The Rocking-Armature Receiver

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A new receiver inset (No. 4T) is described. It has been developed, using the rocking-armature principle, to give substantial improvements in sensitivity and frequency response compared with previous Post Office standard receivers, and it has been embodied in the new Post Office standard telephone (700-type) which will be described in a future article in this Journal.

Introduction

IN 1950 the Post Office drew up, for the guidance of the telephone manufacturers, a target specification for a more sensitive receiver which would be suitable for inclusion in a projected new telephone. The specification called for a flat sensitivity/frequency response over the range 200-3,400 c/s and removed a maximum limit on the sensitivity of new receivers which had earlier been imposed. This limit was removed because it was realized that sensitivity in excess of that required for purely receiving considerations could be usefully employed in a new telephone to improve sending efficiency by change of the Y ratio of the induction coil.[1] Such exchange of efficiency could be made to give balanced increases in sending and receiving efficiencies, even though a more sensitive transmitter were not available. A balanced increase in efficiencies is essential to obtain economic advantages from the use of a new telephone in the Post Office network.

Standard Telephones and Cables, Ltd., who had already carried out some exploratory work, undertook the development of the new receiver and produced a design which differs greatly from receivers previously used in telephones, employing what has come to be known as the "Rocking-Armature" form of construction. The conventional form of construction for telephone receivers, using a magnetic diaphragm, was abandoned in the design of the new receiver because it was found that little increase of sensitivity was possible even when the most modern materials and manufacturing methods were used. The rocking-armature type of construction uses a bi-polar form of balanced magnetic system giving high sensitivity with simplicity of construction and stability; it derives its name from the fact that the armature rocks, or pivots, on a fulcrum resting on the magnet, which supports it.

When the receiver was designed it was realized that there would be considerable maintenance advantages in changing to a capsule type of construction from the open construction of existing receivers such as the No. 2P Receiver Inset. This open construction, with removable diaphragm, is liable to changes of sensitivity and the collection of dirt at the magnetic air gaps whenever the receiver is opened.

This article describes specifically the No. 4T Receiver Inset, which will be used in the 700-type telephone, to be described in a subsequent issue of this Journal. The same physical design of receiver, wound to different impedances, will find other applications in the Post Office, while a miniaturized version forms part of a lightweight headset for operators, at present under development.

Fundamental Factors in the Receiver Design

Before describing the constructional features of the receiver, the basic factors underlying the design will be reviewed.

The Magnetic Circuit.

In the present 2P Receiver Inset and similar receivers, the magnetic diaphragm has to perform a dual function in which both its magnetic and acoustical properties are used; since these conflict in their requirements for highest sensitivity of the receiver, a compromise has to be effected. It was considered important, in the new receiver, to separate these two functions, so the magnetic function is confined to the rocking armature, while the acoustical function is confined to a light flared diaphragm of high effective area coupled to the armature. Fig. 1 and 2 show schematically in elevation the basic elements of the 2P Receiver Inset and the Rocking-Armature Receiver.

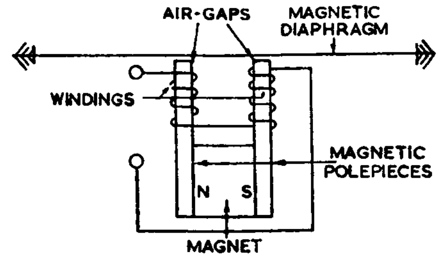

Fig. 1.—Basic Elements of 2P Receiver Inset.

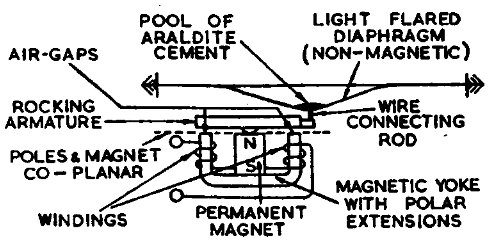

Fig. 2.—Basic Elements of Rocking-Armature Receiver.

Again, in the 2P Receiver Inset and many similar receivers, the high reluctance of the permanent magnet is arranged in series with the alternating flux circuit; this further limits the magnetic sensitivity that can be achieved with such designs. In the new receiver a balanced bridge type of magnetic circuit was chosen in which the permanent magnet is so "bridged" across the alternating flux circuit that its reluctance is excluded therefrom.

The magnetic circuits shown in Fig. 3(*a*) and 4(*a*) together with the analogous electrical networks shown in

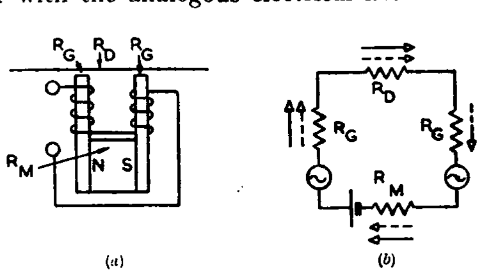

Fig. 3.—Magnetic Circuit and Analogous Electrical Network of 2P Receiver Inset.

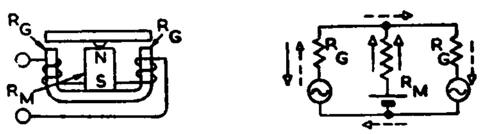

Fig. 4.—Magnetic Circuit and Analogous Electrical Network of Rocking-Armature Receiver.

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[1] H. J. C. Spencer. Some Principles of Anti-Side-Tone Telephone Circuits, *P.O.E.E.J.*, Vol. 48, p. 208, Jan. 1956.

3(b) and **4**(b) make clear these differences between the two designs. In these analogous electrical networks, the magnetic reluctances are represented by electrical resistances, the magnets by d.c. batteries and the windings by sources of a.c. The direct and alternating fluxes of the magnetic circuits are represented by the direct and alternating currents (denoted by the full and broken arrows respectively in Fig. **3**(b) and **4**(b)). It will be noted, in Fig. **3**(a) and **3**(b) for Inset 2P, that whereas the reluctances of the pole-pieces have been omitted, being negligible, it has been necessary to include the diaphragm reluctance R_D which is far from negligible because of the compromise already mentioned. In Fig. **4**(a) and **4**(b) for Inset 4T, on the other hand, only the gap reluctances R_G are shown, because both armature and yoke reluctances can be made small in comparison. It will at once be apparent that the latter design, which has no swamping reluctances in series with the gap reluctances, offers a much greater reward for reduction of the air-gaps to the minimum consistent with requirements of stability, and control in manufacture.

One of the aims of the rocking-armature receiver design was to achieve this reduction of air-gaps while meeting the other requirements.

Control of Air-Gaps.

The two-pole balanced magnetic circuit of the rocking-armature driving system was chosen, in preference to the more usual four-pole balanced magnetic circuit of other receivers, because of its simplicity, leading to much easier control of the small air-gaps in manufacture.

Thus, the length of the two air-gaps of the receiver depends on two manufacturing operations only, both of which are capable of very close control. Firstly, a ridge which forms the fulcrum of the rocking armature is swaged or "coined" upon one of its faces (see Fig. **5**) and secondly

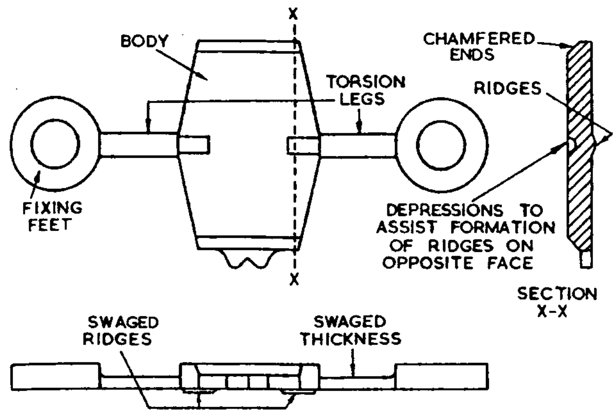


FIG. **5**.—THE ROCKING ARMATURE.

the magnet and yoke assembly is ground across the polar faces into a plane (see Fig. **2**). When the face of the armature is placed parallel to, and with its coined ridge in contact with, the ground plane, the two controlled air-gaps lie between.

In four-pole designs the length of the four gaps depends on the length of the spacers (sometimes the magnet) which separate the two yokes, on the length of their formed pole-pieces, and on the thickness of the armature which lies between them, three dimensions which may vary in production quite widely.

Stability of Rocking Armature.

In balanced magnetic systems, it is important to ensure stability of the armature in the central position of balance, against the high static field force which tends to deflect it further as it is moved off balance towards either of the poles; this high force is of course inseparable from the conditions for high magnetic sensitivity of the receiver. The ratio of this field force to the displacement of the armature at any frequency is generally denoted by s_f, and can be regarded as a negative stiffness because the field force has the opposite sense to a restoring force. Because of hysteresis and eddy current effects the absolute value of the field stiffness falls with increasing frequency, and the maximum value s_{fm} occurs at zero frequency; i.e., the static condition. It is therefore necessary, for static stability, to introduce a correspondingly high, but rather greater, restoring force to the armature.

In the rocking-armature receiver this is done through the torsional stiffness, s_a, of the armature side limbs. The condition for static stability of the armature is that $\int_0^x (s_a + s_{fm})\, dx$ shall be positive for all values of x, the armature displacement from the balance position. However, the preponderance of restoring force must not be too great, or the net positive dynamic stiffness ($s_a + s_f$) of the armature system will become excessive in the range of working frequencies, causing loss of sensitivity. Hence a nice balance must be kept between the restoring stiffness s_a of the armature and the static (negative) field stiffness s_{fm}; this calls for good control of both these stiffnesses. The armature torsional stiffness is controlled by making the side limbs of such large dimensions that their stiffness is not unduly affected by normal manufacturing variations; the closest tolerance required is $\pm 0{\cdot}001$ in. on the thickness of the side limbs, and this thickness is a swaged dimension and therefore largely tool controlled (see Fig. **5**). The field stiffness is largely controlled by the close air-gap control already mentioned, and through a flux adjustment made on the assembled receivers.

In the rocking-armature receiver, the stability under static forces is achieved within the driving system itself, and the diaphragm stiffness which is later added to that of the armature is not essential for this stability.

Further, this added diaphragm stiffness is made as low as practicable compared with the net positive stiffness of the armature under static conditions so that, once the armature air-gaps have been balanced by mechanical adjustment of the side limbs, subsequent slight deflections of the diaphragm which is afterwards connected to it do not appreciably alter the balance.

Sensitivity.

The magnetic sensitivity of electromagnetic receivers can be readily shown to be proportional to the field stiffness, s_f, which equals $B^2/\pi R_a$ where B is the polarizing flux density at the pole tips and R_a is the effective reluctance of the alternating flux circuit to alternating flux. Because of iron saturation, R_a increases rapidly as B is increased beyond a certain limit and the expression B^2/R_a shows a maximum value when plotted against B. To realize the maximum sensitivity in practice, it is necessary to allow for the variations which occur in the properties of the permanent magnets, and, to a less extent, for the variations in air-gaps and pole-piece dimensions. It is therefore necessary to provide a magnet having a sufficient surplus of flux above the optimum value to cover all variations, and then to adjust the flux in a progressive demagnetization process until the maximum sensitivity of the receiver is achieved. In the rocking-armature receiver this process must be applied after adjusting the two airgaps for equality, so that the optimum flux value is realized in both halves of the magnetic circuit individually. If the air-gaps are not balanced, a maximum sensitivity with flux variation can be found, but the value is below that obtained for the balanced condition.

Because of the closer balance between s_a and s_f at lower frequencies (referred to previously) the net positive stiffness $(s_a + s_f)$, by which the receiver sensitivity is judged at low frequencies, is very sensitive to the changes of s_f brought about by flux adjustment. For this reason, when the flux adjustment is made, the sensitivity is tested at a fairly low frequency.

The Drive to the Diaphragm.

High acoustic efficiency is achieved by providing a light diaphragm having the optimum effective area. The diaphragm can be regarded as a transformer linking the mechanical part of the receiver with the acoustical part and the ear. The effective area (about 10 cm²) of the diaphragm employed is correct for matching the mechanical impedance of the receiver to the acoustical impedance, over much of the frequency range, of the receiver. A difficult problem was, how to achieve the true piston motion which would yield such a high effective area without thickening the diaphragm unduly, leading to increased diaphragm mass and flange stiffness.

Centrally driven diaphragms are liable to unwanted modes of vibration, or parasitic oscillation of parts of the diaphragm, unless, in the design, careful attention is given to the shape. Experiments made with various diaphragm shapes led to the conclusion that one having a flared form like a shallow trumpet was less liable to break up into unwanted modes than one having a shape based on pure conical forms. This fact is probably due to the flared shape having curvature in two dimensions, whereas the cone has curvature in only one dimension. A further advantage of the flared trumpet shape is that the stiffness is more nearly constant from the central driving region to the end of the trumpet part of the diaphragm. Thus, starting from the central driving region just outside the solid pool of Araldite cement, the slope of the surface is greatest, giving the greatest stiffening, due to the shape, where the section of material (taken normal to the diaphragm axis) is least; as one moves out to the peripheral flange, the slope decreases, but the increasing section adds to the stiffness.

Because of the rocking motion of the armature its end describes an arc of vibration at the point where it is connected to the diaphragm. Therefore, an unwanted lateral movement as well as the desired axial movement would be imparted to the diaphragm, were it not for a wire connecting rod which is flexible enough to bend under the lateral forces but adequately stiff to transmit axial forces.

Frequency Response.

In order to obtain a flat frequency response, the mechanical-acoustical system of the receiver was designed with two portions containing essentially reactive elements, leading to two resonances in the response separated by a shallow trough. A third part of the system containing essentially a resistive element was used to damp the resonances, more especially the first resonance. The basic mechanical-acoustical system is shown in Fig. **6** in a sectional view of the receiver in a handset resting against an ear. The corresponding analogous electrical network is shown in Fig. **7**(*a*), in which acoustical elements have dash suffixes and the mechanical elements have not. The acoustical elements are divided into two sections corresponding to the acoustical parts of the receiver behind, and in front of, the diaphragm; each section is coupled to the mechanical portion of the receiver through a transformer of ratio 1 : A_e, where A_e represents the effective area of the diaphragm.[2] In Fig. **7**(*b*) the acoustical elements have been transferred to the mechanical sides of the transformers

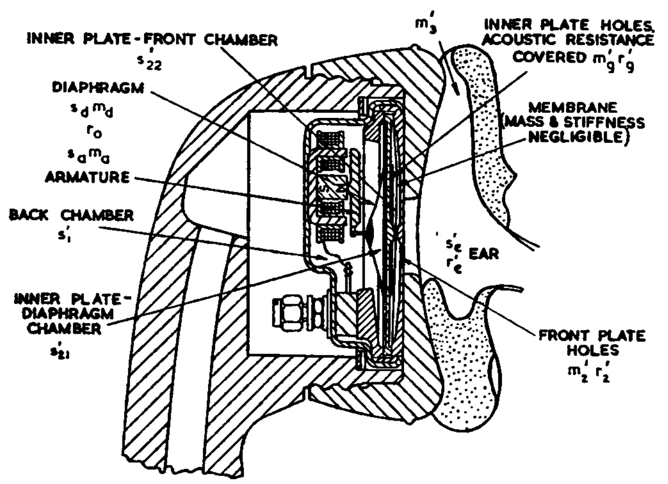
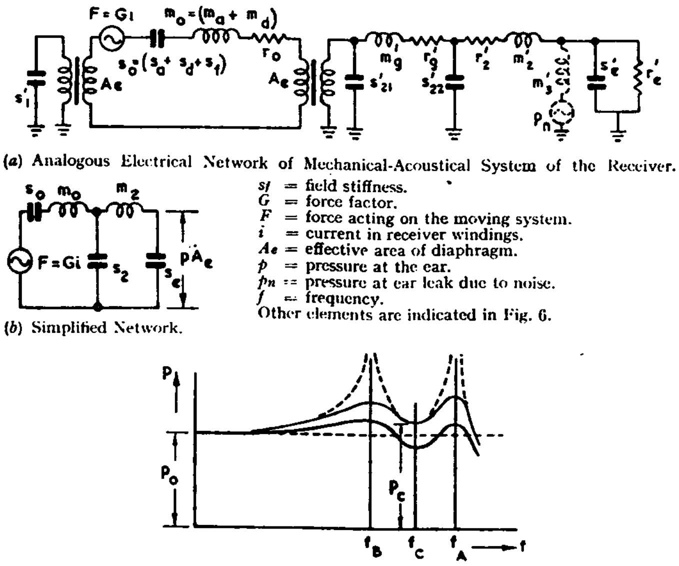


FIG. **6**.—SECTIONAL VIEW OF THE 4T RECEIVER INSET (IN THE NEW HANDSET) HELD AGAINST THE EAR, SHOWING MECHANICAL-ACOUSTICAL SYSTEM.



(*a*) Analogous Electrical Network of Mechanical-Acoustical System of the Receiver.

(*b*) Simplified Network.

s_f = field stiffness.
G = force factor.
F = force acting on the moving system.
i = current in receiver windings.
A_e = effective area of diaphragm.
p = pressure at the ear.
p_n = pressure at ear leak due to noise.
f = frequency.
Other elements are indicated in Fig. 6.

(*c*) (i) —— Target Response of Actual Receiver.
(ii) —— Target Response of Analogous Electrical Network of Receiver.
(iii) ------ Response (ii) without Damping—this is the Theoretical Response of the Simplified Network of Fig. 7 (*b*).

FIG. **7**.—ANALOGOUS ELECTRICAL NETWORKS AND RESPONSES OF 4T RECEIVER INSET.

(thus $s_e = s_e' A_e^2$, etc.); m_g', which is small, and the resistive elements have been omitted, and certain elements consolidated.

An analysis of this simplified network and application of the analysis to the design are given in an appendix to this article, in which reference is made to Fig. **7**(*c*). From this analysis, and from studies made on the more complete analogous network of Fig. **7**(*a*), in which the various elements could readily be changed, it was possible to achieve the network response of Fig. **7**(*c*), curve (ii).

In Fig. **7**(*c*), curve (i) shows the response of a receiver based on the type of mechanical-acoustical system with two damped resonances. The target set for the network study is shown as curve (ii); this differs from curve (i) to compensate for defects of the network analogy as explained in the appendix. Curve (iii) shows a similar response to curve (ii) but without damping; this is the theoretical response of the simplified network (Fig. **7**(*b*)).

Weight.

With a view to its use in headsets, and also ultimately for lighter handsets, it was decided to keep the weight of the receiver as low as possible. Light alloys were therefore

[2] BAUER, B. B. Analogues of Diaphragms. *Journal of the Acoustical Society of America*, Vol. 23, No. 6, Nov. 1951.

chosen where possible for the constructional parts, and the magnetic driving system was made as small and light as possible by the use of the best available magnetic materials. It was realized that the light weight would have the advantage of reducing inertia forces which might damage the structure or upset the magnetic balance of the armature should the capsule be subjected to undue mechanical shocks, for example by accidental dropping. It was also desirable to reduce cost by the use of minimum amounts of critical magnetic materials.

Protection of the Mechanism.

Because of the small air-gaps and the light diaphragm it was essential that adequate protection should be given against entry of dirt, probing through the front-plate apertures, and abnormal changes of pressure on the diaphragm (for example, by clapping the earpiece on the cupped palm of the hand). The necessary protection has been afforded by the capsule construction which totally encloses the receiver except, of course, at the sound outlet. Here protection is afforded by means of an inner plate in which the perforations are offset from those in the front plate, so that it is impossible to insert pointed objects into contact with the diaphragm. Between the inner and outer plates a membrane is arranged to act as a flap valve, closing the holes in either plate upon a momentary abnormal rise or fall of pressure, but readily transmitting vibrations of normal amplitude. The membrane also serves as protection against entry of moisture or dirt into the driving system of the receiver.

The Production Design

The construction of the receiver as designed for large-scale production is shown in the sectional view of Fig. **6**, and in Fig. **8**. The lower half of the photograph shows an "exploded" view of the piece-parts and unit assemblies making up a receiver; the upper half shows complete receivers and supplementary views of piece-parts not fully revealed by the exploded view.

It will be seen that the capsule receiver is constructed around a diecast frame, has an inner diecast perforated plate, and is enclosed by a diecast perforated front plate and a pressed cover, which is stepped from the crown to provide a low-level platform for terminals.

The receiver comprises, essentially, a small electro-magnetic driving unit, mounted towards one side of the frame, which drives a flared light-alloy diaphragm clamped between the frame and the inner plate. The diaphragm, and the armature of the driving unit, are joined by a thin wire connecting rod, shaped at one end to provide a suitable anchor when fixed by Araldite cement to the apex of the diaphragm; later, after balancing the two air-gaps of the driving unit, the connecting rod is soldered at the other end to a V-recess in a tongue of the armature.

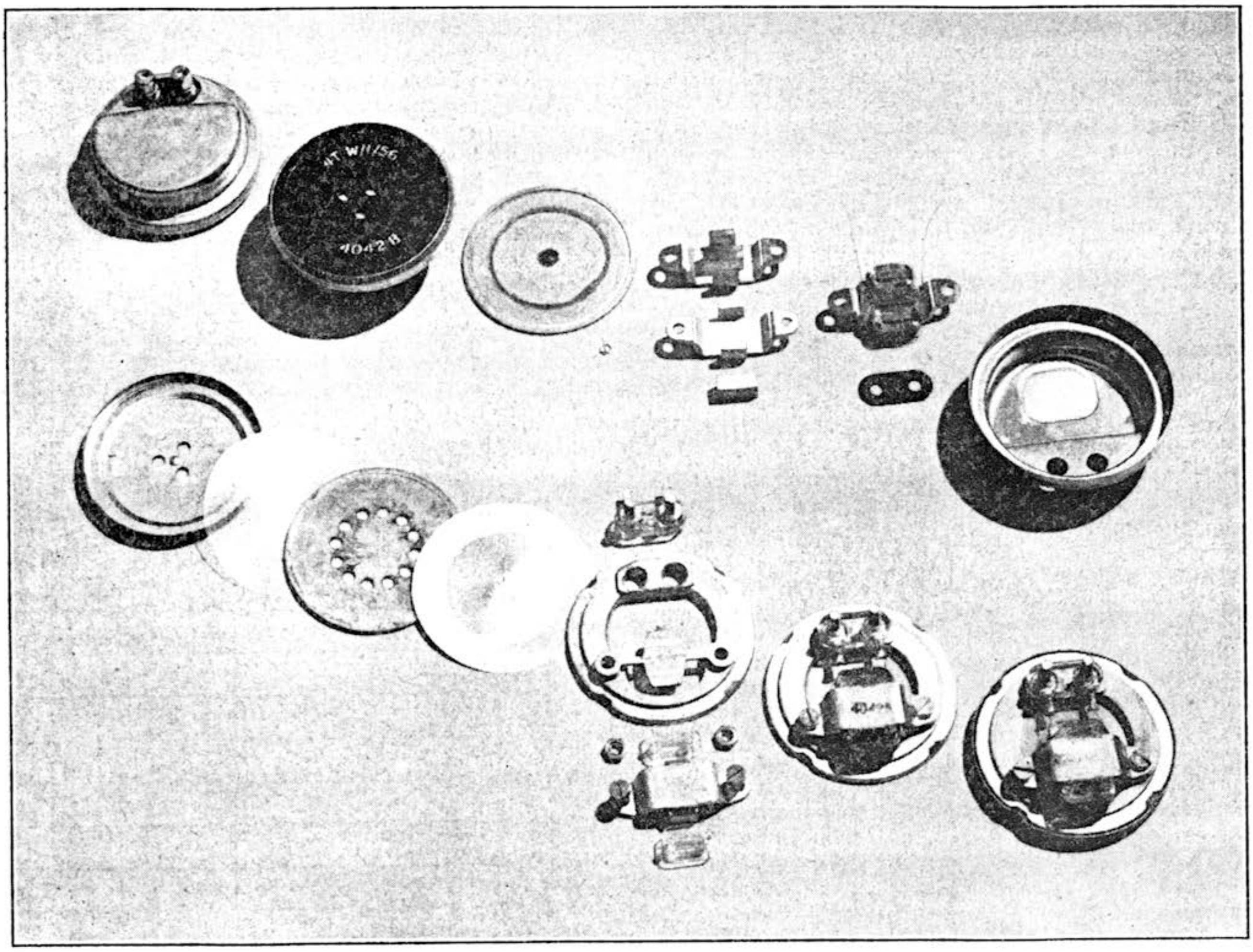


FIG. 8.—THE ROCKING-ARMATURE RECEIVER AND ITS COMPONENT PARTS.

The Magnetic System.

The two-pole balanced magnetic system of the driving unit uses a small high-energy anisotropic permanent magnet (of Alcomax III) having the shape of a rectangular block, which is mounted centrally between the limbs of a U-shaped yoke of Permalloy B (45 per cent nickel-iron alloy) forming the two pole-pieces. To avoid loss of section at the corners of the pole-pieces on forming (which was found to be detrimental magnetically), fillets of material are swaged up on the insides of the corners. The yoke and magnet are joined together by a soldering operation after coating both parts with tin. Following this operation, the surface of the magnet, pole-pieces and two side fixing lugs of the yoke are brought closely into one plane by a grinding operation.

The Windings.

The windings consist of a pair of spools wound on a common mandrel with a continuous length of wire; a spacer between the spools on the winding mandrel ensures the correct length of wire link for the assembly in the receiver. The ends of the winding wire are brought out for direct soldering to the receiver terminals on final assembly. This procedure eliminates the use of conventional stranded lead-wires and five soldered joints (four to lead-out wires, and one between spools). It is therefore cheaper and gives more reliable windings, but since the winding wire is relatively fragile, the windings are made in the assembly line and placed directly on the yokes of the receivers. They are so wound and connected that when assembled one on each pole piece their effects will be in series aiding around the yoke and armature circuit. The fixing is achieved by using the thermoplastic property of the spool material (Diakon) to mould over mushroom-shaped heads, at the back of the yoke, from projecting studs on the spool cheeks. The heads key into notches swaged in the yoke.

The Armature.

The armature, which is also made from Permalloy B, rocks or pivots on the magnet with the end faces of the armature opposed to the two pole-pieces; a ridge, which extends partly across one face of the armature and is of circular section where it bears against the magnet, acts as a fulcrum, and also governs the length of the air-gaps between the armature and the magnet and pole-piece assembly. The ridge is raised up over the sides only of the armature, for better mechanical seating on the magnet and also in order to avoid a magnetic constriction at this section of the armature. Regarding the armature in plan (Fig. 5), it will be seen that the central portion, which constitutes an important part of the magnetic circuit, is tapered from the middle towards the polar ends, allowing adequate section for the magnetic flux at each part of the circuit, combined with minimum effective moving mass. This principle has been followed even in the chamfering of the end-corners, which are unnecessary for carrying flux, resulting in a reduction of six per cent in the armature mass. The side limbs of the armature have shaft portions which provide the required torsional control; equality of the two polar air-gaps is achieved by suitably twisting the shafts near to the supporting lugs, after assembly, so that the shafts take an appropriate set.

Assembly and Testing.

Two side lugs on the yoke and two corresponding side lugs on the armature are clamped to the frame by the same pair of screws and nuts. Since the plane of the armature surface and its fixing lugs is displaced (by the height of the ridges, 0·0035 in.) from the plane of the magnet and yoke fixing lugs, this gap must be closed on assembly by the clamping forces of the two fixing screws. These forces, together with the magnetic force added on magnetization, provide a total force of the order of 20 lb, which holds the ridges in firm contact with the magnet. It will be noted that this direct clamping together of the armature and the yoke adds two side shunt paths for the permanent magnet flux, through the yoke lugs and side limbs of the armature. However, owing to the small section of the armature torsion arms, the leakage flux passing by these paths is small, and the resulting simplification in design (compared with the use of non-magnetic spacers between the yoke and armature lugs) is worthwhile.

The inner plate assembly consists of the perforated die-cast plate, to one face of which a disc of woven silk is secured with Phenolic cement, so as to cover the ring of 12 perforations. Before assembly in the receiver, each plate assembly is tested for acoustic resistance by a flow test under direct air pressure. Between the inner-plate assembly and the front plate is clamped a polythene membrane, which is normally prevented from sagging on to the apertures in either plate by small central bosses raised on the opposing faces.

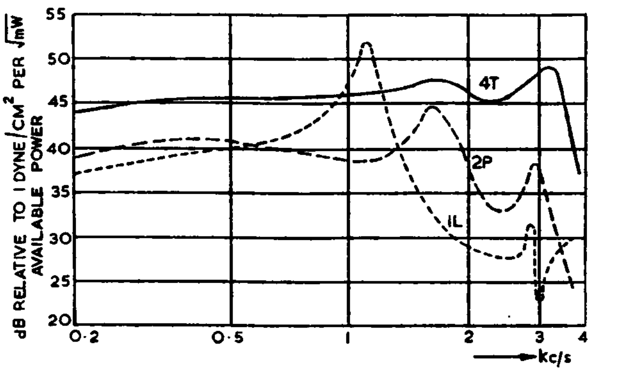
The assembly consisting of the frame with the driving unit, the diaphragm, inner-plate assembly, membrane, and front plate, is secured for initial adjustment and testing by locally forming the skirt of the front plate into recesses at the rear of the frame periphery. The ends of the windings are soldered to the tags of two terminals encased in a small block of thermoplastic material which fits with a frictional grip into recesses in the frame. The terminals have threaded projections which protrude through holes in the cover of the receiver, and are insulated from it by projections of the moulded block and by an external plate insulator which is added after assembly of the cover.

The back of the receiver is enclosed by the cover, the rim of which is formed over the front plate.

The receiver is then tested for sensitivity within three 500 c/s wide frequency bands suitably chosen to provide a check of the shape of the sensitivity/frequency characteristic. The chosen frequency bands are 450-950 c/s, 1,700-2,200 c/s, and 2,950-3,450 c/s.

Performance of the Receiver

Fig. 9 shows the sensitivity/frequency characteristics of the new 4T and older 2P and 1L Receiver Insets, plotted on the basis of constant available power from a



Note:—Measured with Post Office 3-cm³ Artificial Ear.

Fig. 9.—Sensitivity/Frequency Characteristics of 4T, 2P and 1L Receiver Insets.

source impedance matched to the receiver impedance at 1 kc/s. In all cases the receivers in the appropriate handset were measured on the Post Office 3-cm³ Artificial-Ear Coupler. It will be noted that whereas the improvement in the 2F Inset over the 1L Inset was primarily one of shape, th improvement in the 4T Inset over the 2P Inset is both ir sensitivity and shape. Thus the effective gain in volum sensitivity of the 4T Inset over the 2P Inset is about 7 dB while the frequency response curve is flatter, the variatio in sensitivity not exceeding about 5 dB over the frequenc range 200 c/s to 3,500 c/s. Further, the sensitivity of th 4T Inset rises slightly with frequency, whereas that of th 2P Inset has rather a general falling tendency.

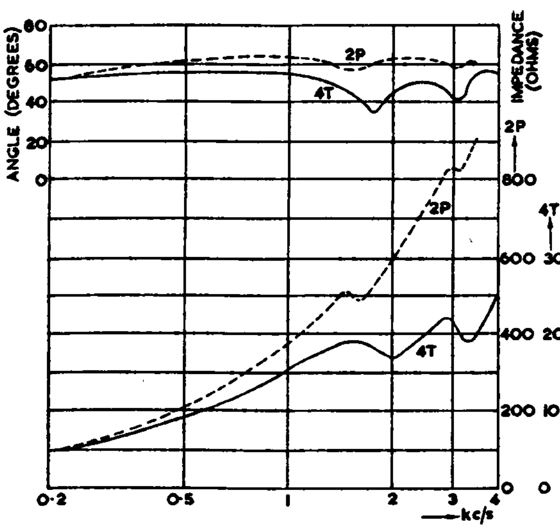


Fig. 10.—Impedance/Frequency Characteristics of 4T and 2P Receiver Insets.

Fig. 10 shows typical impedance/frequency characteristics for 2P and 4T Receiver Insets measured on the Post Office 3-cm^3 artificial ear; the variations of modulus and phase angle are shown separately. It will be seen that the new receiver has a generally lower phase angle, and a smaller percentage variation of the modulus with frequency, these differences being due largely to the increased "motional impedance" effect in the new receiver. The smaller variation of impedance with frequency of the 4T Inset is advantageous in reducing losses due to mis-matching which occur at all frequencies other than the chosen matching frequency.

The smaller nominal impedance of 150 ohms (at 1 kc/s) of the 4T Inset compared with the 400 ohms of the 2P Inset results from the redesign of the induction coil to meet the requirements of the 700-type telephone.

A feature of the design, which is not apparent from the performance figures, is that the new receiver is less susceptible to the effects of imperfect sealing on the ear, owing to its acoustical impedance being lower, than were the older types of receiver. The effect of an imperfect seal on the ear is shown in Fig. 7(*a*) by the acoustical mass m'_3 of the leak, and the source of room noise p_n. It will be clear that, in the new receiver, more of the energy from the noise source will be shunted away from the ear into the lower acoustical impedance of the receiver. Again, in considering the effect of the leak on the signal reaching the ear, it will also be clear that the lower acoustic impedance of the new receiver, which is in series with the ear, means the pressure at the ear is more nearly constant for a given leak. The lower acoustical impedance results partly from the lower effective mass of the mechanical system, and partly because, with the much higher effective area of the diaphragm, consideration of matching between the mechanical and acoustical sections of the receiver demands much lower acoustical impedances of the chambers and outlet holes in the front of the receiver.

Acknowledgments

The author would like to thank colleagues associated in this development for their assistance, and Standard Telephones and Cables, Ltd. for their permission to publish this outline of the principles involved and research background that have made possible the substantial improvements in sensitivity and response characteristics achieved in the Rocking-Armature Receiver.

APPENDIX

Analysis of the simplified network shown in Fig. 7(b)

Let G = force factor, defined as the force generated at the diaphragm when unit (a.c.) current flows in the receiver windings,

i = current in the receiver windings,

F = the total force generated at the receiver diaphragm, assumed to be constant with frequency, $(=Gi)$,

A_e = effective area of the receiver diaphragm,

p = pressure developed at the ear (here assumed to consist of a stiffness s_e only),

ω = $2\pi f$ where f = frequency.

Then it can be shown, by application of Kirchoff's laws, that

$$p = F s_e s_2/A_e [\omega^4 m_0 m_2 - \omega^2(m_0 s_e + m_2 s_0 + m_0 s_2 + m_2 s_2) + s_0 s_e + s_0 s_2 + s_e s_2] \quad (1)$$

This has the form

$$p = 1/(A\omega^4+B\omega^2+C)$$
$$= 1/A(\omega^2-\omega_A{}^2)(\omega^2-\omega_B{}^2) \quad (2)$$

in which ω_A, ω_B correspond with the peaks shown in Fig. 7(*c*), and where

$$\omega_A{}^2+\omega_B{}^2 = -B/A = (s_0+s_2)/m_0+(s_e+s_2)/m_2$$
$$= (s_0+s_2'A_e{}^2)/m_0+(s_e'+s_2')/m_2' \quad (3)$$
$$\omega_A{}^2\omega_B{}^2 = C/A = (s_0 s_e+s_0 s_2+s_e s_2)/m_0 m_2$$
$$= (s_0 s_e'+s_0 s_2'+s_e's_2'A_e{}^2)/m_0 m_2' \quad (4)$$

and A, B, and C have the values defined by identifying coefficients in equations (1) and (2).

To obtain an expression for the response on a power basis, equation (2) must be squared. This yields

$$p^2 = 1/(A\omega^4+B\omega^2+C)^2$$
$$= 1/A^2(\omega^2-\omega_A{}^2)^2(\omega^2-\omega_B{}^2)^2 \quad (5)$$

By differentiation of p^2 with respect to ω^2 we find from (5) that p^2 becomes a minimum when

$$\omega^2 = -B/2A = \tfrac{1}{2}(\omega_A{}^2+\omega_B{}^2) = \omega_c{}^2 \quad (6)$$

Substituting from (6) in (5) and denoting the minimum value of p^2 so obtained by $p_C{}^2$, we have $p_C{}^2 = 16/A^2(\omega_A{}^2-\omega_B{}^2)^4$ ..(7)

When $\omega^2 = 0$ we have $p^2 = p_0{}^2$, obtaining by substituting in (5)

$$p_0{}^2 = 1/C^2 \quad (8)$$

From (7), (8), and (4) $p_0/p_C = A(\omega_A{}^2-\omega_B{}^2)^2/4C$

$$= (\omega_A{}^2-\omega_B{}^2)^2/4\omega_A{}^2\omega_B{}^2 = \tfrac{1}{4}(f_A/f_B-f_B/f_A)^2 \quad (9)$$

The analysis given above will now be applied to the problem of obtaining a level frequency response with a receiver constructed on the basis of such a mechanical-acoustical network.

In the first place it is important to realize that the analysis of the analogous network assumed that the force F, i.e., the product Gi, remained constant with frequency. In the actual receiver, G falls with rising frequency due to the increasing iron losses, and i also falls with rising frequency due to the rising electrical impedance of the receiver. (When used in the telephone set, the receiver impedance is normally matched to the source impedance at some frequency in the middle of the voice range, such as 1 kc/s, hence the current falls, as stated.) For this reason, the response measured on an analogous network would have to show a generally rising tendency with frequency in order that the corresponding real receiver response should be level. Fig. 7(*c*), curve (i) shows the target response of the actual receiver drawn generally level, while curve (ii) shows the corresponding rising target response to be used in studying the design on the analogous network. Both these curves include suitable amounts of resistive damping, which had to be excluded from the network simplified for theoretical analysis. (The amount of damping included, as well as the allowances for defects of the network analogy, do not materially alter the location in frequency of the resonances and trough.) The amount of allowance to be made between curves (i) and (ii) was obtained from measurements on preliminary models of the magnetic driving systems of the receiver. It was found from such measurements that in curve (ii) p_C should be set 6 dB above p_0, which corresponds to a ratio p_0/p_C of 0·502. The solution of equation (9) for this value of p_0/p_C yields $f_A/f_B = 1{\cdot}94$. Since the resonance f_A determines the response near the top of the effective frequency range of the receiver, its value was set at 3,300 c/s; hence f_B = 1,700 c/s (and from equation (6), f_c, the frequency of the trough = 2,625 c/s).

Substituting these values of f_A and f_B in equations (3) and (4) yields two expressions towards the solution of the simplified