LOUDSPEAKERS THE FIRST 111 YEARS

Part 1: The early years

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In 1877, patents for moving-coil loudspeakers were issued to E.W. Siemens in Germany, and, almost simultaneously, to Charles Cuttriss and Jerome Redding in the U.S.A. However, this type of loudspeaker had to wait for more than forty-eight years before becoming widely used, and its invention was both preceded and followed by an enormous number of other inventions, some of which actually worked. Nevertheless, the history of the loudspeaker can be considered to begin in the year of this patent. Even today, loudspeakers are one of the most fascinating subjects for the private inventor, and the flow of ingenious (but usually unproven and/or ineffective) devices from dedicated enthusiasts continues unchecked.

Pre-history

Before 1877, most of the eminent physicists of the nineteenth century had investigated, whether purposely or as a side-issue, the production of sound by electrical means. Although it is possible to do this in several ways, almost all the work was based on the electromagnet, invented by Sturgeon, and the dynamo, invented by Michael Faraday. If d.c. is applied to an electromagnet fitted with a springy armature, a most satisfactory clicking sound can be produced as the circuit is made and broken. This, in fact, is the 'Morse sounder', which featured prominently in early Western films. Faraday's early dynamo produced alternating current (before he invented the commutator, which is actually a synchronous mechanical rectifier), and applying alternating current from a hand-turned dynamo to the aforesaid electromagnet CAN produce an unattractive squalling noise. The reason for the emphasis on 'can' is that the actual sound output from different combinations of dynamo and electromagnet varies vastly, and the reasons for this were not well understood at the time. You can repeat this experiment by using a cycle dynamo and a telephone 'receiver' or a pair of headphones, but make sure to connect a 220Ω resistor in series to limit the current, and DON'T WEAR THE HEADPHONES, because the sound may be deafeningly loud. You can extend the experiment by equipping the receiver or one of the earphones with a conical horn made of rolled-up newspaper. This will make the sound much louder, and this effect has been known from very ancient times. As musical instruments, horns are said to have proved effective weapons of war at the Battle of Jericho (about 1500 BC), and the trumpets of Tutankhamen (1350 BC) have been played and recorded since their rediscovery in 1922.

The Telephone

The slowness of communication by telegraph, using manual Morse, was a considerable spur to the search for a practical telephone, which would convert the human voice into electricity and convert back again at the receiving end of the line. Many inventions were announced before Alexander Graham Bell produced a practical device in 1876. Much of the difficulty, in fact, was concerned with the design of a usable microphone. Both Ries in France and Hughes in England pursued the use of intermittent contacts, which could be made or broken by the vibrations of a diaphragm or other object exposed to the sound waves. Ries used metal contacts, which were unsatisfactory for the purpose but later proved useful as a detector of radio waves, in the 'coherer'. Hughes used carbon, which is very much more suitable, and produced many practical headphones.

Bell, however, used no contacts, his first microphones and receivers were identical and used electromagnetic induction, see Figure 1a. Bell's great contribution, apart from his commercial exploitation of the invention, was to realise that such a device, whether used as a microphone or a receiver, had to have a constant magnetic field, on which, in the receiver, the varying field due to the microphone current was superimposed. It can easily be seen that this constant field is necessary, because if the magnetic field acting on the diaphragm is produced only by the alternating microphone current, the diaphragm will be attracted to the magnet TWICE in each cycle of current, at both the positive and negative peaks. The receiver will thus produce sound at twice the frequency of the incoming current, i.e. there will be fullwave rectification and 67% second-harmonic distortion, see Figure 1b! A microphone with no constant field will just not work, because there is nothing to generate a current, but it is not so obvious that the continuous field in the receiver not only allows the correct reproduction of the input frequency but also dramatically increases the sensitivity.

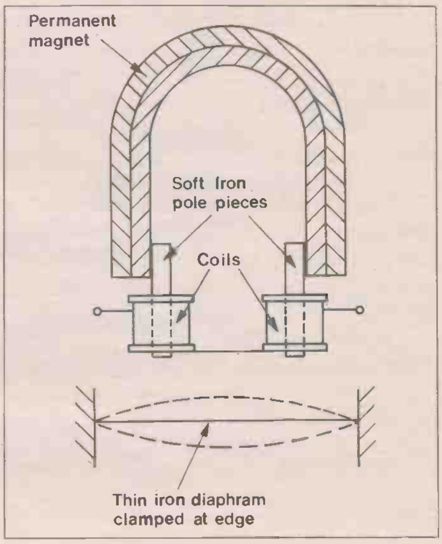

Figure 1a. Bell microphone or receiver with permanent magnet.

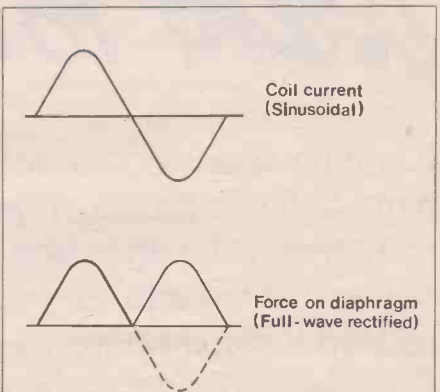

Figure 1b. Distortion produced by non-polarised receiver.

Bell used electromagnets in some early designs of transducer, but later he could make strong permanent magnets, and realised that the elimination of the battery power needed for the electromagnets was highly desirable. However, the best available material for making permanent magnets at that time was glass-hard high-carbon steel, and for the same energy-product, a magnet made of this material has to be far larger than even one made of cobalt steel, which was discovered by Honda and Takei in 1920, so that Bell's microphones and receivers were large and heavy. Their operating principle, however, is the same as that of the diaphragm-type earphone widely used between the World Wars, but the former were much more sensitive; they could be used in a 'sound-powered' system, where the devices were simply connected together, with no battery, and the energy for the system obtained from the sound input.

Later telephones used low-impedance microphones with batteries, and transformer matching to high-impedance receivers. Alternatively (and at that time all alternatives were investigated), a moving-coil receiver could be used with a low impedance microphone. This produced what Sir Oliver Lodge called the 'bellowing telephone', and could be said to be one of the first uses of a loudspeaker. It is used today as a door-answering device. Lodge himself patented a moving-coil loudspeaker in 1898. It must have been sufficiently different from the earlier Siemens device to be patentable. Another early application of the loudspeaker was the relaying of musical concerts to quite large audiences, particularly in France, using Bell-type transducers equipped with horns.

Problems with Bell-type Transducers

The sensitivity of Bell's devices is partly due to the design of their diaphragms. The diaphragm has to be made of ferromagnetic material, and should have a high permeability. But it should also be thin and springy, because it must be positioned very close to the pole-pieces of the magnet system, yet resist the attractive force of the permanent magnet. If the spacing is too small, or the diaphragm too slack, it will collapse in the middle and 'pole', or stick to the pole pieces, causing a great drop in sensitivity and considerable distortion of the sound.

For Bell, the magnetic and mechanical requirements were conflicting, since soft iron had the highest available permeability but not the ideal mechanical properties. Nevertheless, his diaphragms are described as 'soft iron', but are probably not of the purest low-carbon iron (Swedish iron). The thickness, temper and clamping of the edge were arranged, by accident or, most probably, design, to give a high-Q resonance at about 900Hz. This increased the effective sensitivity for speech very considerably. However, the small spacing of the diaphragm from the pole-pieces limited the permissible diaphragm movement (usually termed 'excursion'), and therefore the loudness of the sound produced when the device was used as a loudspeaker. In addition, the mid-band resonance gave an unpleasant coloured and strident sound quality to the reproduction of music, especially as the short, often conical, horn to which it was attached resonated in the same frequency range and would not reproduce lower frequencies properly (Photos 1a, 1b).

Photo 1a. Sterling 'Baby' horn with diaphragm transducer. About 1924.

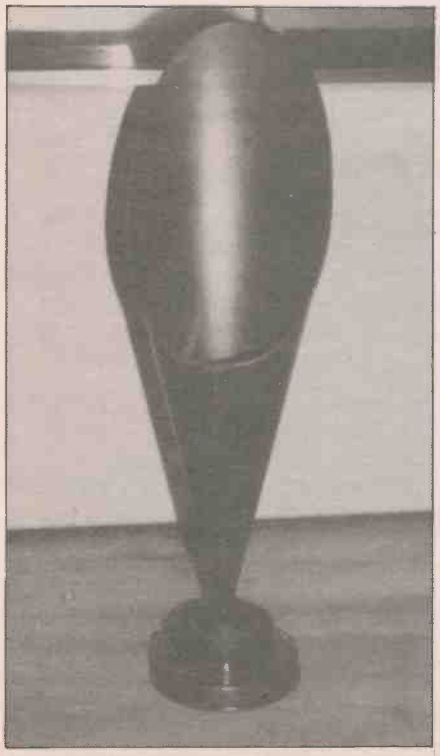

Photo 1b. Early S.G. Brown conical-horn loudspeaker.

The Cantilever Reed-armature Transducer

Based on a 1910 design for an earphone, by S.G. Brown, this device has the advantage of considerable simplicity and robustness, see Figure 2. Unlike the Bell receiver, it can drive a large, preferably conical, diaphragm directly, thus needing no horn (Photo 2a, 2b). Indeed, the mass of the diaphragm is highly desirable, as it lowers the resonant frequency of the reed. Millions of loudspeakers using this principle were made in the early days of broadcasting, and the driver mechanism was also used as a cutting-head for early electrical recordings on (analogue!) disc. Loudspeaker drivers were fitted with a screw adjustment of the spacing between the reed and the pole-pieces, which acts as a very effective volume control, much better than the proverbial sock which was stuffed down a horn to quieten it. However, too close adjustment of the reed results in poling, and the excursion is limited. In addition, as with the Bell transducer, the system is inherently non-linear. The pull on the reed increases when the reed moves towards the pole pieces, and decreases as it moves away, whereas it should be constant. To a certain extent this can be corrected by adjusting the geometry of the system, but it is possible to reduce the non-linearity by modifying the design more fundamentally, leading to the next two variants described below.

A loudspeaker with a large cone radiator can have its low-frequency response improved if a flat baffle-board or a cabinet (now usually called an enclosure) is added, see Figure 3, so that the sound radiated from one side of the cone is separated from the reverse-phase

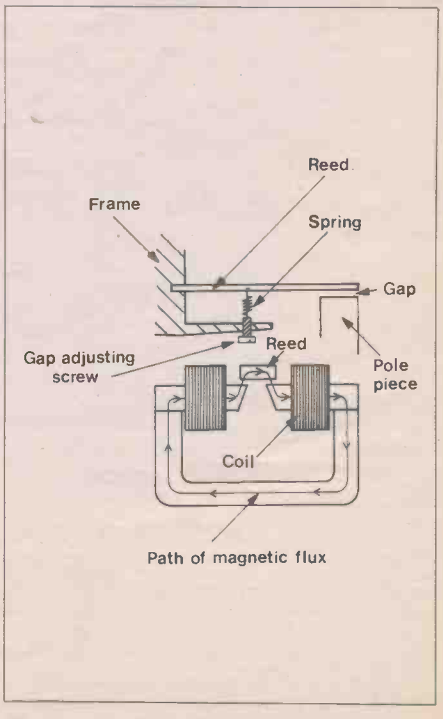

Figure 2. Reed armature driver.

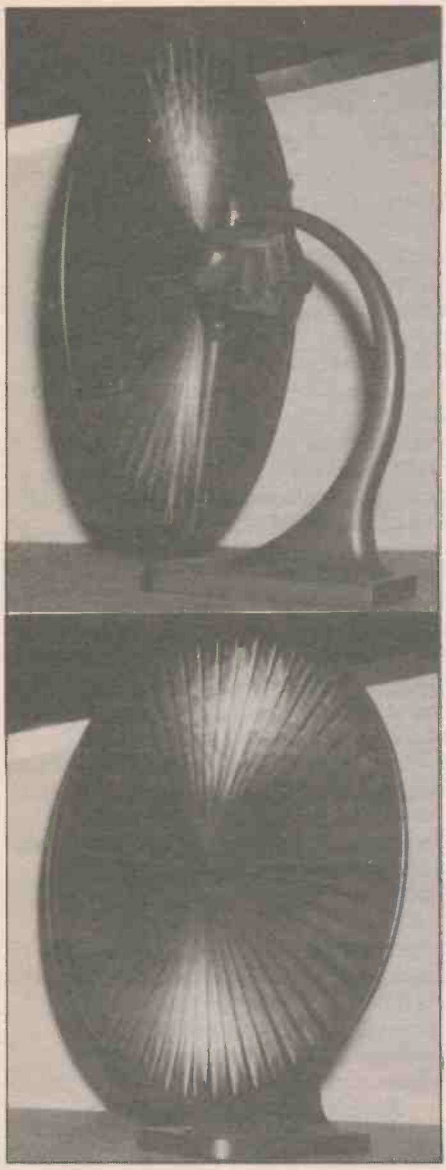

Photo 2a/b. **Sterling 'Primax' pleated-diaphragm reed-driven loudspeaker. Contemporary sectioned exhibition model (1927). Many Sterling products were made under licence from The Gramophone Company Ltd., (later to become EMI).**

radiation from the other side. While the effect of a very large flat baffle, and those of some other simple geometric shapes, such as a sphere, can be calculated, the effects of a rectangular box are quite complex, especially if the box is partly open at the back, as in the table radios and extension loudspeakers widely marketed in the mid-1920's and for the next forty years (Photo 3). Enclosure design has brought forth more oddities and weird theories than practically any other area of audio engineering. Successful theoretical analyses of the low-frequency response of some well-defined types of driver and enclosure combination were published by A.N. Thiele and R.H. Small in the 1970's.

The Inductor-dynamic Transducer

Developed specifically for loudspeaker applications, this device overcomes a major problem of the reed-armature mechanism, the inability to reproduce low frequencies unless a very low sensitivity is accepted. This is because the spring element of the reed has to be stiff enough to resist the steady pull due to the permanent magnet. This gives a high resonant frequency unless the combined mass of the reed and cone is made large, in which case the device requires a high power input, i.e. the sensitivity is low.

In the inductor-dynamic device (Figure 4), the direct pull and the alternating pull are arranged to be at right-angles, and the direct pull is, in addition, substantially balanced out. The residual direct pull is applied to the spring elements, of which there are two, in such a direction as to stretch them, whereas the alternating pull bends them. A simple flat spring is very much more difficult to stretch than to bend, so bending can be made easy without risk of poling. Also, the non-linearity is approximately balanced out, if the pole-piece tips are carefully shaped, because the reduction of force on one armature as it moves away from its pole-pieces is compensated by an increasing force on the other armature. This is an example of a push-pull mechanical system, which, like its electrical analogue, is substantially free of even-order non-linearity. With soft springs and a 25cm paper cone having a leather surround at its outer edge, a resonant frequency in the region of 70Hz could be obtained, whereas the resonance of a reed-armature loudspeaker might be above 200Hz. In addition, the inductor-dynamic driver cannot pole, so the amplitude of movement is limited only by the tolerable non-linearity, and can be increased by appropriate armature and pole-tip design. Thus the quality of music reproduction from an inductor-dynamic loudspeaker could be much better than that from a reed-armature type.

Photo 3. Alphion 4-valve (tube) portable (!) radio with Celestion reed loudspeaker (about

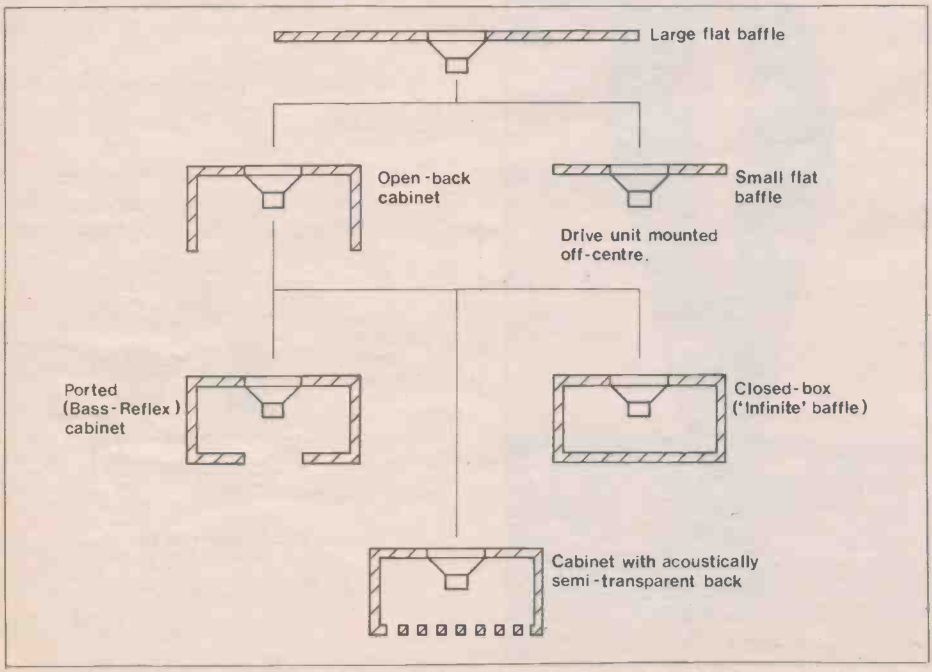

Figure 3. Some types of baffle for direct-radiator loudspeakers (modified and extended from Jordan).

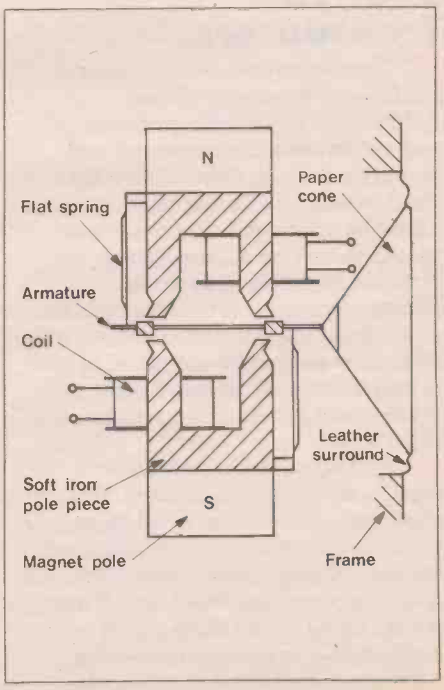

Figure 4. Inductor-dynamic loudspeaker.

The Balanced-armature Driver

This is another way of improving the linearity of the net driving force on the armature system. With the rocking armature (Figure 5) in the exact centre position, there is no net direct pull on it, but it is unstable in this position, like a horizontal see-saw. Consequently, a spring has to be added to prevent poling. This is a pity, because the effective mass of the armature is quite small, so the spring results in a high resonant frequency unless a heavy cone is added. Only the alternating component of the magnetic field passes through the armature, which is therefore not driven close to saturation by the permanent field. The permeability of the armature can therefore be high, with a consequent high sensitivity. This is another push-pull system, and linearity can be similar to that of the inductor-dynamic device. The balanced-armature mechanism may be rather easier to construct, although play in the armature pivot must be prevented.

Electrostatic Loudspeakers

The electrostatic or capacitor microphone predates Bell's telephone by some years, but, because of its high impedance, it could not form part of a practical telephone at that time. Indeed, it is only now, a century later, that this is practicable. The early microphone could also be used as a loudspeaker but required high operating voltages (upwards of 600V) and was not very sensitive. It was not until the end of the 1920's that new materials, such as aluminium foil and thermosetting plastics (Bakelite), became available and new patents for 'condenser loudspeakers' began to appear, in the names of V.F. Greaves *et al.*, C. Kyle, P.E. Edelman and H. Vogt. Greaves, Kyle and their colleagues produced a single-sided unit, see Figure 6a, while Vogt produced a unit with two perforated fixed plates enclosing a stretched moving plate, see Figure 6b. This unit therefore resembled the much later and considerably more successful 'Quad Electrostatic', but did not share the latter's crucial constant-charge drive, and was therefore not very linear in amplitude response, although the frequency response was said to be fairly smooth. The Kyle unit was also said to have a frequency response extending from 100Hz to 10kHz, which was not flat but could be equalised fairly easily. Being single-sided, however, the linearity of the device would be suspect.

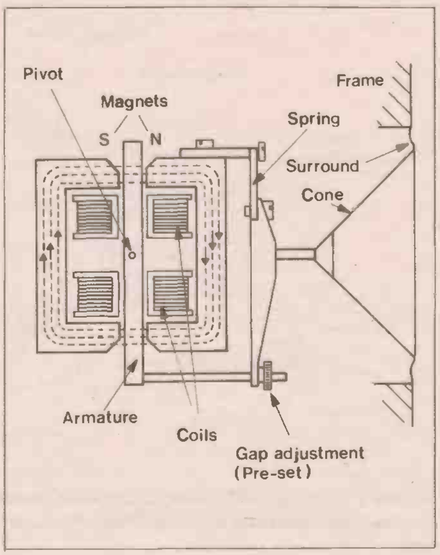

Figure 5. Balanced-armature loudspeaker. Dotted lines show magnetic flux path with no coil current. There is no flux in the armature.

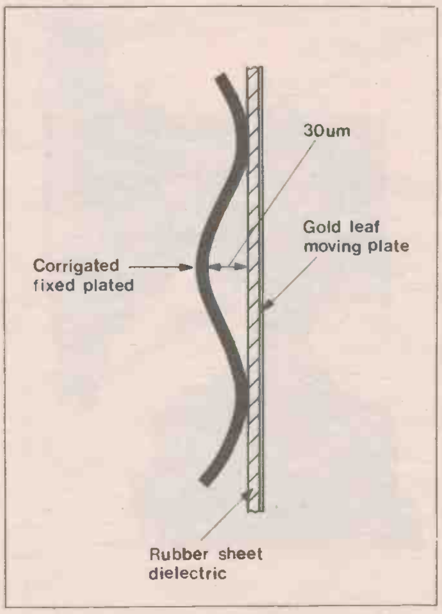

Figure 6a. Modified cross-section of Kyle single-sided electrostatic loudspeaker.

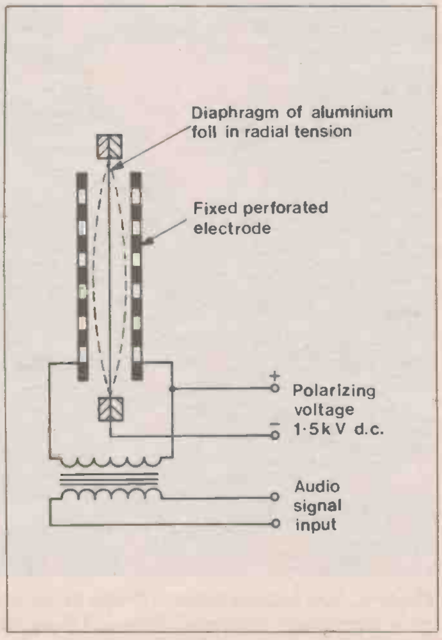

Figure 6b. Cross-section of Vogt double-sided electrostatic loudspeaker.

Piezo-electric Loudspeakers

The term 'piezo-electric' refers to the property of certain materials to deform mechanically when an electric field is applied, and vice versa to generate a voltage when mechanically stressed. In the early 1930's, loudspeakers, mostly for reproducing frequencies above 5kHz, were described by S. Ballantine, C.B. Sawyer and F. Willms. These used crystals of Rochelle salt (sodium potassium dihydrogen tartrate) as the piezo-electric material. This is very difficult to work with, because it attracts moisture from the air and dissolves in it. Quartz or tourmaline would be much more stable but are much too insensitive for use in loudspeakers. The problems of sealing the crystals against moisture were not solved and the principle was abandoned until the 1950's, when it was briefly revived. New ceramic materials developed since 1970 have allowed the production of reliable piezo-electric high-frequency drivers, but the extension to lower frequencies is difficult. Linearity can be poor, and the capacitive input impedance of the device is not easy to drive.

Friction-driven Loudspeakers

In attempts to produce very sensitive loudspeakers, and/or very high sound levels, electromechanical devices were produced in which the friction between a pad, connected to a conical diaphragm, and a rotating disc or roller was varied electrically. This could be done either by varying directly the force between the pad and the moving part, or by impregnating the moving part (a porous cylinder) with a mixture of chemicals which gave off gas bubbles when electrolysed by the applied electrical signal. Such devices were described by Thomas Alva Edison, Johnson Rahbek and S.G. Brown, but were not very reliable and did not give very good or consistent sound quality. The signal-to-noise ratio was also poor, because the friction introduced noise in the absence of an input signal.

Air-operated Loudspeakers

Another high-power system, developed by Creed and Co. in the 1930's, used a supply of compressed air, the flow of which was controlled by an electrically-operated vane valve. Apart from distortion due to deficiencies in the valve operation, there was considerable non-linearity due to the sound pressure variations at the horn throat being far from negligible compared with atmospheric pressure. This problem also occurs with modern high-power horn loudspeakers, which use moving-coil drivers.

The Moving-coil Driver and Direct-radiator Loudspeaker

By far the most widely used type of driver, the moving-coil system (Figure 7) is surprisingly subtle in its mode of operation, and it is this which confused the early workers and was partly responsible for the long delay in its exploitation. The other factor is that the construction of a reliable device depends on the use of stable flexible materials and adhesives, neither of which were easily obtained before the 1920's.

The moving coil and cone assembly can be made very light. If provided with a very soft suspension (Photo 4a, 4b and 4c), the result may be a very large coil excursion under some conditions, causing the destruction of the coil by collision with the magnet structure, or by being forced out of the magnet system. On the other hand, a stiff suspension will result in a very high-Q resonance, giving a squawky or strident sound, and low sensitivity except at the resonant frequency. The major contribution of Rice and Kellogg was not the breakfast cereal but the realisation of how to make a moving-coil loudspeaker with a substantially flat frequency response. This involves three steps:

(a) Adjusting the mass of the coil and cone, and the compliance of the suspension, so that they resonate below, or at the lower end of, the working frequency range.

(b) Adjusting the amount of mechanical loss (mainly in the suspension and surround), and the electrical damping, which depends on the output impedance of the driving amplifier and the field strength of the magnet system, so that the main resonance is reasonably well-damped. (Rice and Kellogg may not have fully analysed this: Theile and Small provided a full explanation and quantified the factors involved some 25 years later.)

(c) Allowing, or even encouraging, the cone to cease to vibrate in one piece above a certain frequency, but not to vibrate in sections in several undesirable ways.

Curiously, Siemens' original patent refers to a conical diphragm with an exponential flare: this shape encourages the correct form of cone break-up and has been used in some of the nicest-sounding commercial (as opposed to high-fidelity, where such simple criteria are inadequate) loudspeakers.

In addition, Rice and Kellogg showed that the diaphragm should be small compared with the wavelength of the sound to be radiated (unless a pronounced directional effect is required), and indicated the need for a baffle or enclosure to prevent destructive interference between front and rear radiation at low frequencies.

Until the late 1930's, permanent magnets were not very suitable for use in moving-coil drivers. The present author remembers dismembering an early example, from a battery radio, in his youth: the magnet was forged from about 30cm of 75mm×25mm steel bar, rolled into a flattened hoop, welded and fully hardened. It was very heavy indeed, yet not a very strong magnet. The earlier Rice-Kellogg products, made by GE in

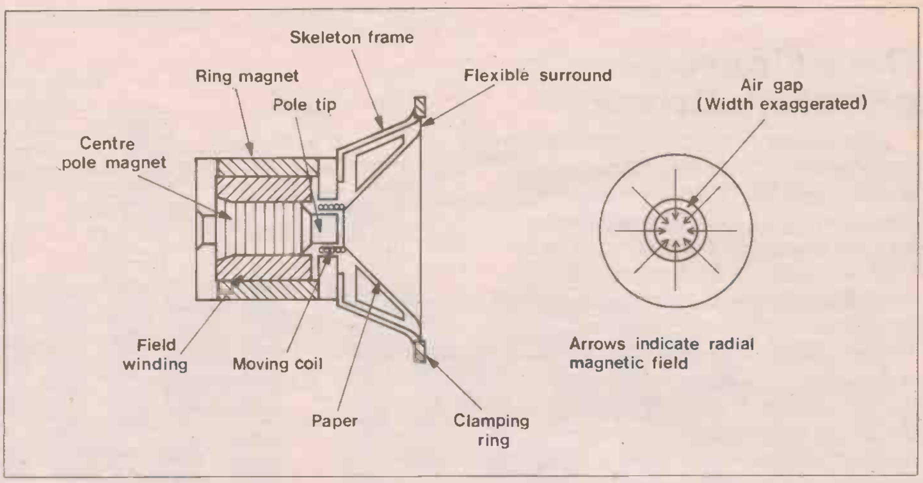

Figure 7. Moving-coil loudspeaker with metal magnet or electromagnet. The two permanent magnets and the field coil are alternatives: whichever magnet is not fitted is replaced by soft iron.

Photo 4a.

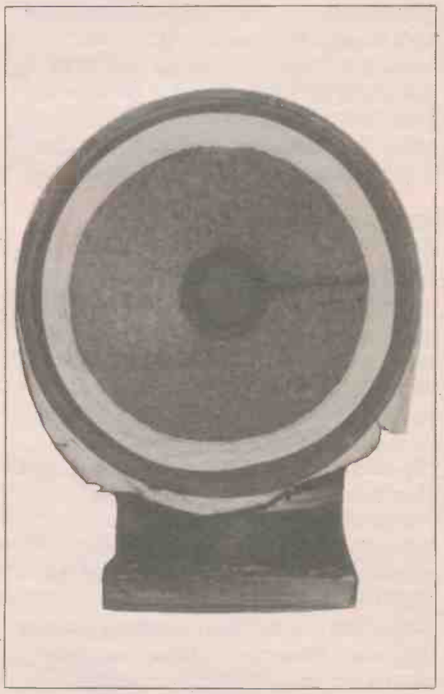

Photo 4b.

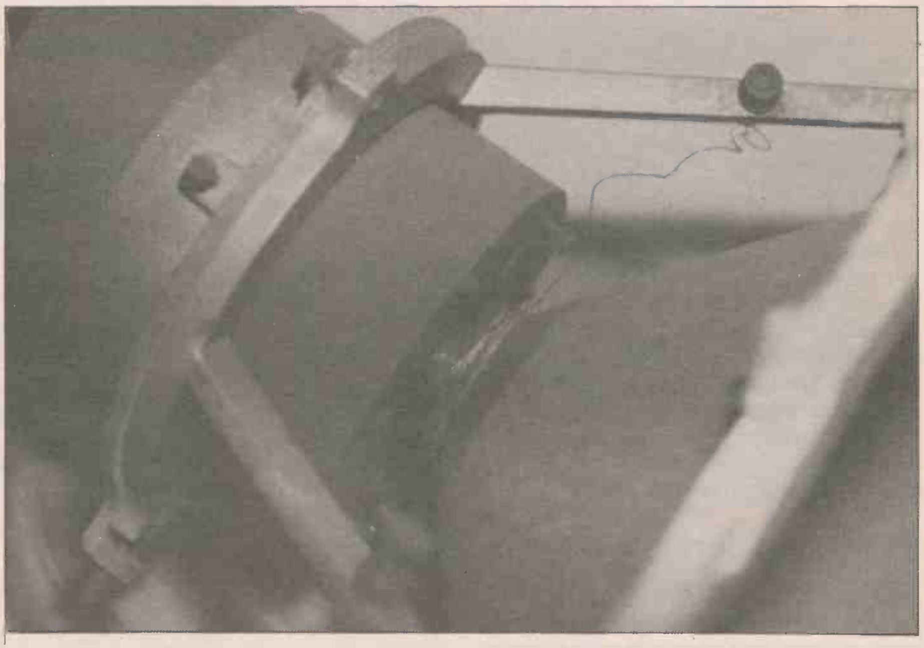

Photo 4a, b, c. Bakers Selhurst Radio 12" moving-coil direct-radiator loudspeaker with a high-impedance voice-coil. This unit has a leather surround and the suspension is formed by two loops of sewing-thread. The resonant frequency is very low, but so is the maximum permissable input.

the USA and marketed in Britain by BTH (Photos 5a, 5b, 5c and 5d), used electromagnets, as did most of the units made at that time. When used in a radio receiver, the field coil served as the smoothing inductor in the power supply. Considerable current at harmonics of the mains supply frequency also flowed through the coil: the reservoir capacitor was only 4μF or 8μF, and the smoothing capacitor, following the inductor, was of the same value. This current would have produced a loud hum from the loudspeaker, so another coil of a few tens of turns was wound next to the field coil and connected in series with the voice-coil. This 'hum-bucking' coil inserted a voltage into the voice-coil circuit which was intended to cancel the effect of the hum current in the field. It did work, but the coil had to be specially designed for each radio, since the number of turns depended on the power supply capacitor values, the anode current drawn by the valves (tubes) and the output source impedance of the output stage.

Flat-diaphragm Moving-coil Loudspeakers

There were some researchers who did not like cones: certainly they are far from ideal, but all other practical shapes have their own disadvantages, which seem to be worse than those of the cone. One of the proponents of the flat diaphragm was J.D. Midgley, who patented several arrangements, including the use of a circular, stretched aluminium foil diaphragm which was driven by a moving coil mounted off-centre (Photo 6a, 6b). The off-centre drive helped to break up the inevitable resonances and spread them out in the frequency domain. Another type of flat radiator was the German Blatthaller (sheet sounder), in which a large corrugated metal sheet (up to several tens of centimetres square) was driven all over its surface by a copper conductor fixed to it at right angles and immersed in the field of a powerful electromagnet. It was very large, very heavy, and very loud.

Horn-loaded Moving-coil Loudspeakers

Moving-coil drive units were not only used in direct radiators. The talking cinema and the growing sound-reinforcement industry both demanded high sound levels and high quality. It was relatively more difficult in those days to provide more amplifier power than to improve the sensitivity of the loudspeakers. E.C. Wente and A.L. Thuras (the inventor of the bass-reflex principle) described in 1928 the Western Electric WE555 horn-loaded moving-coil unit. The coil was made of edge-wound aluminium tape, and, whereas most loudspeakers are of the order of 1% efficient (sound power out divided by electrical power in), this unit was about 50% efficient! Modern horn units approach the same performance (with

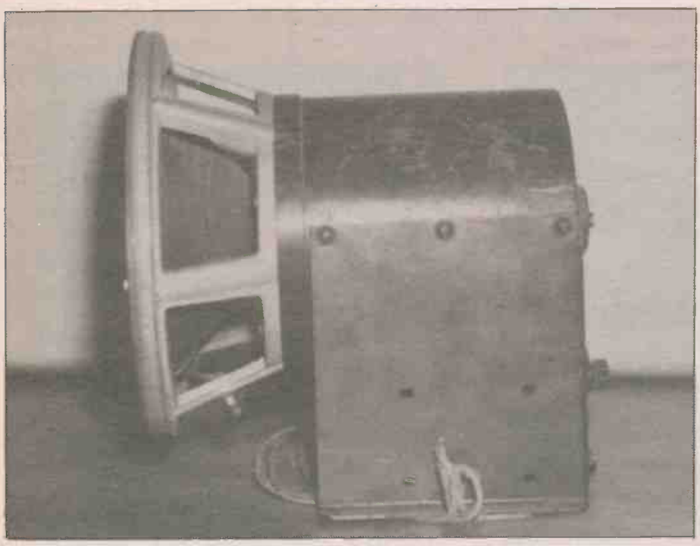

Photo 5a. B.T.H. Rice-Kellogg 12" energised-field loudspeaker 1931.

Photo 5b. A similar unit from 1929, in the original cabinet with its field power-supply.

Photo 5c. A 12" permanent-magnet unit from the same stable (1931). The slot, one of three in the magnet pot, is not for displaying the interior but a feature of the design.

Photo 5d. Rear view of the 1929 unit, showing the mains transformer and copper-oxide rectifier. The transformer on the left is a Wharfedale WMT 1, for 3Ω:15Ω matching. Many thousands of these were made, from the 1930's until relatively recently. This example is a late model, for it is branded 'Rank-Wharfedale'.

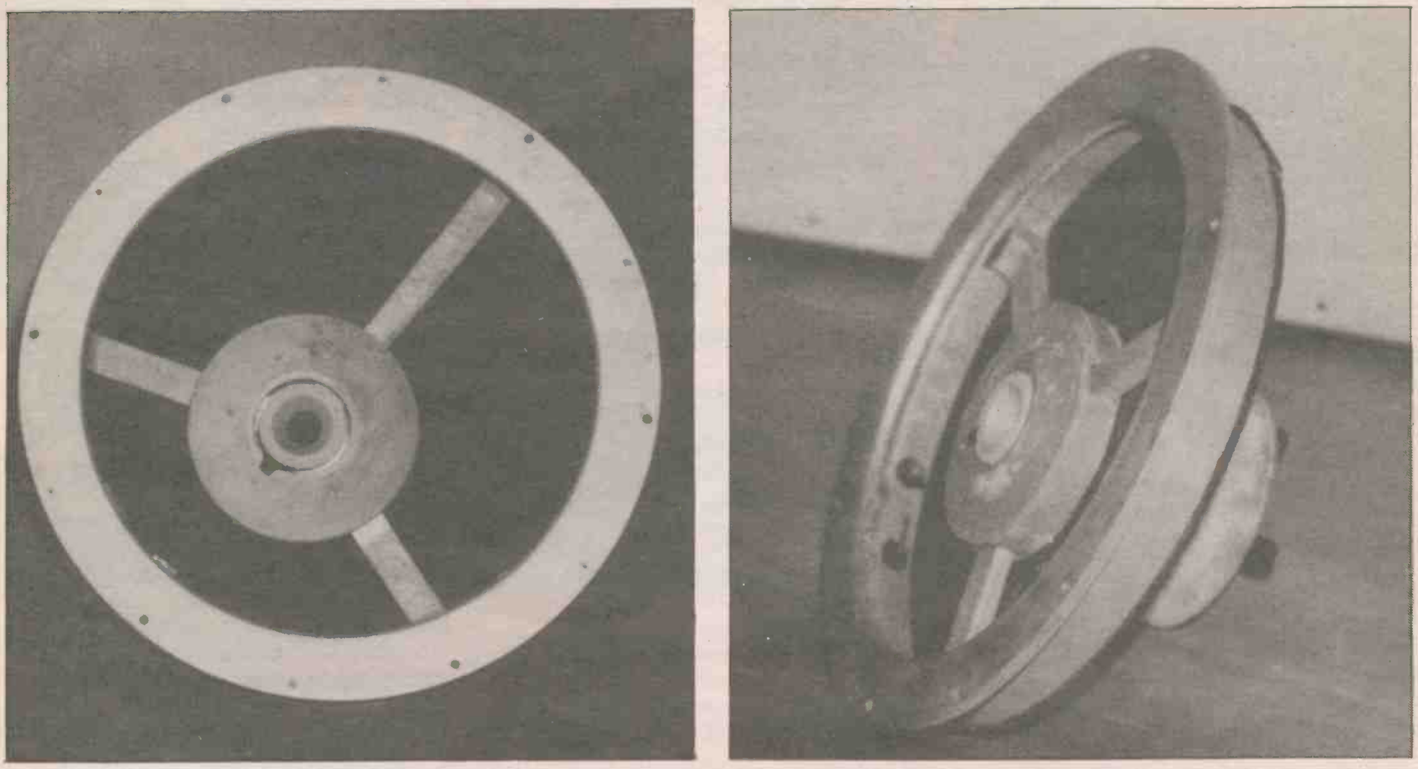

Photo 6a, b. Two views of the chassis of a Midgley flat-diaphragm moving-coil dipole-radiator loudspeaker. Note the off-centre drive, intended to minimise spurious resonances in the thin aluminium diaphragm (absent from this example).

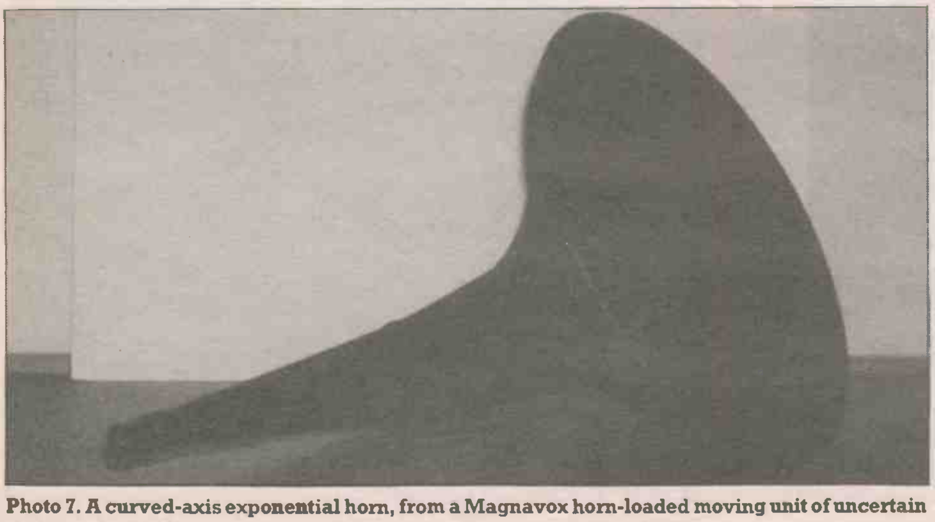

Photo 7. A curved-axis exponential horn, from a Magnavox horn-loaded moving unit of uncertain (but very early) date.

less size and mass and less relative cost) but few indeed exceed it. Mind you, the horn was 10.8 m long! A cross-section of a horn-loaded moving-coil pressure unit is shown in Figure 8. Photo 7 shows a horn from a Magnavox horn-loaded moving-coil unit.

One of the more unusual devices of the day was the 'Crystavox' loudspeaker designed by S.G. Brown, which incorporated a 'microphonic amplifier' (a term with quite a different meaning today!). In photos 8a and 8b, the unit in front of the base of the horn is the amplifier, with its metal cover removed. At the left of the assembly is a reed mechanism which is directly mechanically-coupled to a small carbon microphone cell on the right. This is

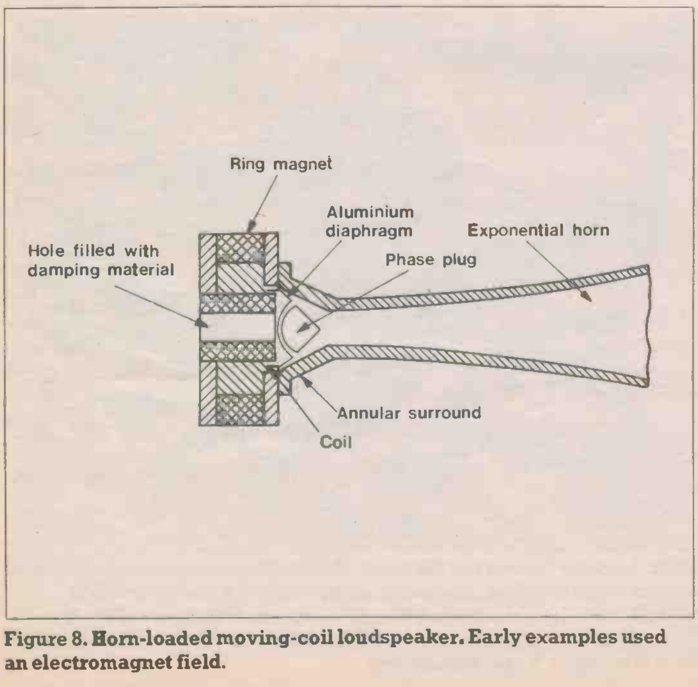

Figure 8. Horn-loaded moving-coil loudspeaker. Early examples used an electromagnet field.

Photo 8a. The 'Crystavox' incorporating a 'microphone amplifier'.

connected in series with an external 3V battery and the low-impedance reed mechanism at the base of the horn. It worked well, and the principle was known and used experimentally before 1900 and certainly long before the triode valve was available as an amplifier.

The End of the Beginning

The start of World War II in 1939 could be regarded as the end of the first stage of the loudspeaker story. Loudspeakers were being produced by the million for mass markets. New magnet materials, iron alloys containing cobalt, nickel and aluminium, and new methods of heat-treatment, were being introduced which would reduce size, weight and, in spite of the exotic metals used in the alloys, cost. The performance of a loudspeaker design could, to a certain extent, be predicted, once the characteristics of the cone to be used had been measured. Cone design was to remain a black art for another thirty years or so, and unpleasant (and even, occasionally, pleasant) surprises still lie in wait for the innocent designer.

Acknowledgement

The assistance of Mr. G.M. Wheeldon of the Science Museum and Ms. J. Marshal of the Science Museum Library is gratefully acknowledged.

Photo 8b. Another view of the 'Crystavox'.

Maplin's Big Heart

By J. Rose

In the last issue I told you about the annual London to Brighton bicycle ride in aid of the British Heart Foundation, this ride has now taken place and was thoroughly enjoyed by all! Over 35,000 cyclists suffered the 56 mile journey with smiles on their faces, joy in their hearts, blisters on their feet and saddle sores on their . . . . ! The event raised an estimated £1,000,000 which will be used to fund the purchase of much needed equipment and be used for invaluable research work. Maplin contributed over £200 to the Foundation and I would like to thank the staff of the Hammersmith and Birmingham shops particularly and those customers who came forward and donated. Money was also raised at the Head Office in Hadleigh, Essex and my gratitude goes to Hazel and Beryl for their gentle bullying! It is hoped that this will become a Maplin tradition with more support building up each year, as this is a very worthy cause and, let's face it, it only costs Dave Kirk and myself a few aches and pains, not to mention those saddle sores!