bandspread and that he has calibrated or can calibrate it to reasonable accuracy. Calibration methods are described in the *Handbook*. Once a half-dozen or so calibration points are obtained a smooth curve can be drawn through them to give accurate-enough indications for experimental purposes. It will be sufficient to read to 10-kc. intervals.

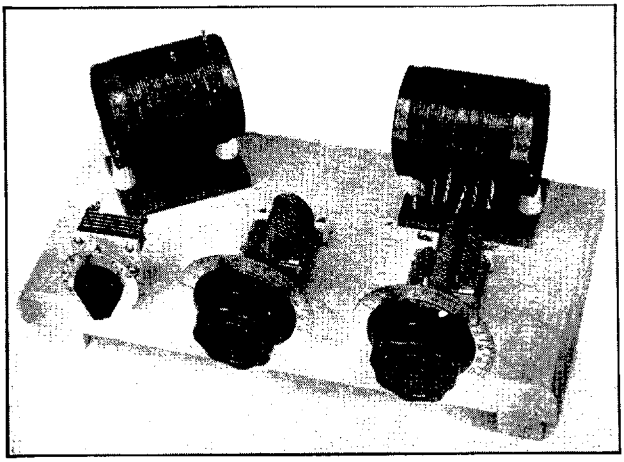


Fig. 8 — A circuit board such as this is convenient for making up various types of resonant circuits. The tuning condensers are 250-$\mu\mu$fd. units; any condensers having this or higher capacity will be satisfactory. The coils, wound on mailing tubes of 2¼-inch outside diameter, have 35 turns each, tapped every 5 turns, with turns spaced to occupy a total length of 2 inches. The wire is No. 18. The small condenser at the left is for coupling purposes and may have a maximum capacity from 25 to 50 $\mu\mu$fd.

ASSIGNMENT 8

Study *Handbook* Section 2–10. Perform Exp. 15.

Questions

1) What is "skin effect"?

2) If a current of one ampere flows through a series-resonant circuit having a resistance of 10 ohms and inductive and capacitive reactances of 500 ohms each, what is the applied voltage? What voltage appears across the terminals of the inductance? Across the terminals of the condenser?

3) When is an ordinary radio circuit resonant?

4) Describe the operating characteristics of a series-resonant circuit; of a parallel-resonant circuit.

5) Define the quantity Q.

6) An inductance of 10 microhenrys is used in a parallel-resonant circuit tuned to 7 megacycles. If the coil has a resistance of 3.5 ohms at this frequency, what is the Q of the circuit? Losses in the condenser may be neglected. What is the parallel-resonant impedance of the circuit?

7) A resistance of 5000 ohms is connected across the circuit of Question 6. What is the new value of circuit Q? What is the equivalent resistance introduced in *series* with the coil by the shunt resistor?

8) How may the Q of an unloaded circuit (one in which all the energy supplied to the circuit is consumed in the circuit itself) be increased? If the circuit is parallel-resonant and is shunted by a fixed value of resistance, how may the circuit Q be increased?

9) In the circuit of Questions 6 and 7, what values should the inductance and capacity have, to give a circuit Q of 25 when the circuit is loaded by the shunt 5000-ohm resistance?

10) Plot a curve showing the values of inductance required to tune to 3.5 megacycles with any value of capacity between 50 and 250 $\mu\mu$fd.

11) Neglecting coil resistance, plot a curve showing the variation in Q of the circuit in Question 10 as the L/C ratio is varied, when a resistance of 10,000 ohms is connected

across the circuit. Plot in terms of the capacity in use. Plot a similar curve for a resistance of 5000 ohms.

12) What is the resonant frequency of a circuit consisting of a coil of 30 microhenrys and a capacity of 60 $\mu\mu$fd.?

13) A resonant circuit is formed by a 50-$\mu\mu$fd. condenser and a coil of 10 microhenrys. The latter has a resistance of 2 ohms at resonance.

a) What is the resonant frequency of the circuit?
b) What is the Q of the circuit?
c) What is the parallel-resonant impedance of the circuit?
d) If one volt at the resonant frequency is applied in series with the circuit, what voltage will appear across either the coil or condenser?
e) If 250 volts at the resonant frequency is applied in parallel with the circuit, what is the equivalent series voltage, corresponding to the series voltage in (d), acting in the circuit? What then is the current circulating in the parallel-resonant circuit? What is the line current (see Exp. 14)? What is the ratio of circulating current to line current, and what circuit quantity does it equal?
f) A resistance of 8000 ohms is connected across the parallel-resonant circuit. Find the new value of circuit impedance. (Use the ordinary formula for resistances in parallel, since the impedance of the tuned circuit alone is a resistance at the resonant frequency.) If the impedance of the tuned circuit alone were neglected in determining the new impedance, would the error be appreciable? What would be the per cent error caused by neglecting the impedance of the tuned circuit alone if the inductance and capacity had the same values but the coil resistance was 40 ohms?
g) If 250 volts at the resonant frequency is applied across the circuit with the 8000-ohm resistor in shunt (assuming the original coil resistance of 2 ohms) what is the circulating current in the circuit? What is the line current? What is the new value of circuit Q?

14) A resonant circuit to operate at 14,200 kilocycles is to be loaded so that the effective parallel impedance will be 4000 ohms. Assuming that the coil resistance will be negligible (that is, nearly all the energy will be dissipated in the load, not in the coil itself) what inductance and capacity should be used to give a Q of 15?

15) If a voltage of lower frequency than the parallel-resonant frequency of a circuit is applied, what type of reactance does the circuit exhibit? Which branch of the circuit carries the greater current, the inductance or capacity? What are the conditions when the applied frequency is higher than the resonant frequency? Compare with a series circuit.

16) What is the piezoelectric effect?

17) What is meant by the term "loaded circuit"?

18) Two coils, one having an inductance of 15 microhenrys and a resistance of 5 ohms, and the other an inductance of 9 microhenrys and a resistance of 3 ohms, are available for use in a circuit to operate at 7500 kc. Which will give the greater selectivity?

19) If the Q of a coil having an inductance of 100 microhenrys is found to be 125 at a frequency of 2000 kc., what is the effective r.f. resistance of the coil?

20) What capacity is necessary to tune the coil of Question 19 to 2000 kc., and what will be the parallel impedance of the circuit?

ASSIGNMENT 9

Study *Handbook* Section 2–11. Perform Exps. 16–20, inclusive.

Questions

1) Name six ways in which radio-frequency energy may be transferred from one resonant circuit to another.

2) What is meant by "critical coupling"?

3) What happens to the effective series resistance of the primary circuit when the coupling to the secondary circuit is increased? What is the effect of increasing coupling on the parallel impedance of the primary circuit? On the overall selectivity of the two circuits?

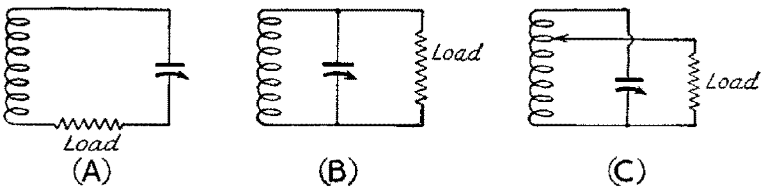
4) What is mutual inductance?

5) On increasing the coupling between two circuits it is found that the primary is thrown off tune. What is the cause?

6) Define coefficient of coupling.

7) A 600-ohm load is connected to a resonant circuit which in turn is coupled to the tuned plate circuit of a transmitter operating at 7100 kc. If the secondary circuit must have a Q of 10 to obtain sufficient energy transfer, what values of inductance and capacity must be used (assuming negligible losses in the coil itself) in the secondary circuit if the inductance, capacity and load are connected in series? Would these values be practicable at this frequency? If the secondary circuit is parallel-resonant and is shunted by the 600-ohm load, what values of inductance and capacity should be used to obtain the required Q? Suppose a condenser of only half this capacity was available; what could be done to obtain sufficient coupling?

8) Assuming that a variable condenser having a maximum capacity of 300 $\mu\mu$fd. and a minimum capacity of 30 $\mu\mu$fd. is available to tune the secondary or load circuit, indicate which of the circuits, A, B, or C in the diagram (page 32) should be used to couple to the primary (at 7100 k.c.) if the secondary circuit must have a Q of 10 for adequate energy transfer, when the load resist-



ance has the following values: 10, 20, 70, 150, 600, 2000, 5000 ohms. Find the value of capacity which should be used in each case, and also the value of inductance necessary to tune to resonance in each case.

9) What is a low-pass filter? How may such a filter be constructed?

10) What are the distinguishing characteristics of a high-pass filter?

11) What is the purpose of shielding? What type of shield eliminates or reduces electrostatic coupling?

12) What materials are satisfactory for magnetic shielding at audio frequencies? At radio frequencies?

13) What happens to the inductance of a coil when it is enclosed in a shield? What is the effect on the Q of the coil? What determines the magnitude of these effects?

14) What is a band-pass filter? Describe a simple form of band-pass filter.

15) Describe the principle of operation of the bridge circuit.

16) How would you arrange two coils to obtain the highest possible mutual inductance?

ASSIGNMENT 10

Study *Handbook* Sections 2–12 and 2–13.

Questions

1) What is meant by the term "standing wave"?

2) What is the wavelength in meters corresponding to a frequency of 3500 kilocycles? What is the wavelength in feet?

3) What is the shortest length of wire in free space which will be resonant at a given frequency?

4) Describe the construction of a concentric line.

5) How is the current distributed along a wire a half wavelength long at the frequency at which it is excited? What is the current distribution if the wire is one wavelength long?

6) Describe the impedance characteristics of a folded quarter-wavelength line.

7) Why can a concentric line be built to have higher Q than a tuned circuit which operates at the same frequency?

8) What is radiation resistance?

9) What beat frequencies are produced when currents having frequencies of 2000 kilocycles and 2450 kilocycles are mixed in a circuit suitable for the production of beats? What beats are produced if the two frequencies to be mixed are 3900 kilocycles and 1500 cycles? 7150 kilocycles and 7149 kilocycles?

10) What is meant by ground potential?

11) When are by-pass condensers necessary?

12) What requirement must a by-pass condenser meet to function properly?

13) What is the purpose of a choke coil, and what requirements must it meet with respect to the characteristics of the circuit in which it is used?

14) A by-pass condenser is to be used to shunt r.f. current at a frequency of 14.15 megacycles around a circuit having an impedance of 6000 ohms. What value of capacity would be suitable?

15) A 500-ohm resistor is to be effectively by-passed for 100-cycle alternating current. What value of capacity is required?

16) Direct current is to be fed to a radio-frequency circuit which has an impedance of 2500 ohms at 3600 kilocycles. What inductance should the choke coil have? (In actual practice, the impedance of the choke coil would be affected by the distributed capacity of the coil, but this need not be considered in the problem.)

17) A 15-henry inductance is being used as a choke coil through which direct current is being fed to an a.c. circuit which has an impedance of 4000 ohms at 500 cycles. Is this value of inductance adequate? Would it be adequate if the frequency were 60 cycles?

EXPERIMENT 15

Resonant Circuits

Apparatus: The oscillator, power supply, vacuum-tube voltmeter, test instrument, circuit board and the calibrated receiver are needed for this experiment, together with two 1-watt resistors, 50,000 and 100,000 ohms. Use the full output voltage of the supply (250 to 300 volts) on the oscillator, which is operated with the coil in the grid circuit to give variable frequency.

Procedure: Connect a condenser and coil on the circuit board in parallel, and connect the input terminals of the v.t. voltmeter across the parallel circuit. Set the oscillator frequency to about 3700 kilocycles as determined by the receiver calibration (keep the gain low so that the signal is weak enough to give a good zero-beat indication) and bring the oscillator and tuned circuit near enough to each other to get a good v.t. voltmeter indication when the circuit is tuned through resonance. A reading of nearly full scale (on either the 30- or 100-volt scale) should be obtained when the circuit is resonant at the oscillator frequency. Once the relative positions of oscillator and circuit to give such a reading have been determined, do not move either unit. Should one or the other be accidentally moved, recheck to obtain the same maximum reading at resonance before going ahead.

Using all the turns in the coil, set the condenser to resonance. Then vary the oscillator frequency in steps of about 20 kc., taking readings on the v.t.v.m. each time, until the frequency is sufficiently far from resonance to bring the v.t.v.m. reading down to the low end of the scale. Do not touch the tuned circuit in the meantime. Take readings on both the low- and high-frequency sides of resonance. Then connect the 100,000-ohm resistor across the tuned circuit and repeat the measurements over the same frequency range. Finally, follow the same procedure with the 50,000-ohm resistor across the circuit. When the run is complete, convert the plate-current readings to volts by means of the v.t.v.m. calibration curve and then plot a curve showing the voltage across the circuit against frequency.

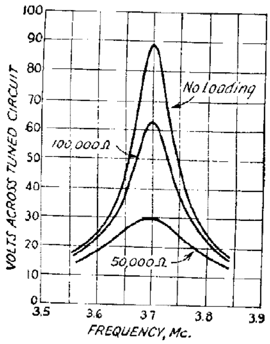


Fig. 9

Typical results of such measurements are shown in Fig. 9. The voltage is highest at resonance, dropping off with frequency on either side at a rate determined by the losses in the circuit. These losses are highest with the lower values of parallel resistance, hence the resonance curves of the loaded circuit become progressively less sharp as the loading is increased (parallel resistance lowered). Since the coupling to the oscillator is not changed during the run the voltage induced in the circuit remains unchanged, but the voltage rise at resonance decreases with loading, indicating that the Q of the circuit is decreasing.

Using a smaller number of turns on the coil, repeat the experiment, plot the data, and compare the curves to those obtained with the whole coil. Take a series of such data with different values of inductance. When the inductance is changed, change the position of the coil, if necessary, to get the same maximum value of voltage at resonance without load, or else convert the new readings to the original scale by multiplying each value by the ratio of the original maximum voltage to the new maximum voltage.

If some low-resistance 1-watt units are available (50 to 200 ohms) the experiment can be varied by taking readings similar to those described above, but with the low-resistance units connected in series with the coil and condenser instead of in parallel. In such case connect the v.t.v.m. across the condenser. When plotted, these readings can be compared to the curves obtained with the parallel resistors, in which case it will be observed that the higher values of series resistance give curves comparable to those obtained with the lower values of parallel resistance. If the losses in the circuit itself are small compared to the loss in the connected resistor, the relationship between parallel resistance and equivalent series resistance can be found from the formula

$$Z = \frac{X^2}{R}$$

where Z is the resistance actually connected in parallel and R is the equivalent series resistance. Conversely the impedance of the circuit can be found when the series resistance R is known. Calculate the values from the experimental data obtained.

EXPERIMENT 16

Inductively-Coupled Circuits

Apparatus: Same as for Exp. 15, with the addition of 25,000- and 10,000-ohm 1-watt resistors.

Procedure: Set up the oscillator for crystal operation, but remove the plate coil and connect the free coil on the circuit board in its place, using flexible leads. Set the plate voltage tap on the power supply for about half voltage (between R_2 and R_3, Fig. 4). Connect the fixed coil on the circuit board in parallel with the nearest variable condenser, using all the turns on the coil. Connect the v.t. voltmeter across this circuit. The general arrangement is shown in Fig. 10.

This experiment involves varying the coupling between the two coils, so it is convenient to make a scale to indicate the degree of coupling. The simplest way to do this is to rule a line on the board to serve as a guide for the movable coil so that its axis always will coincide with that of the fixed coil, and then mark off half-inch intervals along the guide line. Zero spacing will simply be the closest possible spacing between the coil bases on the board, and need have no reference to the actual separation between the turns.

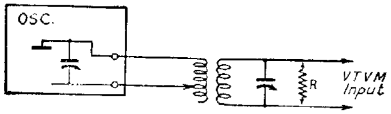


Fig. 10

This method of measuring coupling is purely arbitrary, but will serve the purpose satisfactorily. At the very close spacings, quarter-inch intervals on the guide line will be desirable.

At the start, set the coils at the maximum possible separation on the circuit board. This is about 5 inches in the arrangement shown in Fig. 8. No loading resistor is used in the first run. Use about 25 turns of the movable coil for the crystal oscillator plate tank, or whatever number of turns brings the setting for oscillation at or above half capacity on the oscillator tank condenser. Tune down a bit from the setting of the plate condenser which gives maximum output so that the oscillator operation will not be critical with loading. Move the coil a half inch at a time toward the fixed coil, taking readings at each interval. If the readings show rapid variation with spacing, reduce the interval to a quarter inch in the critical region. The secondary circuit should be adjusted for maximum voltage (resonance) with the loosest coupling between the two coils and then left alone while the coupling is increased.

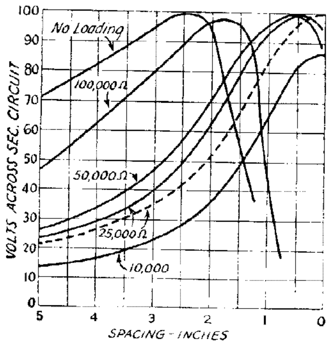


Fig. 11

The same procedure should be followed with parallel resistance loads of 100,000, 50,000, 25,000 and 10,000 ohms. After a run is complete, reduce the number of turns on the secondary coil and repeat. Do this for as many taps as is possible with the tuning capacity available. Make certain that the "ground" end of each circuit is connected to the facing ends of the coils to minimize capacity coupling, and in changing taps keep the active turns in the facing ends. Convert the data into voltage readings and then plot on cross-section paper. A typical set of curves so obtained is shown in Fig. 11. This series of curves was taken with 20 turns in the secondary coil with the exception of the dashed curve, which was taken with 35 turns.

This experiment illustrates the effect of the Q of the secondary circuit on coupling. In the case of the no-load curve, critical coupling — maximum output — is reached when the coils are separated about $2\frac{1}{2}$ inches on the arbitrary scale. When the Q is reduced by the addition of the 100,000-ohm resistor in parallel across the secondary it is necessary to increase the coupling to about $1\frac{3}{4}$ inches for critical coupling, and as the loading is increased still more by shunting lower values of resistance across the secondary the coupling must also be increased to secure maximum energy transfer. It can be seen that critical coupling can be just about reached with the 10,000-ohm resistor in parallel, and with much lower values of resistance it would not be possible to get tight enough coupling for maximum output. Assuming that the losses in the circuit alone are negligible in comparison to the power in the resistor, the Q of the circuit is

$$Q = \frac{Z}{X}$$

and since the reactance of the 20-turn coil is calculated to be approximately 500 ohms, the circuit Q is 10,000/500, or 20. In this particular case, therefore, the secondary circuit must have a Q of the order of 20 at least if maximum energy is to transferred. This is confirmed by the dashed curve, which was taken with 35 turns in the coil and the 25,000-ohm resistor in shunt. Using the new value of coil reactance represented by the larger number of turns the Q again works out to be approximately 20, and in this case the maximum energy transfer also is secured with the coupling distance at zero on the arbitrary scale. (At this "zero" there is still about $\frac{3}{4}$ inch separation between the actual ends of the coils, so that with other construction tighter coupling could be possible.)

From the data accumulated in the experiment, determine the cases where critical coupling is reached with minimum separation between the coils, and calculate the Q by the method above for these cases. The inductance can be calculated by means of the formula in the data chapter in the *Handbook* or by a *Lightning Calculator*. The effect of dead ends in the tapped coil can be ignored for the purpose of this approximate calculation.

After completing a run, go back and repeat any typical one, this time observing the effect on output voltage of varying the secondary tuning capacity at various degrees of coupling. It will be observed that with the coupling less than critical the output voltage will go through a resonance curve much like those in Fig. 9, becoming broader as critical coupling is approached, but that with coupling tighter than critical the secondary curve will have two humps, one on either side of the point where the circuit actually is resonant. The amplitude of the humps is approximately the same as the amplitude of the output voltage at critical coupling and is greater than the voltage at actual resonance (with greater than critical coupling) which drops off as shown by the curves. The tighter the coupling the greater the separation between the humps.

EXPERIMENT 17

Capacity Coupling

Apparatus: Same equipment as for Exps. 15 and 16.

Procedure: Use the grid coil in the oscillator for variable-frequency operation (operate the oscillator at half voltage) and set up the fixed coil and tuning condenser on the circuit board as in the previous two experiments. Because stray coupling between the oscillator and tuned circuit will mask the effects the experiment is intended to illustrate, it is necessary to provide sufficient shielding to reduce stray coupling to the point where it does not cause more than a volt or so to appear across the unloaded circuit. This can be complished by placing a large metal can such as a household sugar can over the oscillator plate coil, tube and tuning condenser (allowing the knob of the latter to project) and connecting the can to the negative "B" oscillator terminal. Reasonable separation between the oscillator and tuned circuit, and keeping the power leads bunched together where they run from the power supply unit to the oscillator and v.t.v.m., respectively, also will help. Connect the v.t. voltmeter to the circuit, set on the lowest range, and try different positions of the apparatus until not more than a volt or so appears across the unloaded circuit when it is tuned to resonance with the oscillator. An additional baffle shield judiciously placed near the oscillator (and also connected to oscillator negative "B") may help.

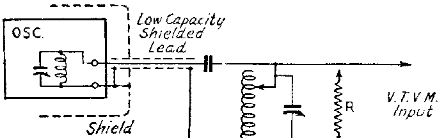


Fig. 12

In this experiment coupling between the oscillator and tuned circuit is by means of a small capacity. The circuit arrangement is shown in Fig. 12. The lead from the "hot" side of the oscillator tank circuit connects to one side of the small coupling condenser on the circuit board, and must be shielded for its entire length to prevent stray pickup. A loosely-fitting piece of shield braid over insulated wire will be satisfactory. A tight-fitting shield is not recommended since the capacity of such a wire will be high. Low-capacity shielded cable is good if available. In any event the lead should not be more than a foot long, to prevent the shunting capacity across the oscillator tank circuit from becoming too high. It will probably be necessary to use the smaller oscillator plate coil.

Stray capacity between the coupling condenser and the tuned circuit will provide enough coupling for the first attempt. Set the oscillator frequency to about 3700 kc., and, using all the turns on the tuned-circuit coil, adjust the circuit to resonance with the oscillator. Vary the oscillator frequency as described in Exp. 15 and take voltage readings. Connect a wire to the "hot" side of the circuit and bring it near the coupling condenser, again varying the frequency and taking a set of readings. Try various positions of the wire and finally connect it to the other set of plates on the coupling condenser. (This will probably result in over-coupling and a double-humped resonance curve with the unloaded tuned circuit.) Shunt the various values of resistance across the tuned circuit and repeat the measurements, noting approximately how much coupling capacity is required each time for maximum energy transfer. In all cases the capacity will be quite small.

When the data are taken and curves plotted, the similarity between capacity coupling and inductive coupling will become apparent, even though the two experiments were not performed on exactly the same basis.

EXPERIMENT 18

Link Coupling

Apparatus: Same as for Exp. 17.

Procedure: The circuit is shown in Fig. 13. The shielding described under Exp. 17 will be required, and stray coupling must be minimized. The link line connecting the two circuits should be twisted and both wires should be the same length. The links in both cases are temporary, consisting of a few turns wound around the ground end of the oscillator plate coil and the corresponding end of the tuned circuit coil. The link for the latter may be arranged to be pushed in and out of the coil to vary the coupling. Start with about 5 turns on each link and successively reduce the number of turns, observing the effect on the output voltage. The oscillator and tuned circuit should be retuned to the original frequency each time a change is made. It will be found that, with fixed coupling (link wound around the coil) changing the number of turns on either link has relatively little effect so long as a turn or two is retained.

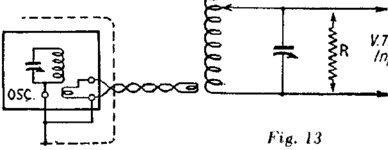


Fig. 13

Make runs in the same ways as in Exp. 15, varying the loading over the range of available resistors and taking a run at each tap on the tuned circuit coil. Repeat for varying degrees of coupling at either end of the link circuit. Compare the results with the information obtained in the experiment on inductive coupling (Exp. 16) with respect to the effect of secondary circuit Q on the energy transfer. For the cases where maximum energy transfer is just attainable with maximum coupling between the link coil and the tuned circuit coil, calculate the minimum Q necessary to secure critical coupling.

EXPERIMENT 19

Coupled Resonant Circuits

Apparatus: Same equipment as for preceding experiments.

Procedure: The object of this experiment is to show the effect on selectivity of operating two resonant circuits in cascade. Set up the oscillator for tuned-circuit frequency control as in Exp. 17, checking stray pickup to make certain that not more than a volt or so is present on the tuned circuit on the circuit board. Connect each coil to a variable condenser, using all the turns in both cases. The general circuit arrangement is shown in Fig. 14. Very loose coupling must be used between the oscillator and the first tuned circuit, the coil in which is movable with respect to the coil in the secondary circuit. No special coupling condenser is necessary; enough coupling can be secured by bringing a wire from the hot side of the primary circuit on the board to within a quarter inch or so of the end of the wire projecting from the shielded lead (described in Exp. 17) from the oscillator. Do not allow more than a half-inch of wire to project from the shield, and fasten the two wires securely so the capacity of this "condenser" cannot change during the experiment. Set the oscillator frequency to about 3700 kc. and adjust the coupling "condenser" to a value which permits the coupled circuit (the primary in this experiment) to be tuned through resonance without changing the oscillator frequency by more than a few hundred cycles. The secondary circuit should be disconnected when this check is made. If the frequency change is appreciable, the capacity must be reduced, since overcoupling (which is very easy to get) will greatly affect the measurements.

With the oscillator frequency at about 3700 kc., tune the primary circuit to resonance. The resonance point can easily be observed on the receiver (the beat oscillator should be on) or can be checked by bringing the hot lead from the v.t. voltmeter near (but not touching) the circuit and using the low range for measurement. The v.t.v.m. should not be connected directly to the circuit because its capacity will change the setting of the tuning condenser, hence the circuit will be out of resonance when the v.t.v.m. is shifted to the secondary circuit where the actual measurements are to be made. With the primary resonant, connect the v.t.v.m. to the secondary circuit and tune the latter to resonance. Move the primary coil away from the secondary until a reasonably high indication is obtained on the medium range — about 20 volts is satisfactory. Then reduce the coupling still more, check the tuning of the two circuits to make sure they are exactly resonant, and vary the oscillator frequency over a range of about 100 kc. either way from the resonant frequency, taking readings at 10-kc. intervals. Then, without touching the tuning of either circuit, increase the coupling and repeat. Follow the same procedure with progressively closer coupling until a quite pronounced double-humped resonance curve is obtained.

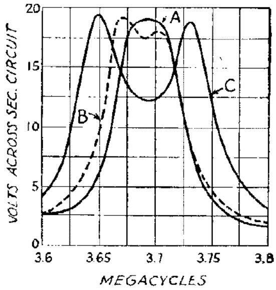


Fig. 15

On plotting the data the curves can be expected to look something like those shown in Fig. 15. Curve A in this group was taken with quite loose coupling, the primary coil being at its maximum distance and its axis turned slightly to give a further reduction in coupling. Nevertheless the slightly flattened top on the curve, as well as the fact that the maximum amplitude is practically the same as that of the largest hump in each of the other two curves, indicates that the coupling is very near the critical value. Curve B is with "4-inch" coupling and shows a double hump, indicating that the coupling is greater than critical. Curve C, with "2-inch" coupling, shows considerable overcoupling and very pronounced double humps. In general, these curves will not be exactly symmetrical, either theoretically or practically. Slight inaccuracies in setting the circuits to resonance will have some effect on the symmetry, and an important cause of dissymmetry is overcoupling between the oscillator and the primary circuit. It is of

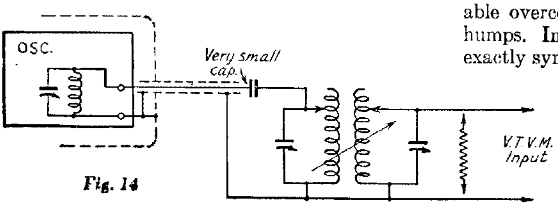


Fig. 14

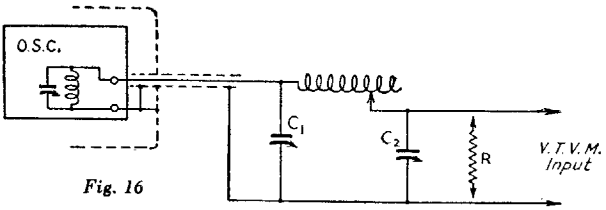


Fig. 16

first importance to make this coupling the loosest possible if reasonably good curves are to be obtained.

After completing a run with no loading on the secondary circuit the same procedure should be followed with the 100,000-ohm resistor connected in parallel with the secondary, and then again with the 50,000-ohm resistor in parallel. Plot the data and compare the curves to those obtained with no loading. It will be found that tighter coupling is necessary for maximum secondary voltage, and that the new maximum will be lower than in the no-load case. The resistance loading also tends to flatten the tops of the overcoupled curves, making the double humps less pronounced.

Compare the set of curves obtained in this experiment with those secured in Exp. 15. How do the curves with corresponding loading compare near resonance? How do they compare at frequencies removed by 100 kc. or so from resonance? To make this comparison it will be necessary to convert the voltage readings to the same scale by plotting selected curves, representing typical sets of conditions, in terms of percentage of the maximum voltage obtained. Suggested curves to plot in this fashion are three corresponding to those shown in Fig. 9, and one set of three (less than critical coupling, critical coupling, and moderate overcoupling) for each condition of loading (no load, 100,000 ohms, and 50,000 ohms) as obtained in the present experiment. Note the "band-pass" effect of a pair of overcoupled circuits with appropriate resistance loading.

EXPERIMENT 20

Pi-Section Filter Operation

Apparatus: Same as for preceding experiment, with the following values of 1-watt resistors: 10,000, 5000, 1000, 500 and 200 ohms.

Procedure: The operating characteristics of the pi-section filter are investigated in this experiment. The circuit arrangement is shown in Fig. 16, the two condensers being connected with one of the coils on the circuit board to form a low-pass filter. The input side of the filter is connected directly across the oscillator tank circuit. A blocking condenser of about 0.001 μfd. should be connected in series with the hot lead if the oscillator plate circuit is series-fed; this condenser is not necessary with the circuit of Fig. 2. The v.t. voltmeter is connected across the filter output to measure the voltage developed across the load. Make sure stray pick-up is minimized.

With the filter disconnected from the oscillator, set the frequency of the latter to about 3700 kc. Then, without touching the oscillator tuning, connect the filter, using an output load of 10,000 ohms. Rotate the input condenser, C_1, until the oscillator frequency returns to its original value. Then try different settings of C_2, the output condenser, until maximum output voltage is obtained. Each time the capacity of C_2 is changed, reset C_1 to bring the frequency back to the original value. When the maximum possible output voltage is obtained in this fashion, vary the oscillator frequency on both sides of the original frequency, taking v.t.v.m. readings simultaneously, until most of the 3.5-4-Mc. band has been covered. It will be satisfactory to take readings at 40- or 50-kc. intervals. Do not touch the tuning condensers in the filter while this frequency run is being made. When this series of data is complete, substitute the next lower value of resistance and repeat the whole procedure. Continue until all the resistance values specified have been used. Plot the data as illustrated in Fig. 17.

In taking the data it will be observed that as the value of load resistance is lowered the capacity required in the output condenser, C_2, for maximum output voltage progressively increases. It is by this means that the "impedance matching" function of the filter is realized, and this characteristic compares to the use of more capacity in a parallel-tuned circuit to maintain sufficient Q when the load resistance is lowered. By comparing the relative power (E^2/R) delivered to the various values of load resistance it can be seen that the

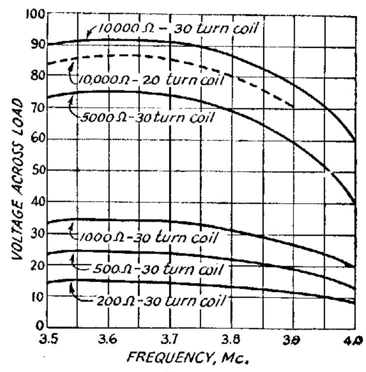


Fig. 17

output is approximately the same over the range of loads shown in Fig. 17, illustrating the ability of such a coupling circuit to provide proper impedance matching over a wide range of load resistances.

The low-pass characteristic of the filter can be observed from the curves, although there is no sharp cut-off. However, the output drops continually on the high-frequency side of resonance, while it is nearly constant for a 200-kc. frequency range on the low-frequency side. The heavy vertical line represents the initial frequency (3700 kc.) at which the filter was adjusted for maximum output.

Continue the experiment by taking a new value of inductance and repeating the original procedure with various loads. Plot curves and compare them with those obtained with the full 35 turns in the coil. Still larger values of inductance also may be used by connecting part of the second coil in series with the first. Changing the L/C ratio of the filter may result in a better impedance match with certain values of load resistance, less inductance and more capacity being required for low-resistance loads. This corresponds to the effect of a similar change in L/C ratio on coupling in an ordinary resonant circuit with the load connected in parallel.

The operation of the filter with loads having a reactance as well as resistance component, a condition frequently met when a pi-section filter is coupled to an antenna or transmission line, can be investigated by connecting various values of capacity or inductance in series with the load resistance. Useful information about the tuning capabilities of the filter can be obtained by observing the limits of reactance which can be compensated for by the filter, for various values of load resistance. The reactance values can be computed from the calculated or known values of inductance or capacity inserted in the load circuit.

Part Four

VACUUM-TUBE FUNDAMENTALS

EXPERIMENTS designed to show comprehensively the operation of the vacuum tube as an amplifier require a fairly elaborate array of test apparatus. Finding the gain-frequency characteristic of an audio amplifier, for example, requires the use of a calibrated source of variable frequency over the audio-frequency range, plus a calibrated attenuator and a means for measuring voltages, with readings independent of frequency. Distortion cannot readily be observed without an oscilloscope. Such equipment is expensive and satisfactory substitutes cannot readily be constructed at home.

However, simple experiments designed to show the properties of vacuum tubes readily can be performed with the gear described in the preceding installments. As a convenience in setting up apparatus, a tube board such as is shown in Fig. 1 can be added. It consists simply of a baseboard with a square piece of bakelite in which is mounted an ordinary octal socket, connections being brought out from the socket prongs to machine-screw terminals. This permits changing tube connections without soldering. The heater terminals are permanently connected to a terminal strip mounted at the back of the board. This strip also has terminals for "B" supply, one negative and two positive. The latter take care of separate plate and screen voltages when a tetrode or pentode is used. A push-button mounted on the board provides a means of closing the plate (or screen) circuit when the milliammeter in the test instrument is being used for other measurements.

In using the plate power supply with its variable voltage divider it should be remembered that only a limited current can be taken through the divider taps for more than very short periods of time. The variable resistor, in particular, is rated at only a few watts, and if the output current is more than 15 milliamperes or so the time during which current flows must be kept to a minimum. Since a reading can be taken in a matter of seconds this is no handicap, but if the supply is used for continuous output the resistor arm should be set at the end connected to the transformer center tap (see Fig. 3, p. 28), or else a switch should be provided for shorting between the negative output terminal and the wire connected to the center-tap of the power transformer.

Tube Characteristics

Some amplification of the *Handbook* material dealing with tube constants may be helpful in connection with the experimental work. In the paragraph on "Characteristics" (§ 3-2), for instance, plate resistance is defined as "the ratio, for a fixed grid voltage, of a small plate voltage change to the plate current change it effects." This can be written in the form of an equation:

$$r_p = \frac{\Delta E_p}{\Delta I_p} \; (E_g \text{ constant})$$

where r_p stands for plate resistance, ΔE_p for the change in plate voltage, and ΔI_p for the corresponding change in plate current. The sign Δ indicates that we are concerned not with one value but with the *difference between two values.* (In other respects the equation is simply the familiar statement of Ohm's Law.) The other two constants, amplification factor and mutual conductance, also can be defined in formulas instead of words:

$$\mu = \frac{\Delta E_p}{\Delta E_g} \; (I_p \text{ constant})$$

$$g_m = \frac{\Delta I_p}{\Delta E_g} \; (E_p \text{ constant})$$

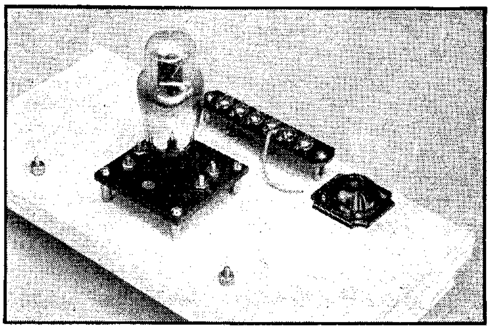


Fig. 1

By simple substitution in these formulas it is found that the three constants are related in this way:

$$g_m = \frac{\mu}{r_p}$$

The values of the constants can be found by plotting characteristic curves and measuring the change which occurs in one quantity when the other is changed any arbitrary amount. However, this method must be used with some caution when the characteristic curve does not turn out to be a straight line. If the line bends, the "constant" is not actually always the same, but varies with the point on the curve at which it is measured. For example, suppose that Fig. 2 represents a curve showing the variation of plate current as the plate voltage is varied, and from it we want to determine the plate resistance. We arbitrarily select A as the point from which to start and, also arbitrarily, decide to make the plate current change, I_p, 2 milliamperes. A 2-milliampere increase brings us to point B on the curve. Then the corresponding change in plate voltage, E_p, is the difference between the plate voltages which cause 1 and 3 milliamperes to flow. Thus $E_p = 70 - 30 = 40$ volts. Then

$$r_p = \frac{\Delta E_p}{\Delta I_p} = \frac{40}{0.002} = 20{,}000 \text{ ohms.}$$

Suppose that instead of 2 milliamperes for I_p we had selected 1 milliampere. This would bring us to point C on the curve, and now $E_p = 53 - 30 = 23$ volts. Substituting these new values in the equation gives us

$$r_p = \frac{23}{0.001} = 23{,}000 \text{ ohms.}$$

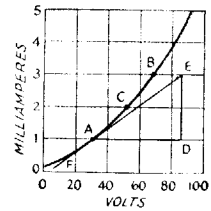
Because of the curvature of the characteristic the value of the "constant" r_p as measured by this method will depend considerably upon the value of Δ selected. As the value of Δ is made smaller and smaller the value of ratio $\Delta E_p/\Delta I_p$ approaches the ratio AD/DE, where the line FE is drawn tangent to the curve at point A (that is, the line FE touches but does not intersect the curve at point A). In Fig. 2 this ratio is

$$\frac{AD}{DE} = \frac{85 - 30}{0.003 - 0.001} = \frac{55}{0.002} = 27{,}500 \text{ ohms}$$

which is the value of the plate resistance at point A on the curve. If points B or C had been selected instead of A as the starting place (point at which plate resistance is to be determined) different values of plate resistance would be obtained, since it is obvious that tangents drawn through these points would not coincide with the tangent EF.

In determining the values of the tube constants from the curves, therefore, the preferred procedure is to draw a tangent to the curve at the point at which the value of the constant is to be measured, and then use the tangent line as a basis for measurement of ΔE_p and ΔI_p (or whatever pair of quantities is represented by the curve).

Fig. 2



While there is bound to be some inaccuracy in drawing the tangent, in general the results will be nearer the truth than if two points on the curve itself are selected. Of course if the curve is straight the curve and its tangent coincide, so that in the special case of a straight-line curve points can be taken directly from the curve.

Caution!

In the diagrams of the various set-ups for the experiments to follow, milliammeters and voltmeters are indicated where measurements are to be made. If enough separate instruments are at hand, they may be used as shown. However, if only the single combination test instrument is available for measuring currents and voltages, extreme care should be used to see that the proper range is selected before making voltage measurements. In particular, if the instrument is set on the 0–1 ma. range for use with the v.t. voltmeter, and then connected across a high-voltage part of the circuit while inadvertently left on that range, burn-out or other serious damage to the meter movement is almost certain to result. It is important to form the habit of checking the setting of the range switch before making any change in the instrument connections.

ASSIGNMENT 11

Study *Handbook* Sections 3–1 and 3–2. Perform Exps. 21, 22 and 23.

Questions

1) How does conduction take place in a thermionic vacuum tube?

2) What is the space charge?

3) What is the purpose of the grid in a triode?

4) Name the three fundamental tube characteristics and define them.

5) Why is a "load" necessary if a vacuum tube is to perform useful work?

6) What are tube characteristic curves?

7) Why is amplification possible with a triode tube?

8) What is meant by the term "interelectrode capacity"?

9) What is the difference between static and dynamic characteristic curves?

10) In what form is the power supplied to the plate-cathode circuit of a tube dissipated?
11) What is the purpose of tube ratings?
12) What is meant by the term "plate-current cut-off point"?
13) What is grid bias, and why is it used?
14) Define saturation point.
15) What is rectification?

ASSIGNMENT 12

Study *Handbook* Sections 3–3 and 3–4. Perform Exp. 24.

Questions

1) Name three forms which the plate load for a triode amplifier may take.
2) Define voltage amplification; power amplification. What is the essential difference between amplifiers designed for the two purposes?
3) What determines the choice of operating point for an amplifier?
4) Define plate efficiency. How does it vary with different types of operation (Class A, B and C)?
5) What is harmonic distortion and how is it caused?
6) Describe Class-A amplifier operation.
7) What is feed-back? What is the result of application of positive feed-back? Of negative feed-back?
8) How is the input capacity of a triode amplifier affected by its operating conditions?
9) What is driving power?
10) What is the phase relationship between the alternating voltage applied to the grid of an amplifier having a resistance load and the amplified voltage which appears in the plate circuit?
11) What is the effect of the value of load resistance on the amplification obtainable with a given tube?
12) If a certain power amplifier circuit delivers 3.5 watts when a signal voltage of 20 peak volts is applied to the grid, what is the power sensitivity of the amplifier?
13) Describe Class-B amplifier operation.
14) What is the definition of a decibel?
15) If the power level at one point in an amplifier is 0.25 watt and at a later point is 4 watts, what is the gain in db.?
16) What are the distinguishing characteristics of a Class-C amplifier?
17) What is the difference between parallel and push-pull operation?
18) A certain circuit provides an attenuation of 15 db. What is the ratio of power levels in the circuit?
19) If a signal of 0.6 volt is applied to an amplifier having a voltage amplification of 125, what is the output voltage?
20) In a certain amplifier an input voltage of 0.01 volt produces an output voltage of 50 across 500 ohms. The input resistance of the amplifier is 0.1 megohm. What is the gain of the amplifier in db.?

ASSIGNMENT 13

Study *Handbook* Sections 3–5 and 3–6. Perform Exp. 25.

Questions

1) What is the purpose of the screen grid in a tetrode or pentode tube intended for use as a radio-frequency amplifier?
2) Does the shielding afforded by the screen grid have to be as complete in a tetrode or pentode designed for audio-frequency amplification as in one designed for radio-frequency amplification?
3) Describe secondary emission.
4) How may the effects of secondary emission be reduced in a screen-grid tube?
5) What is the difference between a "variable-μ" and a "sharp cut-off" tube?
6) Why is a mercury-vapor rectifier preferred to a high-vacuum rectifier when the rectifier tube must handle a considerable amount of power?
7) How does a mercury-vapor grid-control rectifier differ from a high-vacuum triode? Could such a "gas triode" be used for amplification in the ordinary sense of the word?
8) Identify five general types of multipurpose tubes.
9) What is a beam tube?
10) Name the two general types of cathodes used in thermionic vacuum tubes.
11) What is the advantage of the unipotential cathode?
12) What is the purpose of center-tapping the filament supply of a tube whose cathode is heated by alternating current?
13) A certain r.f. power amplifier requires a negative grid bias of 200 volts for Class-C operation. The d.c. grid current is to be 16 milliamperes under operating conditions. If the bias is to be obtained entirely from grid leak action, what value of grid-leak resistance is required?
14) A triode amplifier requires a negative grid bias of 30 volts, at which bias the plate current is 45 milliamperes. What value of cathode resistance will give the required bias? If the amplifier is to be used at audio frequencies as low as 100 cycles, what value of by-pass capacity should be shunted across the resistor to minimize negative feed-back?
15) What value of cathode bias resistance should be provided for a 6F6 used as a Class-A pentode audio amplifier with 250 volts on the plate? (Use published operating conditions.) What value of by-pass condenser should be used to prevent negative feed-back at frequencies down to 80 cycles?
16) A push-pull r.f. power amplifier requires 400 volts bias and a d.c. grid current of 15 milliamperes per tube under rated operating condi-

tions. If 130 volts of fixed bias is to be provided by batteries, what grid leak resistance should be used?

ASSIGNMENT 14

Study *Handbook* Section 3–7. Perform Exp. 26.

Questions

1) How may a vacuum-tube circuit be made to generate self-sustained oscillations?

2) Can oscillations be set up in a circuit in which the feed-back is negative?

3) What is negative resistance?

4) Define series feed; parallel feed.

5) Draw two circuits utilizing magnetic feed-back.

6) How can the amount of feed-back be controlled in the Colpitts circuit?

7) Draw a simple triode crystal oscillator circuit. Which of the ordinary oscillator circuits does it resemble most closely?

8) Define the plate efficiency of an oscillator.

9) Name four factors which can affect the frequency of oscillation.

10) What is a multivibrator? Name one of the uses for this type of oscillator.

11) How can the effect of plate voltage variations on frequency of oscillation be minimized?

12) Draw three oscillator circuits with capacity feed-back, and describe how the feed-back may be controlled in each.

13) What is the usual method of obtaining grid bias in an oscillator circuit? Why is it used in preference to other methods?

14) How can frequency drift in an oscillator be reduced?

15) A 25-microhenry coil is available for use in an oscillator circuit which is to operate at approximately 2000 kc. What capacity will be required to tune the coil?

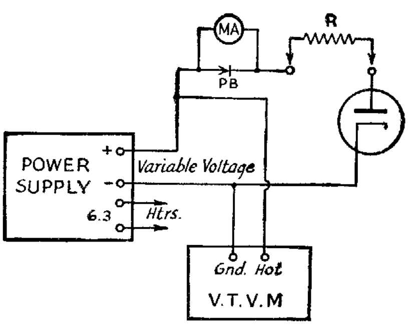


Fig. 3

ASSIGNMENT 15

Study *Handbook* Sections 3–8 and 3–9.

Questions

1) What is a fluorescent screen?

2) Describe the construction and operation of a simple cathode-ray oscilloscope tube.

3) By what methods may an electron beam be deflected?

4) Define deflection sensitivity.

5) How is the intensity of the fluorescent spot controlled?

6) What is the purpose of the sweep circuit in an oscilloscope?

7) Name two common forms of sweep. What are the advantages and disadvantages of each?

8) What is an electron gun?

9) Why is it desirable to use amplifiers for the deflection voltages for a cathode ray tube?

10) Why should the time of the return trace in a linear sweep circuit be as short as possible?

11) Explain the method by which patterns are formed on the fluorescent screen. Construct a pattern, using a linear sweep with return trace time equal to 1/20 of the total time of the sweep cycle, for two cycles of a sine wave applied to the vertical plates. Construct a pattern, using the same two sine-wave cycles applied to the vertical plates, but with a single sine wave for the horizontal sweep. Compare with the linear sweep.

12) Describe the operation of a gas-triode linear sweep generator.

EXPERIMENT 21

Diode Characteristics

Apparatus: This experiment uses the plate power supply, tube board, test set, vacuum-tube voltmeter, and three 1-watt resistors, 25,000, 50,000 and 100,000 ohms. The circuit arrangement is shown in Fig. 3. Measurements must be made of the voltage applied to the tube and the current flowing in its plate-cathode circuit; the single test instrument can be used for both purposes by being shifted back and forth for each pair of readings. However, the small current consumed by the instrument when used as a voltmeter will cause the actual output voltage to be lower when the voltage is being measured than when the instrument is shifted to read plate current. Unless a separate voltmeter which can be left permanently in the circuit is available, it is advisable to use the v.t. voltmeter, thus avoiding the loading effect. The test instrument is therefore shifted between the plate circuit of the tube being tested and the plate circuit of the voltmeter tube.

The tube to be tested may be a 6H6, the diode section of a combination diode-amplifier tube, or simply a small triode such as the 6J5 with the grid and plate connected together to act as a single plate.

Procedure: The object of the experiment is to plot characteristic curves, plate voltage vs. plate current, for the tube alone (static characteristic) and with various values of load resistance in series with the plate circuit (dynamic characteristics).

Starting at zero plate voltage, increase the plate voltage in small steps, taking plate current readings at each voltage step. With no load resistor in the circuit, take readings at intervals of voltage

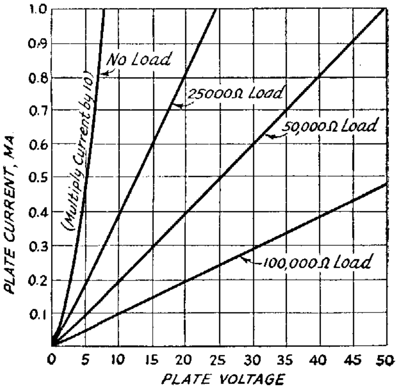


Fig. 4

which will give current intervals of about 1 milliampere so that enough points will be secured to give a smooth curve when the points are plotted. In the case of the 6H6 tube, using one plate and cathode only, one-volt intervals are suitable. Proceed similarly when the load resistance is inserted in the circuit; in this case larger voltage intervals (5-volt steps, for instance) can be used.

In using the single test set for all measurements, the push-button should be closed while the voltage measurement is being made so that the voltage can be adjusted to the proper value with plate current flowing. If the plate circuit is not closed at the time the voltage is adjusted, the voltage will drop when the milliammeter is connected in the plate circuit of the tube to measure plate current. It is not necessary to make provision for closing the plate circuit of the v.t.v.m. when the meter is being used elsewhere.

The observed data should be plotted in the fashion shown in Fig. 4, which gives characteristic curves taken on a 6H6. With no load the current is quite high, reaching 10 milliamperes with about 7.5 volts applied. Other types of tubes may give considerably different plate-current values without load, but should approximate the load curves given since the current which flows at a given voltage is principally determined by the load resistance rather than the tube. As is to be expected, the current decreases, at a given applied voltage, as the load resistance is increased.

If the no-load curve is inspected carefully, it will be observed that it is not a straight line, particularly near the low-voltage end. The lamp in Exp. 10 was another example of a non-linear circuit, although for a different reason. In the present case, the non-linearity arises from the fact that the number of electrons drawn to the plate is not strictly proportional to the voltage applied between plate and cathode. The *d.c. resistance* of the diode at any voltage is equal to that voltage divided by the current which it forces through the tube. In practice the behavior of the tube when an alternating voltage is applied is of more interest, in which case the a.c. plate resistance, or resistance effective to small *changes* in applied voltage, is important. The value of this plate resistance is found as described in the introduction to this installment.

When a load resistance is inserted in the plate circuit the linearity of the circuit consisting of the resistance and the tube is better than that of the tube alone. This improvement, which increases as the load resistance is increased, is because the load resistor tends to reduce the effect of variations in the resistance of the tube. For example, if the resistance of the tube varies between 1000 and 3000 ohms with a certain range of applied voltage the resistance change is 2000 ohms, or an increase of 200 per cent, using the smaller number as a base. If a 10,000-ohm resistor is connected in series, the minimum resistance becomes 11,000 ohms and the maximum resistance 13,000 ohms, so that the increase in resistance is now only 2000/11,000, or 18 per cent. With 100,000 ohms in series, the increase is from 101,000 to 103,000 ohms, so that the percentage increase is now 2 per cent. In the curves of Fig. 3 the addition of the load resistance makes all the points fall on a line which is practically straight except at the low voltage end where the tube resistance has its highest value. The higher the load resistance the less marked does this slight curvature become.

In taking data it will be observed that a small current flows in the plate circuit even at zero plate voltage. This current is the result of the fact that some electrons are emitted from the cathode with sufficient velocity to reach the plate even though there is no positive charge on the plate to attract

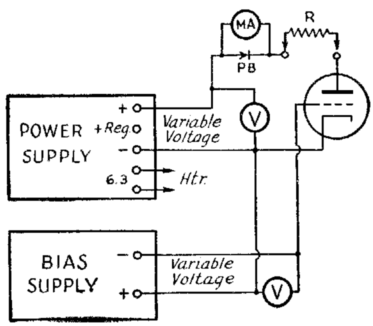


Fig. 5

them. For complete cut-off of plate current it would be necessary to make the plate a volt or two negative with respect to the cathode, thus repelling these high-energy electrons from the plate. Since the current in any case is very small

— a very small fraction of a milliampere — it can be neglected in most applications of the tube. However, in flowing through an external load resistance of high value a volt or two may be developed across the load, which may need to be taken into account in some cases.

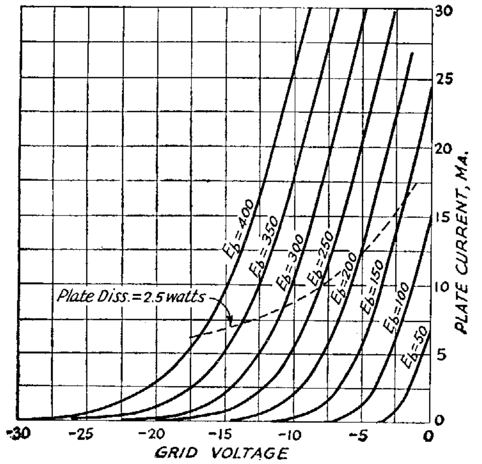


Fig. 6

EXPERIMENT 22

Triode Static Characteristics

Apparatus: The set-up for this experiment is shown in Fig. 5. Insofar as the plate circuit of the triode is concerned, the arrangement is practically the same as that used for diode measurements, Fig. 3, except that it is possible to measure plate voltage with the test instrument rather than the v.t. voltmeter. This is because larger plate-voltage steps may be used so that a high range (500 volts or the nearest provided on the test instrument), which will have a resistance of a half megohm or so, will give sufficient accuracy for all measurements. The bias supply is incorporated in the set-up to provide variable grid bias, and its voltage output also may be measured by the test instrument on the condition that the voltmeter resistance is 25,000 ohms or so (25-volt scale). Be sure that the positive output terminal of the bias supply is connected to the grounded side of the 115-volt line, using the lamp provided for checking as described in Part 2. In using a single instrument in place of the three indicated, the push-button should be closed each time the plate voltage is measured so that the voltage will be that existing when plate current flows.

The resistor R shown in Fig. 5 is not needed in this experiment, so the push-button may be connected directly to the plate.

Procedure: The object of the experiment is to determine the relationship between plate voltage, plate current and grid voltage of a small triode. One quantity is held constant throughout a run, the second is varied, and corresponding measurements of the third are made. A receiving triode such as the 6J5 is suitable. Three sets of characteristics can be taken, the first, with the plate voltage held fixed while the behavior of plate current with varying grid voltage is observed, is called the "grid voltage-plate current" characteristic. When a series of such data is taken with several fixed values of plate voltage, a "family" of curves results. A typical grid voltage-plate current family taken in this way on a 6J5 is shown in Fig. 6. The plate voltage was set at 50-volt intervals from 50 to 400 volts (the maximum output voltage of the power supply described in Part 3), enough points being taken at each plate voltage to permit smooth curves to be drawn. Notice that for each value of plate voltage the curve bends at the higher values of negative grid voltage (as the plate current decreases toward the cut-off point) but that the curvature decreases as the grid bias becomes less negative. The curves eventually straighten out and become practically parallel, and the distances between the 50-volt intervals also approach equality. The dashed line shows the value of plate current at which the plate dissipation (plate voltage multiplied by plate current) is equal to the maximum rated value for the tube; above this line the plate dissipation is exceeded.

The "plate family," shown plotted from experimental data in Fig. 7, is obtained by holding the grid bias constant at selected values and measuring the plate current as the plate voltage is varied. These curves show the same general tendency to bend when the plate current is near cut-off, and to straighten out at higher values of plate current. The plate family is frequently more useful than the set of grid voltage-plate current curves represented by Fig. 6.

When the remaining quantity, plate current, is

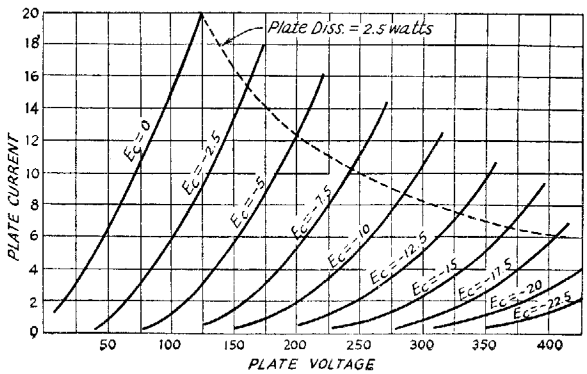


Fig. 7

held constant while the grid voltage is varied (the plate voltage being adjusted for each value of grid bias to give the selected value of plate current) the set of curves shown in Fig. 8 results, again plotted from experimental data on a 6J5. These "constant current" curves show the relative effect of grid

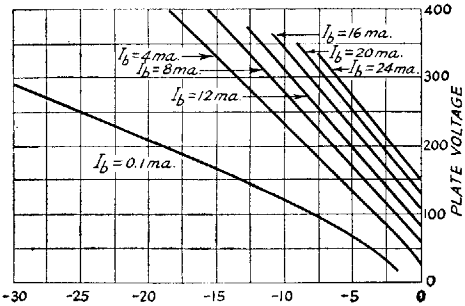


Fig. 8

voltage and plate voltage on plate current. The curves are nearly straight lines for all except very small values of plate current, showing that the amplification factor is practically constant for a given plate-current value regardless of the plate and grid voltages. The fact that, with the exception of the curve for a plate current of 0.1 milliampere, the curves are very nearly parallel indicates that the amplification factor also is nearly independent of the plate current so long as the latter is not near the cut-off point.

The values of amplification factor, μ, plate resistance, r_p, and mutual conductance, g_m, can be measured from these three sets of curves. The mutual conductance, $\Delta I_p \Delta E_g$, can be found from the curves of Fig. 6 since these curves show the relationship between grid voltage and plate current. The plate resistance, $\Delta E_p/\Delta I_p$, can be measured from the curves of Fig. 7, which relate plate current to plate voltage for various values of grid bias, while the amplification factor $\Delta E_p/\Delta E_g$, can be taken from the curves of Fig. 8. The method of making these measurements is described in the introduction to this installment. Since these "constants" are a function of three variables a large number of graphs would be required to give their behavior even partially completely, but one special case is shown in Fig. 9. This graph shows the variation in μ, r_p and g_m as a function of grid bias when the plate voltage is held constant at 250 volts, the normal rated operating voltage for the tube, and is a plot of values measured at 250-volt points on each of the three sets of curves in Figs. 6, 7 and 8. It is plain that the amplification factor changes relatively little compared to the changes in the other two quantities. Increasing negative grid bias causes the mutual conductance to decrease, which means that the amplification obtainable from the tube also decreases since amplification is proportional to mutual conductance, other things being equal. On the other hand, the plate resistance increases with increasing negative grid bias. As a check on the accuracy of measurement, the three curves should satisfy the relationship

$$g_m = \frac{\mu}{r_p}$$

within reasonable limits of accuracy, for any given value of grid bias.

If published average curves for the type of tube measured are available, it will be of interest to compare them to the curves determined experimentally. Exact duplication of the published curves is not to be expected, of course, because of slight variations in manufacture.

EXPERIMENT 23

Triode Dynamic Operation

Apparatus: Same equipment as for Exp. 22, with the addition of the following resistors: 5000, 10,000, 25,000, 50,000 and 100,000 ohms. Resistors of 1-watt rating will be satisfactory.

Procedure: The object of this experiment is to plot dynamic grid voltage-plate current characteristics for representative values of plate load resistance. Using a fixed value of plate-supply voltage, insert a resistor at *R*, Fig. 5, and measure the plate current as the grid bias is varied in steps of 2.5 volts or so. Each time the grid bias is changed, readjust the plate-supply voltage (measured across the supply terminals, not from plate to cathode of the tube being investigated) with the push-button closed so that the voltage under load will be the actual value selected. The voltage will need to be re-set as the plate current increases, because of voltage drop in the power supply. When a complete set of data has been obtained with one value of plate load resistance, change to another value and take another run. When finished with all values of resistance, plot the data in the form of curves showing plate current against grid bias.

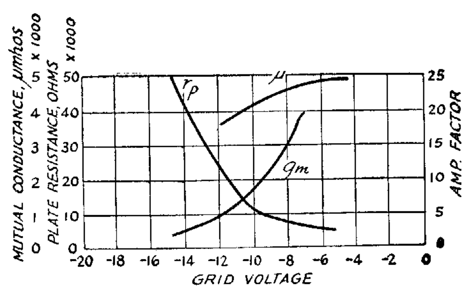


Fig. 9

A typical set of such curves, taken on a 6J5 with the plate voltage constant at 300, is shown in Fig. 10. As the plate load resistance is made larger the maximum plate current (at zero grid bias) becomes smaller, as is to be expected. The plate current cut-off point, however, occurs at approximately the same value of negative grid bias in each case, since the plate voltage is fixed and at

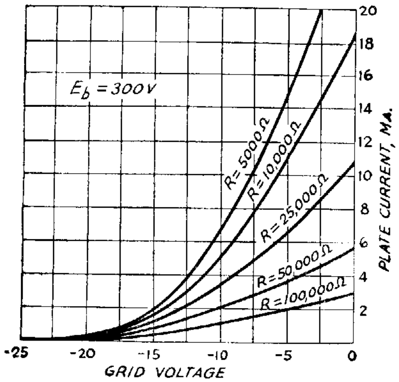


Fig. 10

zero current there is no voltage drop in the load resistor. As in the case of the diode which was the subject of Exp. 21, increasing the value of load resistance has the effect of straightening out the curve, so that the curves taken with high values of load show less bending than curves with no load or small values of load resistance.

The effect of the load resistance on the amplification obtainable from the tube, and also the distortion it introduces, can be found graphically from curves such as these. In Fig. 11, as an illustration, the curve for R = 10,000 ohms has been plotted singly for the purpose of showing the relationship between varying grid signal voltage and the corresponding variations in plate current. An operating point should be chosen somewhere near the middle of the relatively-straight part of the curve, such that the product of the plate current by the voltage between plate and cathode will not exceed the rated plate dissipation of the tube. In Fig. 11 the operating point selected is the point A, at − 7.5 volts grid bias, making the no-signal plate current slightly less than 8 milliamperes. The dashed line extending downward from A is the axis of grid voltage, and the line extending to the right is the axis of plate current. On the grid voltage axis a sine wave is plotted as the assumed signal voltage (the actual shape of the signal wave is not highly important, but the sine wave is representative of a single frequency) as a function of time, one complete cycle being represented. In Fig. 11 the signal has a maximum amplitude of 5 volts, so that the instantaneous grid voltage swings between the limits of − 2.5 volts and − 12.5 volts about the fixed grid bias of − 7.5 volts. A corresponding time scale is applied to the plate current axis so that the plate current corresponding to the grid voltage at a given instant can be plotted.

At zero time (beginning of the cycle) the grid voltage is − 7.5 and the plate current 7.8 ma., approximately. One-eighth cycle later (point B) the grid signal voltage has risen to 71 per cent of its maximum value so that the instantaneous grid voltage is − 4 volts. The plate current, C, at that same instant is 12.3 milliamperes, and this value is plotted at D, one-eighth cycle from zero time on the plate-current axis. Points for other instants are similarly obtained until enough are plotted to permit drawing a smooth curve. When the cycle is complete it can be compared for shape to the original grid signal. As Fig. 11 shows, the two halves of the plate current cycle are not exactly the same shape, as they were in the grid signal. This difference in shape represents distortion, and the greater the difference the more distortion there is present. As is obvious from the drawing, the distortion is caused by the curvature of the tube characteristic, since if the characteristic were perfectly straight the plate current would be proportional to the grid voltage. Plotting similar graphs from dynamic curves taken with different values of load resistance readily will show the effect of the load resistance on distortion.

The gain of the tube as an amplifier can also be found from the graph of Fig. 11 or from the curves of Fig. 10. Referring to Fig. 12, it can be seen that with fixed plate supply voltage, E_b, the current flowing in the plate circuit will cause a voltage drop across the load resistance, this drop being equal to I_pR, where I_p is the value of the plate current and R the resistance. The voltage actually between plate and cathode of the tube is the plate-supply voltage minus the voltage drop in the resistance. When an a.c. signal is applied to the grid, the plate current varies at the same frequency, hence a corresponding a.c. voltage is de-

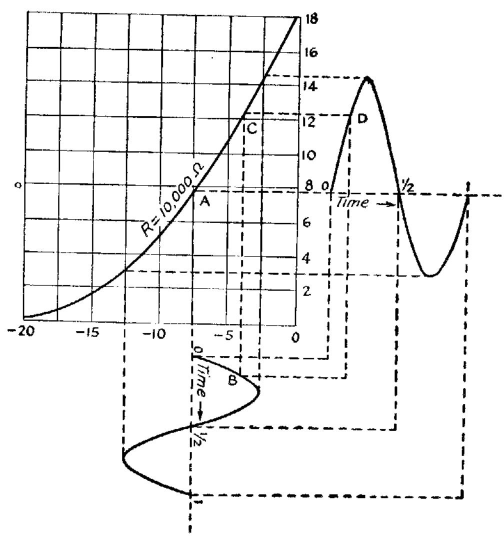


Fig. 11

veloped across the load resistor. This a.c. voltage is the useful output of the tube. The maximum drop in the resistor occurs when the plate current is maximum, corresponding to the most positive value of instantaneous grid voltage, and the mini-

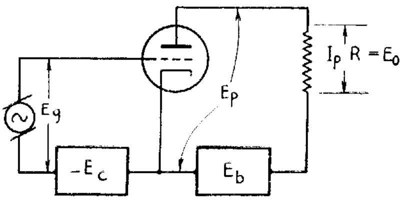


Fig. 12

mum drop occurs when the plate current is minimum, corresponding to the most negative value of instantaneous grid voltage. In Fig. 11 these plate-current values are 14.5 milliamperes for an instantaneous grid voltage of -2.5, and 3.0 ma. for a grid voltage of -12.5. Since the plate load resistance is 10,000 ohms, the maximum voltage drop is $0.0145 \times 10{,}000$, or 145 volts, and the minimum drop is $0.003 \times 10{,}000$, or 30 volts. The difference, $145 - 30$, or 115 volts, is the total change in voltage across the load corresponding to a total change in grid voltage of 10 volts. Hence the voltage gain is 115/10, or 11.5. The same information could be obtained from the curves of Fig. 10 by finding the currents corresponding to any chosen change in grid voltage, and then proceeding as above to find the voltage output. From such information a curve can be plotted showing the variation of amplification with load resistance.

EXPERIMENT 24

Class-A Amplification

Apparatus: The power supply, bias supply, v.t. voltmeter and tube board are used in this experiment, together with a potentiometer or volume control and the resistors specified in Exp. 23. Almost any potentiometer resistance may be used, although values higher than about 100,000 ohms should be avoided if possible. The circuit arrangement is shown in Fig. 13. The heater voltage for the tubes is used as a source of a.c. voltage for the grid of the tube being tested, the value of voltage applied to the grid being adjusted by means of the potentiometer. The a.c. voltage in either the grid or plate circuit is measured by the vacuum-tube voltmeter, the input circuit of which is connected to the circuit being measured through the 0.01-μfd. condenser. This condenser blocks the d.c. voltages present and permits only the a.c. to be measured.

Before performing the experiment the v.t. voltmeter should be calibrated on a.c. A source of variable a.c. voltage can most conveniently be obtained by making a slight change in the bias supply so that its voltage divider can be connected directly across the a.c. line. Referring to Fig. 2, page 18, Part 2, disconnect the top end of R_2 from the filter and connect it to the a.c. output terminal. Then proceed to calibrate the voltmeter by the same method used in making the d.c. calibration, using the 0.01-μfd. blocking condenser in the "hot" voltmeter lead. Connect the 1-μfd. condenser, C_3, to the cathode of the voltmeter tube (Fig. 6, page 29, Part 3). The calibration will be in terms of r.m.s. voltages, since the test set calibration is r.m.s. The a.c. calibration will resemble that taken on d.c., except that the curve above about 40 volts on the high range may show considerable departure from linearity. If so, use only the linear part of this scale. This effect is attributable to the fact that with a capacity of only 1 μfd. at C_3 the time constant of the circuit is too small at 60 cycles to permit the cathode bias to build up to a value sufficient to prevent grid current from flowing at the higher applied voltages. In performing the experiment care should be taken to keep the maximum voltage to be measured within the linear part of the high-range curve.

Procedure: The purpose of this experiment is to confirm by measurement the results of the gain calculations carried out as described in Exp. 23. Adjust the grid bias (restore the voltage divider connection to the filter after completing the a.c. calibration) and plate voltage to the values used in the calculations, using the same tube. These were -7.5 and 300 volts respectively in our example, using a 6J5. Set the potentiometer so that the voltage applied to the grid is about 2 volts r.m.s. as measured between grid and cathode (Fig. 13). Insert a resistor in the plate circuit of the tube at R, and adjust the plate-supply voltage

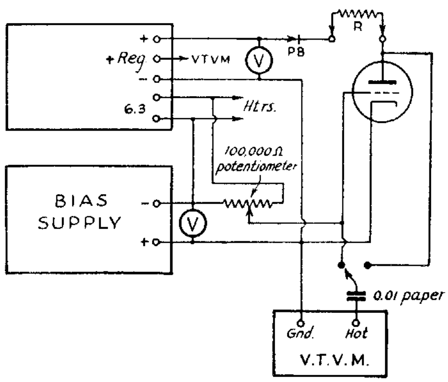


Fig. 13

to the selected value (300 in this illustration) with plate current flowing (push-button closed). Shift the v.t.v.m. to the plate circuit and measure the a.c. output voltage, keeping the push-button closed. Repeat for various values of plate load resistance, using two resistors in series to make up values intermediate to those available in the single units. The results of a typical set of measurements are given below, for 2 volts r.m.s. applied to the grid:

Plate load resistance, ohms	*Output voltage*
5000	21.5
10,000	27
15,000	29
25,000	31
50,000	34
75,000	34.5
100,000	35

The gain of the amplifier will be equal to the output voltage divided by the input voltage, or just half (input voltage = 2) the figures above. Plot the data in the form of a curve, as shown in Fig. 14.

Note that the gain rises as the plate load resistance is increased, but eventually a point is reached where a considerable increase in load resistance causes only a negligibly small increase in gain. The gain obtainable is proportional to the amplification factor and also to the ratio of the plate load resistance to the sum of the plate load resistance and the a.c. plate resistance of the tube, and when the plate load resistance is large compared to the tube resistance this ratio changes very slowly. Hence the amplification tends to level off as the plate load resistance is increased. From the curves of Fig. 9 the tube plate resistance is seen to be about 7500 ohms. When the plate load resistance is about 5 times the plate resistance, or approximately 40,000 ohms, the amplification increases very slowly with further increases in load resistance. Hence a load in the vicinity of 50,000 ohms is a suitable value for this tube as a resistance-coupled voltage amplifier.

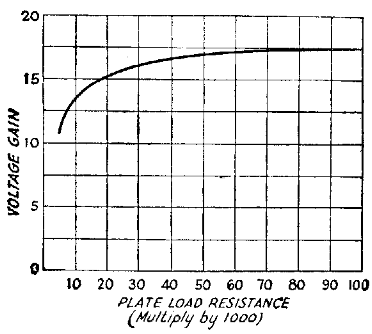


Fig. 14

At 10,000 ohms, the value used in the illustration of Exp. 23, the measured gain is about 13.5 as compared to the calculated value of 11.5. The percentage difference, while fairly large, is to be expected in view of unavoidable errors in measurement and in plotting and reading the curves. Also, the resistance was assumed to be exactly 10,000 ohms in the calculations, while the manufacturing tolerances on these resistors is ± 10 per cent. Ohmmeter measurement of the resistor actually used in the experiment showed the resistance to be on the high side of 10,000 ohms.

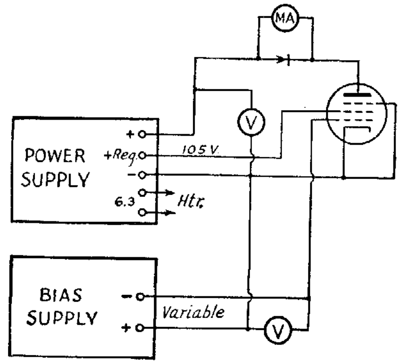


Fig. 15

EXPERIMENT 25

Pentode Characteristics

Apparatus: The apparatus set-up used in this experiment is shown in Fig. 15. The power supply, bias supply, tube board and test instrument are required. In taking one set of data it is necessary to maintain the screen grid at constant voltage, preferably the rated value, and for this purpose a VR-105-30 is substituted in the power supply for the VR-150-30 previously specified. The tube tested can be a small receiving pentode such as the 6J7.

In making voltage measurements, the highest voltage range on the test instrument which will permit reasonably accurate reading should be used so that the effects of voltage regulation will be minimized. The 500-volt scale for plate voltage and 25-volt scale for grid voltage will be satisfactory (or nearest equivalent ranges provided on the actual instrument).

Procedure: In this experiment curves equivalent to those plotted for the triode (Exp. 22) are to be obtained, for the purpose of determining the relationships between plate current and grid and plate voltages in a pentode. It is advisable to take data for the plate-voltage-plate current family first. Using a 6J7, first set the grid bias at zero and then vary the plate voltage, taking plate current readings at each value of plate voltage selected.

From a plate voltage of 100 up to the maximum available from the supply (about 400), 50-volt steps will be satisfactory. Below 100 volts it is suggested that readings be taken at 10, 25, 50 and 75 volts. Each time the plate voltage is adjusted be sure the push-button in the plate circuit is closed so that the voltage will be set to the proper value with plate current flowing.

When a set of measurements has been made with zero grid bias, increase the bias to 1 volt negative and repeat. Continue at 1-volt intervals in bias until a set of measurements has been taken for − 6 volts. At higher bias the plate current will be cut off, or else so small in value as to be negligible. Plot the data in curves such as are shown in Fig. 16.

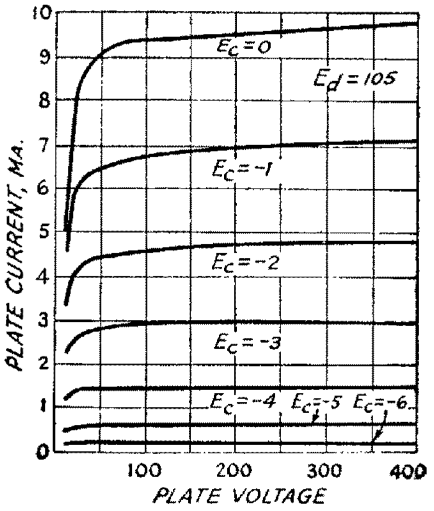


Fig. 16

Comparing these curves to the equivalent triode family in Fig. 7 shows a tremendous difference in the behavior of plate current with varying plate voltage. In the triode case (Fig. 7) the plate current is very markedly dependent upon the plate voltage. On the other hand, except for the region of plate voltage lower than the screen voltage, the plate current of the pentode is practically unaffected by the plate voltage. The curves begin to droop as the plate voltage is reduced below 100, but the drop-off is not really marked until the plate voltage is quite low. The fact that the plate voltage has relatively little effect on plate current while the grid voltage has a very great effect indicates that the amplification factor, $\Delta E_p/\Delta E_g$, is very high.

The cause of this behavior is the screen grid. Since the screen grid is an electrostatic shield, it prevents the electric field set up by the plate from

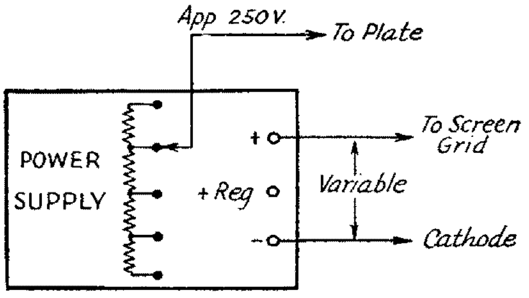


Fig. 17

penetrating to the region occupied by the cathode and control grid, hence electrons in this region are unaffected by the plate potential. The control grid, however, has just as much effect on the electron stream as it does in a triode. Electrons passing through the control grid are attracted to the screen because the latter is operated at a positive potential, but many of them have sufficient velocity to pass between the screen-grid wires without being caught by the screen grid itself. These electrons then come under the influence of the electric field set up by the plate and are attracted to it, forming the plate current. Since the plate can attract only the electrons which get through the screen, it is obvious that the plate current will be determined almost wholly by the screen potential and the structure of the screen grid.

The effect of the screen grid on plate current can be found by holding the plate voltage at a fixed value and varying the screen voltage (for a fixed value of grid bias) while observing the plate current. A slight modification of the experimental set-up of Fig. 15 is necessary. Connect the screen grid to the variable tap on the power supply as shown in Fig. 17, and tap the plate connection on the power-supply voltage divider so that the plate voltage will be about 250 volts. The first tap below maximum will be satisfactory. If the plate voltage varies slightly during a run no harm will be done since the plate current is only slightly

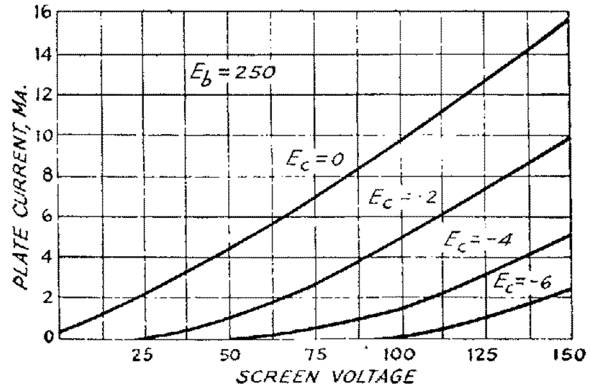


Fig. 18

affected by the plate voltage so long as it is appreciably higher than the screen voltage. Vary the screen voltage in small enough steps so that smooth curves can be plotted from the data. Do this for several values of grid-bias voltage. Typical experimental curves obtained by this method are shown in Fig. 18, taken on a 6J7. These curves have essentially the same nature as the curves of Fig. 7, which is to be expected from the explanation of the operation of the screen-grid tube given above.

Since the plate voltage has relatively little effect on the plate current, a single-grid voltage-plate current curve will suffice for practically all plate voltages above the screen voltage, so long as the latter is not changed. Such a characteristic can be taken by holding the plate and screen voltages fixed, reading plate current while varying the grid bias. An experimental curve on a 6J7 is shown in Fig. 19. Although in the triode case the corresponding curves (Fig. 6) had to be drawn for several values of plate voltage, in this case such a series would lie so close together as to merge into one curve, for all practical purposes. It can be seen, however, that the curve has the same general characteristics as those typical of triodes, and

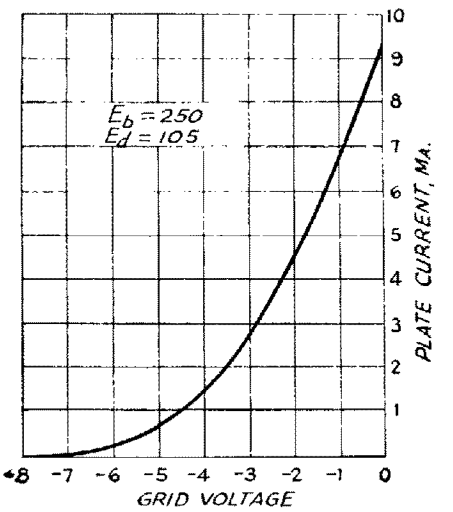


Fig. 19

if the mutual conductance is measured it will be found to be approximately the same as for a triode of the same size. The plate resistance is obviously high, since a large change in plate voltage is required to make a comparatively small change in plate current. Both plate resistance and amplification factor are very difficult to measure with any reasonable accuracy because in each case the ratio of the two quantities involved is so high that the probable error in measuring the smaller of the two reflects a large error in the ratio.

Further experimental work may be done with the tube by plotting a series of grid voltage-plate current curves for different values of screen voltage. Also, the effect of secondary emission may be investigated by running a series of plate voltage-plate current curves, corresponding to those of Fig. 16, but with the suppressor grid connected to plate instead of cathode. The characteristics of a variable-μ tube of the same general type, such as the 6K7, also may be taken and compared to the sharp cut-off 6J7.

EXPERIMENT 26

Oscillator Operation

Apparatus: The power supply, v.t. voltmeter and tube board are needed for this experiment, together with the additional parts indicated in the diagram of Fig. 20. The Hartley oscillator circuit is indicated in this diagram, with parallel feed in both plate and grid circuits. The radio-frequency chokes are 2.5-millihenry pie-wound units, and the blocking capacities are midget mica condensers. Provision should be made for changing the grid-leak resistance and for using different values of load resistance. The 1-watt resistors used in previous experiments will be satisfactory in both cases.

Procedure: The object of this experiment is to show the effect of grid-leak resistance on oscillator plate current, grid current, and r.f. output voltage, the plate voltage being fixed at some convenient value and other circuit conditions left unchanged. In the circuit of Fig. 20 the tuned circuit is formed by one of the condensers and coils on the circuit board, the whole 35-turn coil being used with the cathode of the oscillator tube (a 6J5) tapped on the coil 10 turns from the grid end. The v.t. voltmeter is connected between the cathode and plate of the tube (through the plate blocking condenser) to measure the r.f. plate voltage. The 1-μfd. by-pass condenser in the v.t.v.m. cathode circuit (C_3) should not be used.

With the plate voltage at some value which prevents excessive plate current, such as 100 volts, insert a 5000-ohm resistor as a grid leak and measure the plate current, grid current, and r.f. plate voltage. Adjust the plate voltage to the chosen value with the plate circuit closed so that the tube draws plate current. There should be no load on the oscillator on the first run. Change the grid leak to 10,000 ohms and repeat, then continue with successively higher values of grid-leak resistance up to 100,000 ohms. Connect a 25,000-ohm resistor across the v.t.v.m. input circuit as a load and repeat the measurements. Continue with lower values of load resistance until the circuit refuses to oscillate. The data may then be plotted in graphical form.

Typical results of such measurements are shown in the curves of Fig. 21. Curves for no load and for a load of 10,000 ohms are shown for comparison, although if several values of load resistance are used it would be better to use separate sheets for each, to avoid confusion. With no load the variation in r.f. output voltage over the whole range of grid-leak resistance is relatively small. The plate current is low and decreases somewhat as the grid-leak resistance is increased. The grid current at the lowest grid-leak resistance is rela-

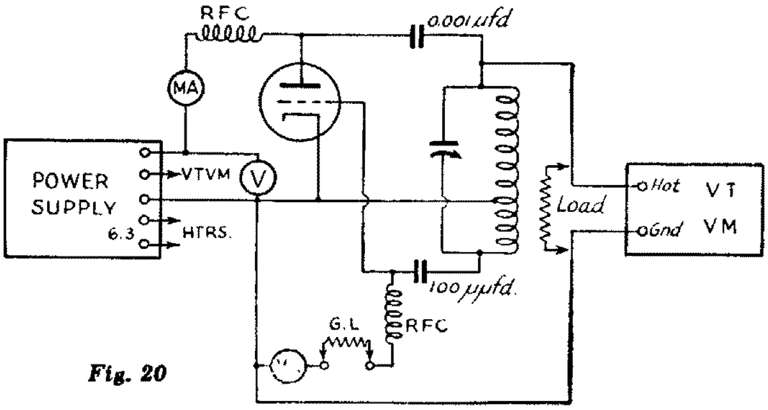


Fig. 20

tively high, but decreases with increasing grid-leak resistance. The grid bias — product of grid current by grid-leak resistance — shows comparatively little variation, indicating the self-regulating properties of the oscillator in this respect; that is, the grid current regulates itself so as to develop about the same bias over a wide range of grid resistance.

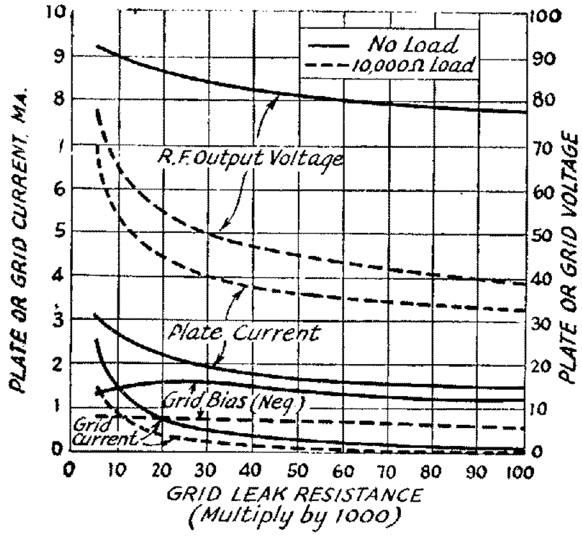


Fig. 21

When the circuit is loaded the plate current shows a pronounced increase. This is partly because the load reduces the Q of the tuned circuit, thus lowering its parallel impedance and hence allowing more plate current to flow, much in the same way that the plate current increased in the curves of Fig. 10 with lower load resistance for a fixed value of grid bias. At the same time the r.f. output voltage decreases while the internal voltage drop in the tube increases. This effect is comparable to the decrease in amplification with lower load resistance which was observed in Exp. 24. The plate-current increase is exaggerated in the case of the oscillator because the decrease in r.f. plate voltage is accompanied by a proportional decrease in r.f. grid voltage, since the r.f. grid voltage is obtained from the plate circuit. Hence the grid bias also decreases, if the grid-leak resistance and feed-back coupling are fixed. With lower grid bias more plate current will flow, and to some extent the amplification increases so that the r.f. output voltage tends to become greater. Thus two tendencies working in opposite directions are present, but with the net result that there is a decrease in both r.f. output voltage and grid bias and an increase in plate current. Increasing the value of grid-leak resistance again results in self-regulating action with respect to grid bias, while r.f. output voltage and plate current decrease together.

The experiment can be extended by making a similar set of observations with a new value of feed-back, obtained by changing the position of the cathode tap on the coil. It is also of interest to compare the operation of the various oscillator circuits which can be made up from the coils and condensers on the circuit board.

Part Five

RADIO-FREQUENCY POWER GENERATION

THE experiments in this part do not require any equipment additional to that already used in the preceding work. Much of the useful practical knowledge of the operation of the various parts of transmitters comes from actual construction and use, and the average amateur, for whom this course is intended, usually has acquired a fair fund of such knowledge. Supplementary to the experiments, the beginner can get a great deal of practical benefit from building up various basic circuits shown in the *Handbook* and observing their operation. This additional work also is recommended as part of a classroom program. The experiments devised for this installment have for their purpose the focussing of attention on points which ordinarily are somewhat obscure to the practicing amateur and which, because of their basic nature, form a good background for understanding otherwise puzzling phenomena which arise occasionally in the course of adjusting a transmitter.

Circuit Note

In the 1942 Standard edition of the *Handbook* and the first three printings of the Defense edition, circuit (E) in the group of circuits showing capacity coupling between driver and amplifier stages (§ 4–6) should be revised so that the driver plate-supply lead is tapped on the center of the driver tank coil. The connection shown, while not actually incorrect, would necessitate operating the cathode of the amplifier at a radio-frequency potential above ground, which is usually undesirable when it can be avoided. The driver and amplifier cathodes in both this and circuit (F) should be assumed to be grounded.

ASSIGNMENT 16

Study *Handbook* Sections 4–1 to 4–5, inclusive. Perform Exp. 27.

Questions

1) Why is it general practice, on frequencies below 60 megacycles, to use multi-stage transmitters in preference to the much simpler arrangement of an oscillator coupled to an antenna?
2) What is a buffer amplifier?
3) What are the advantages and disadvantages of a self-controlled oscillator as compared to the crystal-controlled type?
4) Describe the electron-coupled oscillator. What features make it preferable to simpler self-controlled oscillator circuits?
5) What requirement must be met by the oscillator tank circuit to give the highest frequency stability? How can this be accomplished in practice?
6) How should an oscillator be adjusted and operated to secure a high order of frequency stability? What constructional precautions should be observed?
7) Draw an electron-coupled oscillator circuit, using a tube having an indirectly-heated cathode, with tuned output.
8) Draw a crystal oscillator circuit using a pentode tube.
9) If a crystal oscillator refuses to function, what are some of the possible causes?
10) Compare the triode with a tetrode or pentode as a crystal oscillator tube.
11) What determines the frequency at which a crystal will oscillate?
12) Name four factors which can cause the frequency of a crystal to shift from its calibrated value.
13) Show a crystal oscillator circuit which will give output at a harmonic of the crystal frequency.
14) Describe the behavior of the plate current of a crystal oscillator as the plate tank circuit is tuned through resonance.
15) What is the correct method of adjusting a Tri-tet oscillator?
16) What determines the safe power input to a crystal oscillator circuit?
17) What are the distinguishing characteristics of some of the better known crystal cuts, such as the *X*, *Y* and *AT*?
18) What is a "harmonic" crystal?
19) Why is frequency multiplication generally necessary in transmitters operating above about 7 megacycles?
20) What precautionary measures can be taken to prevent fracturing a crystal from excessive r.f. voltage?
21) What is the effect on r.f. crystal voltage of taking power output from a crystal oscillator?

ASSIGNMENT 17

Study *Handbook* Sections 4–6 and 4–7. Perform Exps. 28 and 29.

Questions

1) Draw a circuit diagram showing link coupling between a single-ended driver stage and a push-pull amplifier. Indicate series-fed plate supply for the driver and series-fed bias supply for the amplifier.

2) When is it desirable to use link coupling between driver and amplifier stages?

3) If the effect of shunting capacities can be neglected, as at low frequencies, would you expect the same coupling efficiency to be obtained with capacity and with link coupling, assuming optimum adjustments in each case?

4) Draw a circuit diagram showing capacity coupling between a single-ended driver and single-ended amplifier. Indicate a method for obtaining optimum energy transfer ("impedance matching").

5) To what part of the tank coil should a link winding be coupled in order to minimize capacity coupling?

6) Why is neutralization necessary in a triode r.f. amplifier?

7) If, when adjusting a link-coupled driver-amplifier circuit, it is found that the amplifier excitation is insufficient even though the driver power output capability is known to be ample, what is the probable cause? How may the condition be remedied?

8) What precautions must be taken to prevent self-oscillation in screen-grid r.f. amplifiers?

9) Draw a circuit of a plate-neutralized single-tube triode amplifier using a split-stator plate tank condenser. Show a driver stage with capacity coupling to the amplifier.

10) Draw a cross-neutralized push-pull triode amplifier circuit, with a link-coupled single-ended screen-grid driver. Use split-stator or balanced condensers in the amplifier plate and grid tank circuits.

11) Why is it possible, as a general rule, to obtain more complete neutralization of a push-pull than a single-ended amplifier?

12) Draw a circuit of a grid-neutralized amplifier using a single-ended or unbalanced grid tank condenser. Show link coupling to a plate-neutralized driver stage.

13) Describe the procedure used in neutralizing an amplifier, using a milliammeter in the grid circuit as an indicator.

14) If it is found impossible to neutralize an amplifier completely, how would you test for coupling (external to the tube) between the input and output circuits?

15) What is the principle of inductive neutralization?

16) If the impedance in the plate circuit of a 3.5-Mc. amplifier is 2000 ohms, what value of by-pass capacity will be suitable in the plate circuit if series feed is used?

17) A certain amplifier exhibits a grid impedance of 4000 ohms under normal operating conditions. If the driver stage requires a load of 6000 ohms for optimum efficiency, what means can be used to secure optimum power transfer with capacity coupling? If the operating frequency is 7 Mc., what values of coupling capacity will be satisfactory?

18) If the amplifier of Question 17 is link-coupled to the driver stage, and a Q of 10 is necessary in both the driver plate tank circuit and amplifier grid tank circuit to assure sufficient coupling, what values of inductance and capacity should be used in each circuit?

ASSIGNMENT 18

Study *Handbook* Sections 4–8 and 4–9. Perform Exp. 30.

Questions

1) What is the minimum permissible Q (with load) in a plate tank circuit constructed in accordance with good design principles? Why is it necessary to set such a lower limit for Q?

2) Given a fixed value of load resistance, how may the Q of a tank circuit be adjusted to the proper value?

3) Of what order is the plate efficiency of a properly-operated r.f. amplifier? Is this the same as the ratio of actual useful power output to d.c. input?

4) Define operating angle. What is the usual range of values of operating angle for a Class-C amplifier?

5) How may the load on a Class-C amplifier be adjusted?

6) A certain power tube requires a negative bias of 70 volts to cut off plate current at the recommended value of d.c. plate voltage. If the peak grid voltage for full output under a given set of operating conditions is +120 volts and the operating angle is to be 150 degrees, what operating grid bias is required and what is the r.m.s. value of r.f. grid voltage which must be applied to the tube?

7) What operating bias and what value of r.f. grid voltage (peak) would be required with the tube of Question 6 if the operating angle were changed to 120 degrees, other conditions remaining the same?

8) The grid loss in the tube of Question 6 is 4 watts. What is the approximate value of d.c. grid current?

9) A Class-C amplifier is operating on 3600 kc. with a plate input of 120 milliamperes at 750 volts. What tank capacity should be used if the plate circuit is that shown at (B), in the *Handbook* diagram showing various types of plate tank

circuits (§ 4–8)? What capacity is necessary if the circuit is that shown at (E)?

10) A push-pull amplifier operating on 7200 kc. is loaded so that the plate current is 250 ma. The applied plate voltage is 1500. What value of inductance should be used in the tank circuit if the Q of the circuit is to be 12?

11) Describe the behavior of plate current with plate tank tuning of a Class-C amplifier.

12) Why is the plate current of a Class-C amplifier least when the plate tank circuit is tuned to resonance with the frequency of the r.f. grid voltage? Why is the plate dissipation also minimum at this point?

13) On coupling an antenna circuit to a Class-C amplifier it is found that it is necessary to retune the plate tank circuit. What is the cause?

14) Why is it necessary to supply more driving power to a Class-C amplifier than that actually consumed in heating the grid? What effect does the operating frequency have upon the relative amount of additional power which must be supplied?

15) What is the purpose of a dummy antenna? Describe a circuit arrangement suitable for the purpose.

16) Why should an r.f. power amplifier initially be tuned up with low plate voltage?

17) If the plate current of a Class-C stage rises continually after a period of steady operation, what is the likely cause?

18) Describe the construction and use of a Faraday screen (electrostatic shield). What is the purpose of such a device?

ASSIGNMENT 19

Study *Handbook* Sections 4–10 to 4–12, inclusive.

Questions

1) In what way does a frequency multiplier differ from a straight-through amplifier?

2) Why is frequency multiplication necessary in high-frequency transmitters?

3) Why is the frequency doubler the most common type of frequency multiplier?

4) Can a push-pull circuit be used satisfactorily for frequency doubling? Explain.

5) How do the operating conditions for frequency doubling compare with those for straight amplification? Is it possible to obtain as high plate efficiency with a doubler as with a straight amplifier? If so, how can it be accomplished?

6) What is a parasitic oscillation? Why is such an oscillation undesirable?

7) Describe three forms of parasitic oscillations and the means for suppressing each type.

8) Explain how you would go about testing an amplifier for parasitic oscillations. How could a parasitic be distinguished from oscillation resulting from improper neutralization of a triode amplifier or insufficient screening in the case of a screen-grid amplifier?

9) What is a linear tank circuit?

10) Why are linear tank circuits preferable at ultrahigh frequencies to ordinary circuits consisting of coils and condensers?

11) Draw an oscillator circuit using a single tube working into a quarter-wave parallel-line tank circuit.

12) What is the advantage of increasing the length, in terms of quarter wavelengths, of a resonant line used as a tank circuit?

13) Why is it frequently necessary to use inductances in the cathode leads of u.h.f. oscillators?

14) What are the advantages of a concentric line over the parallel-conductor line? Name some mechanical disadvantages.

15) Draw a circuit of a single-tube oscillator using a quarter-wave concentric line. Indicate a method of coupling to the output circuit.

16) What is the customary method of adjusting the resonant frequency of a linear circuit?

17) A parallel-conductor line is to be used as a tank circuit in a 112-Mc. oscillator. What should its approximate length be if it is to resonate to the operating frequency without the tube connected? When the tube is connected, would you expect the actual frequency to be higher or lower than the frequency of the line alone? How may the effect of the tube on the frequency be reduced?

18) Why is it desirable to "tap down" on a line used for frequency control in an oscillator circuit?

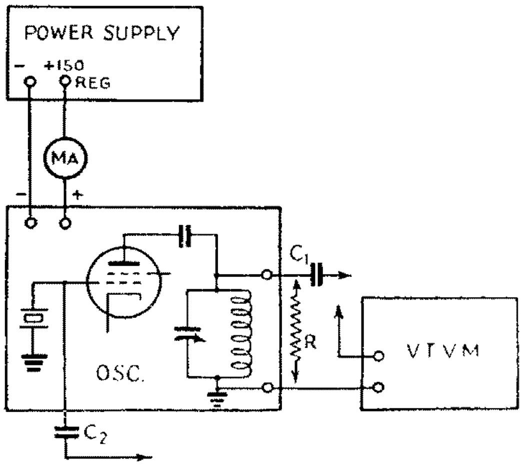


Fig. 1

EXPERIMENT 27

Crystal Oscillator Operation

Apparatus: The power supply, vacuum-tube voltmeter, test instrument and crystal oscillator are used in this experiment. The circuit arrangement is shown in Fig. 1. The plate voltage for both oscillator and v.t.v.m. is taken from the 150-volt regulated tap in the power supply. The push-button on the tube board can be used to close the plate-supply circuit of the oscillator when the milliammeter is used with the v.t.v.m., in case the test set is used for all current measurements.

The v.t. voltmeter is coupled to the output circuit of the oscillator through a small condenser, C_1, as shown in Fig. 1, or to the grid of the oscillator tube through a second condenser, C_2. (Complete oscillator connections are not shown; only the parts of the circuit to which the v.t.v.m. should be coupled are indicated.) These condensers must be adjusted so that the v.t.v.m. reads half to full scale on the medium range. It will be convenient to use a 30-$\mu\mu$fd. trimmer for C_1. The same type of condenser can also be used at C_2, although a fixed condenser of about 5 $\mu\mu$fd can be substituted.

Procedure: The object of this experiment is to determine the operating characteristics of a crystal oscillator with respect to plate current, r.f. grid voltage and r.f. output voltage. While the actual r.f. voltages cannot be determined accurately with the simple equipment available, the relative voltage in either the plate or grid circuit of the oscillator can be determined with sufficient accuracy for the purpose. The d.c. calibration of the v.t.v.m. may be used. The setting of the plate tank condenser of the oscillator is used as an arbitrary reference in the experiment. If the oscillator does not already have a tuning dial which can be read to a division or so on a 100-division scale, such a dial or scale should be provided.

Using the 6F6 in the oscillator, connect the v.t.v.m. to the plate circuit and set the oscillator in operation. Adjust C_1 to give a suitable reading near full scale on the medium range of the voltmeter. Starting at maximum capacity on the oscillator tank condenser, reduce the capacity until the oscillator just starts, as indicated by a reading on the v.t.v.m. (a receiver may be used for monitoring the oscillator signal) and take voltmeter readings as the capacity is decreased to minimum. In the region immediately after oscillations begin it will be necessary to take readings at quite small capacity intervals in order to get enough points to plot a smooth curve. Take care not to disturb the leads to the v.t.v.m. once the run is started, because variable stray pickup will make the readings inconsistent. If a second milliammeter is available, take simultaneous readings of plate current; if not, the procedure may be repeated for the plate-current readings, leaving the v.t.v.m. connected to the plate circuit.

When these data have been taken, the v.t.v.m. should be connected to the grid of the oscillator and C_2 adjusted, if necessary, to give a maximum reading between half and full scale. Observe the dial setting at which oscillations start, and if it differs from that noted previously, connect C_1 across the tank circuit and adjust it to make oscillations begin at the same tank condenser setting. This compensates for the capacity of the v.t.v.m. tube which was shunted across the circuit in the first run. Repeat the run, taking readings of the r.f. grid voltage. When this is completed, connect a 5000-ohm 1-watt resistor across the tank circuit, as shown at R in Fig. 1, and repeat the whole procedure. It may be necessary to readjust C_1 and C_2 to get suitable readings, or to shift to the low-voltage scale on the v.t.v.m. when reading the r.f. grid voltage.

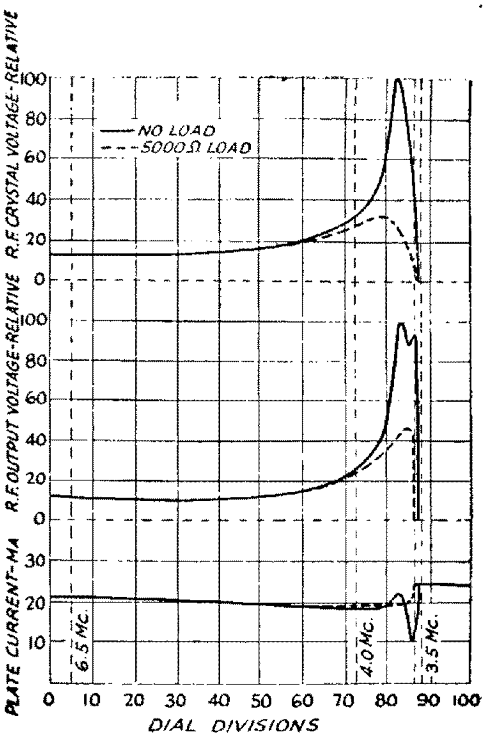


Fig. 2

To get a proper comparison between the no-load and load conditions, the following procedure is advisable: With no load on the oscillator, connect the v.t.v.m. to the grid and adjust C_2 to give a reading of half to full scale on the medium voltage range. Adjust the oscillator tuning for maximum r.f. grid voltage and note the value. Then, without moving the connecting wires, connect the load resistor to the plate tank and retune the oscillator condenser for maximum r.f. grid voltage. The latter figure divided by the former gives the ratio of load voltage to no-load voltage. Similar readings should be taken of the r.f. plate voltage with and without load to determine the load/no-load ratio in the plate circuit.

In plotting the data the form shown in Fig. 2 is recommended. The r.f. grid voltage is plotted in terms of percentage of the maximum grid voltage observed in the no-load condition; the load data are also in terms of percentage of the maximum voltage observed, but reduced by the ratio of load to no-load voltage found as described above. The same method is used in plotting the r.f. plate voltage. The plate current values shown are the actual values measured.

The curves of Fig. 2 give the results of experimental measurements on a 6F6 oscillator. As additional information, the vertical broken lines indicate the frequency to which the tuned circuit is resonant at that setting of the tuning condenser. The line just to the left of the 3.5-Mc. line

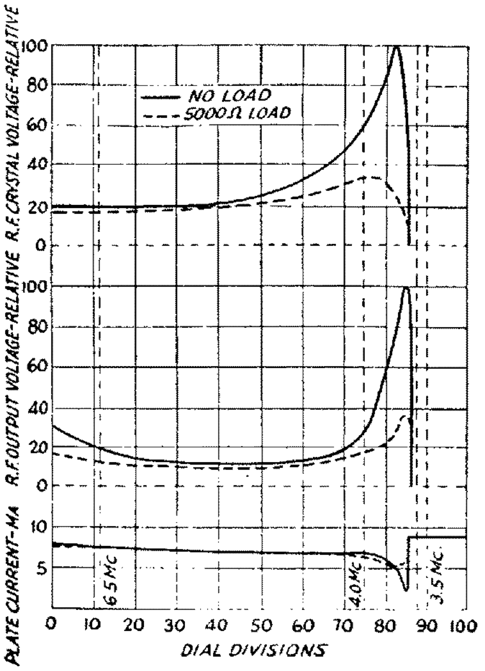


Fig. 3

is the frequency of the crystal used, 3550 kc. As the tuning capacity is decreased from maximum, oscillation starts at approximately the capacity which represents resonance with the crystal. The plate current immediately drops to about half its non-oscillating value, goes through a minimum and then rises again to a maximum. This is followed by a relatively small decrease to a broad minimum and then a slow rise. Oscillation continues throughout the remainder of the condenser range, so that the non-oscillating value of plate current does not recur on the low-capacity side of resonance. The r.f. plate voltage rises rather abruptly once oscillations start, and goes through a maximum at a condenser setting somewhat below actual resonance in the plate circuit. The r.f. grid voltage curve is similar, but reaches its maximum at a still lower setting of the condenser.

This behavior is the result of the necessity for adjusting the tank circuit tuning to maintain the proper phase relationship between the fed-back voltage in the grid circuit and the generated r.f. voltage in the plate circuit. This requires that the plate circuit show inductive reactance; that is, the plate circuit must be tuned slightly to the high-frequency side of resonance with the crystal frequency. The tank circuit impedance decreases as the circuit is detuned. The plate current is lowest near resonance, where the tank impedance is highest, and there is also a small maximum in the r.f. plate voltage at this point. However, this tuning condition is not that which gives strongest oscillation. With slightly lower capacity the r.f. plate voltage reaches a peak, but the tank is detuned and its impedances decreases, hence the plate current rises. Further detuning gives the phase relationship which results in maximum feed-back, as shown by the peak of r.f. grid voltage, but there is some decrease in actual output at this point because the tank circuit is now detuned still farther from resonance. The peak of r.f. grid voltage is accompanied by a maximum in the d.c. plate current, corresponding to high grid excitation with a detuned tank circuit. With further detuning the feed-back decreases, causing the plate current to drop once more, while the r.f. output (plate) voltage drops rapidly because the tank circuit is no longer near resonance. There is relatively little change in the three quantities when the tank circuit is considerably off resonance and the oscillations are weak. The net operation is thus the result of several conflicting factors, since there is no one setting of the tank condenser which will give, simultaneously, maximum output, maximum feed-back voltage, and minimum plate current.

When the oscillator is loaded, oscillations commence at a slightly lower capacity setting than in the unloaded case; that is more feed-back is needed to cause oscillations to begin. Since the impedance of the loaded tank is lower than in the case without load, the minimum plate current is considerably higher than without load. Thus the d.c. plate input to the tubes rises as the power consumption in the tank and load increases. For the same reason the r.f. plate and grid voltages are lower than in the unloaded case, and the maxima are fairly broad as compared to the solid curves. This shows the result of lowering the Q of the tank circuit by loading; the selectivity of the tank is decreased to such an extent that the sharp humps are smoothed down, and the double-hump effects observed in the case of the plate current and the r.f. plate voltage disappear completely. With these modifications, the operation is similar to that without load.

To compare the operation of a triode with that of the pentode, substitute a 6J5 for the 6F6 (the 6J5 will fit in the same socket and no circuit changes are necessary) and repeat the procedure described above for the pentode. Plot a second set of curves in the same manner. A typical set for a 6J5 is shown in Fig. 3. Note that the double-hump effects are not present with this tube in the unloaded case; this is because the effective Q of the tank circuit is lower since it is shunted by the comparatively low plate resistance of the triode, whereas the plate resistance of the pentode is so high that the selectivity of the tank circuit is affected very little. The no-load curves for the triode resemble in shape, although not in amplitude, the load curves for the pentode. The effect of loading is similar in both cases. Once the oscillator tuning is well on the high frequency side of resonance the voltages and currents are about the same with or without load, illustrating that the effect of loading a tuned circuit is largely confined to the region near resonance.

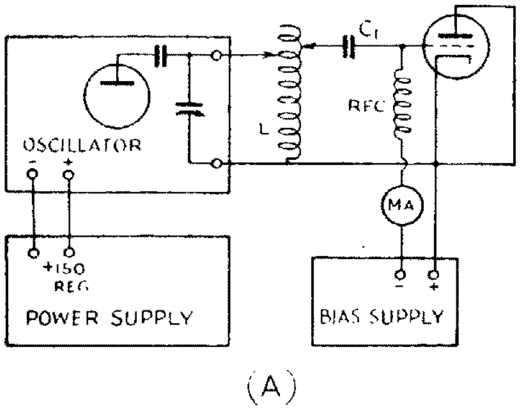
Near minimum capacity on the tuning condenser the r.f. output voltage rises, although neither the plate current nor r.f. grid voltage show any particular change. The reason for this is that the plate circuit is nearing resonance at the second harmonic of the crystal frequency, with the result that the impedance for the second-harmonic component of the plate current is increasing, hence a larger voltage appears across the tank circuit. The effect is also present, although not so marked, in the pentode curve for r.f. plate voltage.

EXPERIMENT 28

Interstage Coupling

Apparatus: This experiment requires the crystal oscillator, power supply, bias supply, tube board and test instrument. The circuit arrangement is shown in Fig. 4. Power for the oscillator is taken from the 150-volt regulated tap on the power supply so that the plate voltage will stay constant as the r.f. power taken from the oscillator is varied. (Should the regulator tube cease to glow at any time during the experiment, the dropping resistor in the power supply in series with the VR-150-30 should be decreased in value until the tube glows under all conditions. The 10,000-ohm resistor recommended in Fig. 3, page 28, Part 3, may be shunted by a 15,000-ohm unit to accomplish this.)

The coil L is the movable coil from the circuit board. C_1 is a small fixed mica condenser; a capacity of 100 $\mu\mu$fd. is satisfactory, but larger values may be used without affecting the results of the experiment. *RFC* is a 2.5-millihenry choke coil and C_2 is one of the tuning condensers (250 $\mu\mu$fd.) on the circuit board. The tube used in the experiment should be a 6J5 or 6C5.



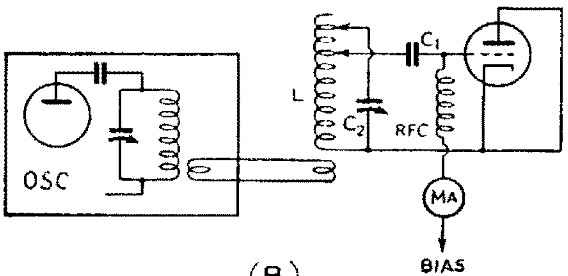


Fig. 4

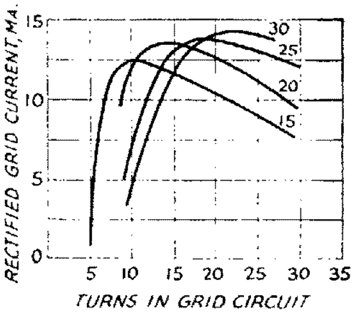


Fig. 5

Procedure: Capacity coupling may be checked by means of the set-up shown in Fig. 4-A. The plug-in tank coil is removed from the oscillator and the coil L is connected across the tank condenser in its place, using a clip connection at the ungrounded end so that the number of turns can be varied. The coil is set up on the tube board near the tube socket and connected to the tube as shown. The plate of the tube is connected to the cathode to prevent its acquiring a charge by collecting stray electrons. The bias should be adjusted to about 50 volts.

Connect the two clips to the end of the coil, putting all 35 turns in circuit, and rotate the oscillator tank condenser to obtain oscillation. It will be helpful to monitor the oscillator by a receiver set to the crystal frequency. The shunting capacity of the tube, together with the large inductance, may make it impossible to set the circuit to resonance with the crystal so if oscillation does not take place move the taps down to 30 turns and try again. Using the equipment previously described, 30 turns was the maximum number permissible with this circuit and a crystal having a frequency of about 3550 kc. When the largest usable value of inductance has been found, leave the oscillator plate tap set and take grid current readings as the grid clip is moved down one tap at a time. Each time the tap is changed, readjust the oscillator plate condenser to obtain maximum grid current. Then move the oscillator plate clip down one tap (5 turns) toward the ground or cathode end of the coil and repeat, starting at the end of the coil with the grid tap. Move the plate tap down another 5 turns and repeat, continuing in this way until the plate tap is carried down at least to the 15th turn from the bottom end of the coil. The data so obtained may then be plotted in the form of curves showing the relationship between rectified grid current and number of turns included in the grid circuit of the tube.

A typical set of such curves, taken with a 6J5, is shown in Fig. 5. The number on each curve indicates the number of turns in use in the oscillator plate circuit.

Note that maximum output (maximum rectified grid current) is obtained when the grid tap includes fewer turns than are in use in the oscillator plate circuit. If the curves are inspected carefully it will be found that maximum current occurs when the grid circuit has approximately 70 per cent as many turns as the oscillator plate circuit, in each case. This indicates that the load represented by the grid-cathode circuit of the 6J5 has a lower value of resistance than the value required by the oscillator tube for maximum output. The tapped coil is thus used as an autotransformer for the purpose of transforming the actual load resistance into the value required by the tube. Since practically the same turns ratio is required in each case the operation is evidently quite independent of the constants of the tuned circuit. Actually, the maximum rectified current obtainable decreases as the number of turns in the plate circuit of the oscillator is made smaller. This is because the decreasing L/C ratio is accompanied by an increase in the r.f. current circulating in the tank (the Q of the loaded circuit is raised) causing the internal losses of the tank circuit to increase. Hence a somewhat smaller proportion of the power developed by the oscillator tube is available for the load. If the L/C ratio could be decreased without increasing the tank losses the output current would be the same in each case. In the experimental set-up some of the loss undoubtedly is "dead-end" loss in the unused turns of the coil, caused by current circulating through the distributed capacity of the unused turns.

The effect of a change in load impedance can be observed by changing the bias on the tube and following the experimental procedure just described. As the bias is increased the impedance of the grid-cathode circuit increases, since a considerably larger r.f. grid voltage must be applied to overcome the bias and cause the same or less grid current to flow. The curves of Fig. 6 show the results of such a run, using four different values

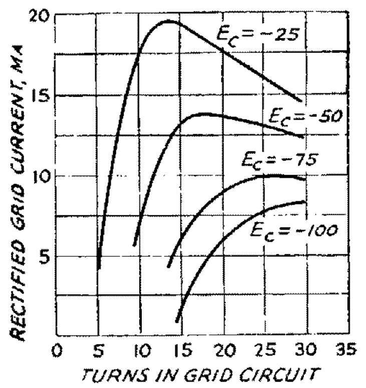


Fig. 6

of negative grid bias, 25, 50, 75 and 100 volts. In all four cases the oscillator plate was tapped on the coil at the 25th turn. At the highest bias, 100 volts, the grid current is just reaching maximum with 30 turns in the grid circuit; that is, a step-up impedance ratio is required, showing that the grid impedance is higher than the value required by the oscillator tube for maximum output. With 75 volts bias the maximum current is secured with the same number of turns in the grid circuit as in the plate circuit. The curve for $E_C = -50$ is simply a repetition of the corresponding curve

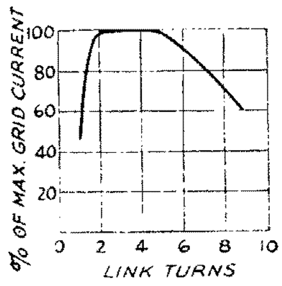


Fig. 7

in Fig. 5. With −25 volts bias the grid circuit must be tapped across approximately half the number of turns used in the plate circuit, indicating that the impedance has decreased very considerably. The resistance (or impedance) of the grid circuit therefore depends not only on the characteristics of the tube but also on the conditions under which it is operated. If the tube had been actually operating as an amplifier, still different conditions would obtain and the curves would show maximum points at different turn ratios than those indicated. In such a case the effect of the plate voltage would be to attract some of the electrons which in the experimental set-up are drawn to the grid, and this would tend to reduce the grid current and thus raise the grid impedance, since less current would flow for the same applied r.f. grid voltage.

In the second part of the experiment link coupling is investigated. The circuit arrangement is shown in Fig. 4-B. The regular plug-in tank coil is returned to the oscillator circuit, and is provided with an output link winding of three turns or so wound close to the "ground" end of the coil. The coil L is connected to C_2, one of the variable condensers on the circuit board, as shown. As a preliminary experiment, wind about 10 turns at the ground end of L, and connect C_2 and the grid tap to the other end of the coil so that the full 35 turns are used. Using about 50 volts bias, adjust C_2 and the oscillator tank condenser for maximum rectified grid current. There may be some interaction between the two condensers, so "rock" C_2 back and forth while adjusting the oscillator tank condenser until it is certain that maximum output is secured. Take one turn off the link and again adjust for maximum grid current; continue in this way until only one link turn is left. The result of such an experimental procedure is shown in Fig. 7, where the number of link turns on L is plotted against grid current in terms of percentage of the maximum current obtainable. Note that there is a broad maximum to the curve, the output showing negligible variation with links having from 2 to 5 turns. The value for one turn is probably low, since the turn was not held very tightly to the coil form. Obviously the number of turns is not critical. The maximum output is in the region where the link has enough turns to give a sufficiently-high coefficient of coupling without having enough reactance to limit the flow of r.f. current in the link circuit.

Using a link of about three turns on L, set the tap from C_2 at the end of the coil (35 turns) and tap the grid on the same spot. Adjust C_2 and the oscillator plate condenser for maximum grid current, then move the grid clip down one tap (30 turns) and again adjust the two condensers for maximum grid current. Continue moving the grid clip down the coil. As the tap approaches the bottom end the loading on the oscillator increases and may cause the oscillator to stop. The best procedure is to keep the oscillator tank condenser well on the low-capacity side of resonance, then rock C_2 back and forth through resonance while carefully increasing the oscillator condenser capacity until it is set just below the point where oscillation ceases when C_2 goes through resonance. (Monitoring the oscillator in a receiver will be helpful.) This point usually will result in maximum output. When the run is completed, move the clip from C_2 down one tap and repeat. Continue until the tap from C_2 has been moved down to the 15th or 20th turn. Plot the data in the same way as in the case of capacity coupling.

A set of experimental data so obtained is shown graphically in Fig. 8. The tube and grid bias were the same as in Fig. 5. There is quite a marked difference between these curves and those of Fig. 5, showing that more than simple autotransformer action is involved. Maximum grid current is secured with approximately the same number of turns between grid and cathode in all four cases shown (the numbers on the curves indicate the number of turns across which C_2 is connected). This is because in the link-coupled case — link coupling is equivalent to inductive coupling — the coupling depends very largely on the effective Q of the secondary circuit, the constants of the primary circuit being fixed. With a fixed value of load resistance, represented by the grid circuit of the tube, the Q of the circuit depends on the L/C ratio and/or the ratio of turns in the tuned circuit to turns in the load (grid-cathode) circuit. Using 35 turns in the tuned circuit, maximum output is

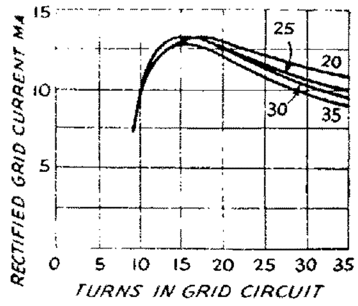


Fig. 8

secured with about 15 turns in the grid or load circuit, illustrating the increase in effective Q — and hence increase in coupling to the primary — afforded by tapping the load down on the coil. A similar effect is observed with smaller numbers of turns in the tuned circuit, until with C_2 across 20 turns maximum output also is secured with 20 turns in the grid circuit. In this case the Q has been raised to the value required for optimum coupling solely by reducing the L/C ratio, whereas in the 35-turn case the same effect was secured by tapping down. With 35 turns across C_2 and 35 turns also in the grid circuit, the maximum grid current is about 9 milliamperes. This is the value represented by "100%" in Fig. 7, and is the maximum obtainable with *any* number of link turns with this circuit and loading. Hence adjustment of the link turns alone cannot result in maximum energy transfer unless the effective Q of the circuit is high enough to provide optimum coupling. If the Q is too low, it must be increased either by tapping the load down on the coil or by decreasing the L/C ratio; unless this is done, maximum output cannot be secured.

Note that the maximum grid current obtainable with link coupling is less than with capacity coupling. The difference is attributable to the additional losses in the second tuned circuit used in link coupling. Other considerations, such as the effect of too-high shunt capacity, may result in a reversal of this situation at higher frequencies, but at the frequency used in this experiment (3550 kc.) these effects are negligible.

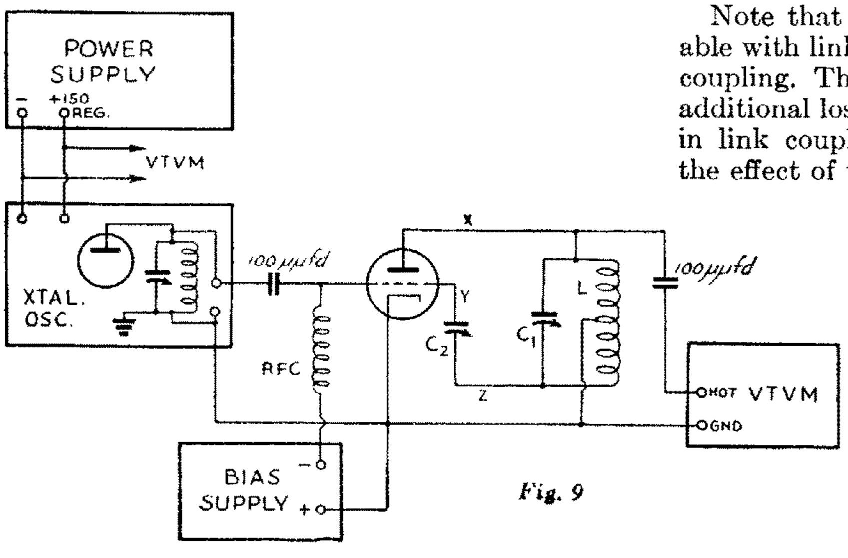


Fig. 9

EXPERIMENT 29

Neutralizing an Amplifier

Apparatus: The set-up for this experiment is shown in Fig. 9. Equipment required includes the power supply, bias supply, crystal oscillator, vacuum-tube voltmeter, tube board, circuit board, and test instrument. The tube used is a 6J5 or similar small triode. The coil L is the fixed coil on the circuit board and condenser C_1 is the variable condenser associated with that coil. C_1 should be connected across 30 turns of L, with the tap to ground placed at the 15th turn on the coil. C_2 is the small condenser (25 to 50 $\mu\mu$fd. maximum capacity) on the circuit board. The 100-$\mu\mu$fd. condensers are small fixed mica units. RFC is a 2.5-millihenry r.f. choke.

The connections "X," "Y" and "Z" preferably should be flexible leads with clips at both ends so that they can be connected and disconnected conveniently. The crystal oscillator plate voltage can be taken from the 150-volt regulated tap on the plate power supply. The bias on the tube under test should be set to about 75 volts.

Procedure: This experiment is an exercise in neutralizing an r.f. amplifier. Connect the circuit as shown, omitting for the moment the leads "X," "Y" and "Z." Set the crystal oscillator in operation and, with the turned circuit LC_1 in about the position it will occupy (near the tube), tune C_1 for maximum deflection on the v.t. voltmeter. If the deflection is more than a flicker on the low range, move the tuned circuit as far as possible from the oscillator, while still keeping within reasonable distance of the tube so that long connecting leads will not be necessary. It should be possible to get the v.t.v.m. reading down to less than 1 volt without much difficulty. When this has been done, connect the leads "X," "Y" and "Z," set C_2 to minimum capacity, put the v.t.v.m. on the high range, and adjust C_1 for maximum v.t.v.m. deflection. Increase the capacity of C_2 slightly and again tune C_1 for maximum deflection. Continue this process, observing that the deflection decreases as the capacity of C_2 increases, until a point is reached where an increase in capacity causes the deflection to increase again. The setting of C_2 which gives minimum output voltage is that at which the tube is neutralized as well as the circuit conditions will permit. In most cases it will not be possible to adjust the circuit so that the r.f. voltage disappears completely from the plate circuit, but it should be possible to get it down to around half scale on the low range of the v.t.v.m.

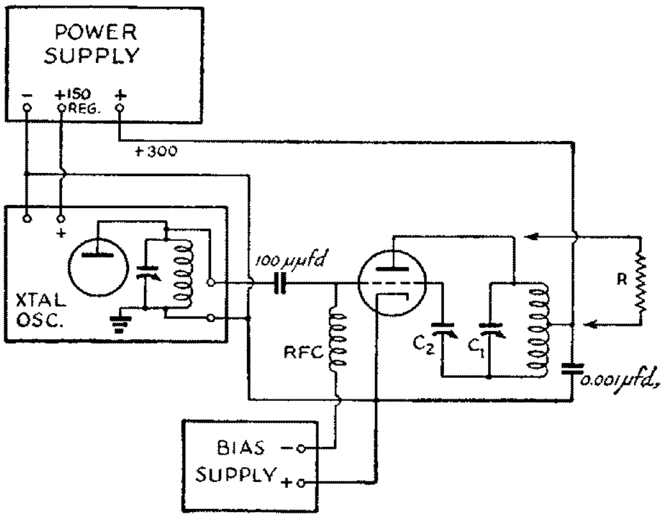


Fig. 10

It will be observed that hand-capacity effects are quite evident in adjusting both condensers. This is partly because the hand adds a small amount of capacity which detunes the circuit, since the shafts of both condensers are above ground for r.f., and partly because the body picks up some r.f. voltage from the oscillator and couples it to the circuit when the hand is brought near either condenser. This effect can be eliminated by dispensing with the ordinary tuning knobs and, instead, sawing slots in the ends of the condenser shafts, the condensers then being turned by means of an 8- or 10-inch length of wooden rod (any other insulating material will do) cut at one end to fit the slots.

Connect the test instrument as a milliammeter in series with the grid-bias lead to the amplifier and repeat the experiment, using grid-current as a neutralizing indicator. Disconnect the v.t.v.m. in this case. Adjust the neutralizing condenser, C_2, so that there is least change in rectified grid current as C_1 is tuned through resonance. It should be possible to neutralize well enough so that there is the barest flicker, or none at all, in grid current. How does this method compare in sensitivity with the v.t.v.m. method?

EXPERIMENT 30

Class-C Amplifier Operation

Apparatus: This experiment uses the apparatus set-up shown in Fig. 10. It resembles quite closely the circuit used in the preceding experiment except that provision is made for applying plate voltage to the amplifier tube and for connecting a load resistance in the plate circuit. The 0.001-μfd. blocking condenser in the plate circuit replaces the direct ground used in Exp. 29; this is necessary to prevent short-circuiting the plate-supply voltage. The crystal oscillator again gets its plate power from the 150-volt regulated tap on the power supply.

Procedure: The object of this experiment is to observe the behavior of a Class-C amplifier under different load conditions. A small tube such as a 6J5 will be suitable. Set the variable resistor on the power supply so that only the bleeder current flows through it (arm to the left end in Fig. 3, page 28, Part 3) since the current drawn will exceed a safe value for this resistor. The plate voltage for the amplifier may be adjusted to a suitable value by tapping the output clip on the divider at a point which gives 250 to 300 volts.

With the amplifier plate voltage tap disconnected, neutralize the amplifier by the grid-current method described in the preceding experiment. Set the bias at 30 volts so that the tube is biased well beyond the cut-off point for that plate voltage. With the 6J5 cut-off bias is approximately 15 volts, neglecting the "tailing-off" effect associated with the change in amplification factor near the cut-off point (see Exp. 22). Although the plate current may not actually reach zero until the bias is 20 volts or more, the plate current in the region between the cut-off bias calculated on the assumption that the amplification factor is constant (E_b/μ, in this case 300/20) and the actual cut-off point is so small that its influence on the operation of the tube as a Class-C amplifier is practically negligible. Adjust the oscillator tuning so that the grid current is approximately 10 milliamperes with no plate voltage on the amplifier.

After neutralization, apply plate voltage and measure the amplifier plate current. If the tank circuit is not set at resonance with the crystal oscillator frequency the plate current probably will be in the vicinity of 30 milliamperes. Carefully tune the amplifier tank circuit, observing that at resonance the plate current drops to a comparatively low value — well below 10 milliamperes. The resonance point should be quite sharp. The plate current is minimum at resonance because at this point the impedance of the tank circuit is highest to r.f. current of the frequency generated by the crystal oscillator, and tuning to resonance is equivalent to connecting a high value of load resistance in series with the amplifier plate circuit. Hence there is a large r.f. voltage drop in the tank circuit and the average voltage acting to cause plate current to flow is reduced. The d.c. plate current is likewise reduced. When the tank circuit is off resonance its impedance to the crystal frequency is low and the r.f. voltage drop is negligible, hence practically the full d.c. plate voltage is continuously applied to the tube and the plate current is high. It is higher than in Class-A applications because the r.f. grid voltage drives the grid considerably positive with respect to the cathode over a part of the r.f. cycle. The variation in r.f. tank voltage can be observed by touching a neon bulb to one side of the tank condenser. The bulb will glow brightly when the tank is tuned to resonance but goes out when the condenser is detuned.

Note also that the grid current drops when the plate voltage is applied to the amplifier. When there is plate voltage on the tube some of the electrons which formerly were attracted to the grid go to the plate instead. The number thus diverted depends upon the effective plate voltage, which in turn depends upon the tuning of the tank circuit for the reasons mentioned above. With the tank circuit tuned to resonance the drop in grid current is slight, but if the tank is detuned the grid current may drop to as little as half its value with the plate voltage off.

Connect a 25,000-ohm 1-watt resistor between the plate of the tube and the positive plate voltage lead as shown at *R* in Fig. 10. Apply plate voltage and observe the plate current as the plate tank circuit is tuned through resonance, leaving the excitation the same as before — that is, adjusted to give a rectified grid current of about 10 ma. with no plate voltage on the amplifier. In this case the resonance point will not be quite as sharp and the minimum plate current will be higher than without load. Note that the off-resonance plate current is the same as before, showing that the off-resonance impedance of the tank circuit is so low that the presence of the load resistor does not affect it. At resonance, however, the tank impedance is reduced by the load resistor and the r.f. voltage drop consequently is less. Hence the average plate voltage causing plate current flow is higher and the plate current also is higher. The grid current also shows a greater drop, at resonance, with the load resistor connected, again because the effective plate voltage is higher and more electrons are diverted from the grid to the plate.

The same procedure should be followed with 10,000- and 5000-ohm 1-watt resistors as loads, when it will be found that the greater the loading, i.e., the lower the load resistance, the higher the plate current and the lower the grid current. As the load resistance progressively decreases the tank impedance also decreases, resulting in a lower r.f. voltage drop and consequently higher average plate voltage during the part of the cycle when plate current flows. If the tank circuit is detuned off resonance, however, the presence of the load resistor has relatively little effect on the impedance and the off-resonance conditions are practically the same regardless of load resistance.

Observations on Class-C amplifiers can be carried farther by using the v.t. voltmeter to measure the r.f. output voltage. For this purpose the voltmeter may be connected to the plate circuit as shown in Fig. 9, using a very small value of coupling capacity so that the indication will come on the medium range of the v.t.v.m. If care is taken not to disturb the v.t.v.m. position or leads when changing load resistors, the relative variation of r.f. tank voltage with changes in load can be measured. It is also of interest, with a fixed value of load resistance, to measure the variation in r.f. tank or output voltage as the excitation is changed; the rectified grid current can be used as a measure of the excitation. Since power output is proportional to the square of the voltage, a series of such observations can be plotted in terms of power output vs. grid current, for a fixed load resistance and grid bias.

Part Six

MODULATION AND KEYING

THIS section deals with various methods for modulating a radio-frequency carrier. The experimental work consists in determining the modulation characteristics of r.f. amplifiers, using the point-by-point method, under different conditions of operation. The influence of various factors on the linearity of a modulated amplifier is the chief subject investigated.

Contrary to what might be anticipated, the experiments outlined do not involve actual modulation of a carrier. Unless an oscilloscope is available for depicting actual operation with modulation, the use of a modulating signal would add comparatively little to the instructional value of the experiments. Those who do have an oscilloscope and an audio amplifier suitable for modulating the experimental amplifiers can, of course, extend the work. The obvious direction for such an extension to take is in comparing oscilloscope patterns with the performance curves obtained as described in the experiments.

ASSIGNMENT 20

Study *Handbook* Sections 5–1, 5–2 and 5–3. Perform Exps. 31 and 32.

Questions

1) What is meant by the term "modulation"?

2) What is the function of the microphone in a radiotelephone system?

3) Name the three fundamental methods of modulating a radio-frequency current.

4) What is the "carrier"?

5) In present-day practice, what requirements must be met by the carrier in radiotelephone transmission on communication frequencies?

6) Why is a "buffer" amplifier necessary?

7) Define percentage of modulation.

8) What is meant by "linearity" of a modulated amplifier?

9) Define modulation capability.

10) An unmodulated carrier produces a current of 2.5 amperes in an antenna system. When modulation is applied it is found that the maximum instantaneous amplitude of the current is 4.3 amperes. What is the percentage of modulation, assuming that the modulated amplifier is linear?

11) What is the ratio of average power in a 100 per cent amplitude-modulated wave to the power in the carrier alone, assuming sinusoidal modulation?

12) What is meant by the term "modulation envelope"?

13) What are sidebands?

14) If the modulation applied to a carrier is unsymmetrical, how should the modulation percentage be computed?

15) Describe overmodulation. Why should overmodulation be avoided?

16) A 3900-kc. carrier is modulated by a sinusoidal signal having a frequency of 1600 cycles. What are the sideband frequencies?

17) The audio-frequency output of the modulator of a certain radiotelephone transmitter contains substantially no audio frequencies higher than 4200 cycles. What channel width is required for the modulated output of the transmitter?

18) A transmitter is modulated by a 1000-cycle tone which has pronounced harmonics up to the fifth. If the carrier frequency is 28,650 kc., what are the frequency limits of the channel occupied by the signal?

19) What are spurious sidebands?

20) Name three systems used for amplitude modulation.

21) What is the average ratio of power in speech waveforms to power in a sine wave? How does this affect the required power capacity of the modulator, when plate modulation is used?

22) Define modulating impedance of a Class-C plate-modulated amplifier.

23) A Class-C amplifier is operating at a plate voltage of 2000 and is adjusted so that the plate current is 150 milliamperes. How much audio power is required for plate modulation of the amplifier, for a modulation percentage of 100, assuming that the modulating signal is sinusoidal?

24) What is the modulating impedance of the amplifier in Question 23?

25) Draw a circuit diagram showing plate modulation of a neutralized triode Class-C amplifier, using a Class-B modulator.

26) An amplifier having an audio-frequency power output of 130 watts is available for plate modulating a transmitter. If the modulation is to be 100 per cent, what is the maximum possible power input to the Class-C modulated amplifier?

27) How can the power input to a Class-C

plate-modulated amplifier be adjusted to the proper value for 100 per cent modulation?

28) How may plate modulation be applied to a tetrode or pentode Class-C amplifier? Draw a circuit diagram.

29) Describe the method of using choke coupling between the modulator and modulated amplifier. Why is this system seldom used?

30) Does the d.c. plate current of a properly-operating Class-C amplifier change when the amplifier is plate modulated? Why?

31) A screen-grid Class-C plate-modulated amplifier operates under the following conditions; plate voltage, 2500 volts; plate current, 125 ma.; screen voltage, 400 volts; screen current, 30 ma. If the screen current is to be taken from the plate supply, what value of screen dropping resistor is required, and what is the modulating impedance of the amplifier? How much audio power is necessary for 100 per cent modulation?

32) Why is it necessary to neutralize a triode amplifier as completely as possible when the amplifier is to be modulated?

33) Describe the general operating conditions necessary if a Class-C amplifier is to have a linear modulation characteristic.

ASSIGNMENT 21

Study *Handbook* Sections 5-4 and 5–5. Perform Exp. 33.

Questions

1) What are the advantages and disadvantages of grid-bias modulation as compared with plate modulation?

2) Describe the essential principles of the grid-bias modulation system.

3) Why should the source of fixed bias used with a grid-bias modulated amplifier have low internal resistance?

4) A tube having a rated plate dissipation of 80 watts is to be used as a grid-bias modulated amplifier. What is the approximate carrier power output obtainable? How much power could be secured from the same tube if plate modulation was used?

5) In a grid-bias modulated amplifier, what is the effect on linearity of adjusting for too-high carrier efficiency?

6) Draw a circuit diagram of a Class-C amplifier arranged for grid-bias modulation.

7) Describe the operating principles of suppressor-grid modulation. How does this method compare with grid-bias modulation?

8) Why is it necessary that the r.f. stage driving a grid-bias modulated amplifier have good output-voltage regulation? How can good regulation be secured?

9) Describe a method of adjusting a grid-bias modulated amplifier for proper operating conditions.

10) Why should the d.c. plate current of a properly-operated grid-bias modulated amplifier be constant under modulation? What is the permissible tolerance in this respect? Is constant plate current a certain indication that the amplifier is operating linearly?

11) What is the effect of load resistance on the carrier power output obtainable from a grid-bias modulated amplifier, assuming that the amplifier is adjusted for linear operation?

12) What is the effect of excitation voltage on the linearity of a grid-bias modulated amplifier, assuming that load resistance, d.c. grid-bias voltage, etc., are fixed?

13) Explain the operating principles of cathode modulation.

14) Two tubes each having a plate dissipation rating of 60 watts are to be used in push-pull as a cathode-modulated amplifier. If a modulator having an audio-frequency power output of 80 watts is available, what is the maximum carrier output power obtainable if the modulation percentage is to be 100 per cent? If the plate voltage on the modulated amplifier is 1500, what is the modulating impedance?

15) How should a cathode-modulated amplifier be adjusted for linear operation?

ASSIGNMENT 22

Study *Handbook* Sections 5–6, 5–7, 5–8 and 5–9.

Questions

1) Why is a Class-B type audio amplifier generally used for plate modulation of a Class-C amplifier?

2) Why is it necessary to have good regulation of the output voltage of the stage driving a Class-B amplifier?

3) What design precautions should be taken to ensure good output voltage regulation of the driver stage?

4) A Class-C amplifier taking a plate current of 180 ma. at a plate voltage of 1250 is to be plate modulated. How much audio-frequency power is required? If the Class-B modulator requires a plate-to-plate load of 10,000 ohms, what is the proper turns ratio of the coupling transformer, assuming that the transformer losses are negligible?

5) Why is it necessary to use a voltage source having low internal resistance to supply grid bias for a Class-B amplifier?

6) Is it safe to operate a Class-B modulator without load?

7) What is the result of overdriving a Class-B modulator?

8) What requirements should be met by the plate supply for a Class-B modulator?

9) What is meant by the terms "sensitivity" and "frequency response" when used in connection with microphones?

10) Describe the principle of operation of four

types of microphones and show suitable circuits for connecting them to an amplifier.

11) About what order of output voltage can be expected from a crystal microphone under normal conditions — that is, speech of average intensity — from single-button carbon, double-button carbon, and velocity microphones, when provided with appropriate coupling transformers?

12) What is meant by "stage gain"?

13) What is the general function of a speech amplifier in a modulation system?

14) Why is resistance coupling generally used in voltage-amplifier stages? Under what conditions is resistance coupling inapplicable?

15) What determines the frequency response characteristic of a resistance-coupled amplifier? Over what frequency range is it necessary to have "flat" amplification for satisfactory speech transmission?

16) What is a decoupling circuit, and why is it used?

17) What considerations determine the point in the circuit at which the gain control is placed?

18) An amplifier is to deliver an audio power output of 2 watts when excited by a crystal microphone having a peak output voltage of 0.02 volts with normal speech. Using the tube characteristic tables and the data in Table I (§ 5-9) of the *Handbook*, select a suitable tube line-up and draw a circuit diagram, marking proper values on the components. Indicate proper plate voltages on the circuit diagram.

19) Describe the operation of a phase inverter. For what purpose is such a circuit used?

20) What precautions should be taken to minimize hum in a speech amplifier?

ASSIGNMENT 23

Study *Handbook* Section 5-10. If an oscilloscope is available, use it in conjunction with Exps. 31, 32 and 33, making connections as described in the *Handbook*. Compare the oscilloscope patterns with the data obtained by measurement and plotted graphically. A suitable modulating voltage must be available for this purpose; 60-cycle a.c. will be quite satisfactory if the voltage can be adjusted to the proper value. A transformer having suitable turns ratio should be used between the modulated amplifier and the 115-volt a.c. line.

Questions

1) What is the difference between the "wave-envelope" and "trapezoidal" patterns used in checking modulation?

2) What connections are necessary between the transmitter and oscilloscope to obtain the wave-envelope pattern?

3) Show a method of connecting the oscilloscope and transmitter for securing a wedge pattern. What precautions are necessary in making these connections?

4) How can percentage of modulation be measured with the oscilloscope?

5) If the voice waveform is found to be unsymmetrical, what can be done in the speech amplifier to insure that "splatter," or spurious sidebands, will be minimized on occasional voice peaks which cause overmodulation?

6) Why is it frequently desirable to connect a tuned circuit to the vertical-plate terminals of the oscilloscope, coupling through a link circuit to the transmitter?

7) In using the wedge pattern, from what part of the audio system should the audio voltage for the horizontal sweep be taken?

8) How can the oscilloscope be used to check the linearity of a 'phone transmitter? Which type of pattern is preferable?

9) If indications of a carrier appear on the oscilloscope screen when the plate current of the modulated amplifier is completely cut off but the transmitter is otherwise operating, what are the possible causes?

10) What is the effect on the modulation pattern of the presence of a radio-frequency voltage on the horizontal plates of the oscilloscope? What can be done to prevent such a voltage from reaching the horizontal plates?

11) Describe a method of checking for spurious sidebands.

12) Name some possible causes for an upward shift in plate current with plate modulation; with grid-bias modulation.

13) If the carrier is found to have excessive hum modulation, how can the cause of the hum be localized?

14) What is the common indication of the presence of r.f. in the audio system? What precautions are necessary to prevent such r.f. pickup?

15) Name some possible causes of a downward shift in plate current with plate modulation; with grid-bias modulation.

ASSIGNMENT 24

Study *Handbook* Sections 5-11 and 5-12. Perform Exp. 34.

Questions

1) How does frequency modulation differ from amplitude modulation?

2) Define frequency deviation and deviation ratio.

3) In what two respects does frequency modulation have distinct advantages over amplitude modulation? What is the chief disadvantage of frequency modulation from a practical communication standpoint?

4) Explain why a large deviation ratio gives an improvement in signal-to-noise ratio as compared to a low deviation ratio.

5) Why is a frequency modulation system less sensitive to natural static and other electrical noises than an amplitude modulation system?