Amplifiers

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An analysis of the fundamental nature of amplification, and a description of the working principles of pneumatic, mechanical, carbon, vacuum-tube, transistor, magnetic, and dielectric amplifiers.

A COMMON-SENSE DEFINITION of the word "amplifier" is "a device that makes things bigger." But in technical language the term has a much more restricted meaning; the device referred to becomes an amplifier only when the things that are made bigger consist of energy-patterns. The nature of amplification can probably be better understood by considering first the operation of another energy transmission device that is *not* an amplifier—an instrument that is called, in mechanics, a machine.

The machine receives input power, shapes it for the required task, and releases it, less the inevitable losses from friction, in its new form. Were it not for these losses the amount of energy released would be exactly equal to that received. Although the Indian hunter was able to bring down buffalo with bow and arrow, his arrow was driven by less energy than had been put into flexing the bow. His machine was able to store and concentrate the power that it received when the string was drawn back, so that the shaft sped with lethal velocity. Without the machine the hunter's strength would have been totally ineffective.

The mechanical lever, the acoustical horn, and the electrical transformer are other examples of transmission devices whose useful output energy, while re-formed in such a way as to be most suitable for the application at hand, must always be somewhat less than the input energy. The word "machine" applies to mechanical devices only; the term which includes all instruments of this nature, whatever type of energy is transmitted, is *passive transducer* (from *traducere,* to lead across).

An amplifier is also an energy transmission device, and hence a transducer, but it is an active one. It does that which would be impossible without a sort of engineering sleight-of-hand—it provides a transmission channel whose output, seemingly the same in identity to the received stimulus, contains more energy than its input. The difference is that between a pulley and a powered capstan. It is obvious that the useful output energy of an amplifier cannot be greater than the total energy supplied, any more than it is possible for such a condition to exist in the case of a passive transducer, or energy will have been created out of nothing. The trick is that the input stimulus borrows and directs power from an independent second source (such as the electric company's generators), and shapes this independent power to its own form.

The need for amplifiers arises when we are dealing with impulses which must remain in a very definite time pattern if they are to be useful. One of the earliest amplifying devices was the pipe organ, whose player was able to control, with relatively light pressures of his fingers, the steady flow of air produced by sweating bellows-operators. Amplifiers in the more generally accepted sense, however, were invented when nineteenth century technology became concerned with the transmission and reproduction of vibratory power: first sound, and then radio waves.

Sound consists of successive and alternating compressions and rarefactions radiated by an oscillating source. The telephone and the phonograph therefore depended for their operation on acoustical, mechnical, or electrical forces which continually reversed their directions and which carried the transmitted intelligence in the time sequence and pattern of these oscillations. The problem that faced engineers was to extend telephonic communication over longer distances, to make phonograph reproduction louder than was possible with the original, limited power. The first approach, successful up to a point, was to increase the efficiency of the passive transducer elements. But the best acoustical and electrical passive transducers that could be designed to harness effectively the sources of this oscillatory energy proved inadequate. Sound generators like the human voice mechanism, or the phonograph pick-up diaphragm following the record groove, simply didn't have enough driving power for the work they were called upon to perform, even with the carefully designed horns that increased their radiating efficiency. The solution was to inject outside energy into the systems and to use the original stimuli as controlling rather than driving forces, which is to say, to amplify.

Early Amplifiers

In 1876 Edison patented a device which he called an *aerophone.* It was a pneumatic public-address amplifier, illustrated in *Fig. 1,* in which the speaker's voice controlled the instantaneous flow of compressed air by means of a sound-actuated valve. The air was thus released in vibratory bursts and puffs similiar to those that came from the speaker's mouth, except that they were more powerful, and the speech, still intelligible, was louder. Edison envisioned broadcasting in stentorian tones over distances of several miles. Such a system has actually been used in ports, but it found its main application in the designs of two British inventors who applied it to the phonograph. Short developed, and Parsons further improved the *auxetophone,* whose pneumatic valve was attached directly to a phonograph reproducing stylus. Although pneumatic phonographs produced a constant background hissing noise due to escaping air, they were fairly popular in Europe, and in the early nineteen hundreds the French Pathé company experimented with them

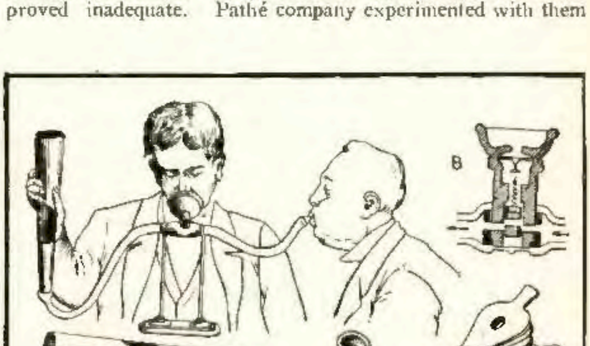

Fig. 1. Edison's aerophone, or pneumatic amplifier, provided a sound transmission channel into which additional energy was injected in the form of compressed air. Inset shows how the sound-actuated valve throttled a steady flow of air, to create an instantaneous variation in flow that imitated the original sound vibrations.

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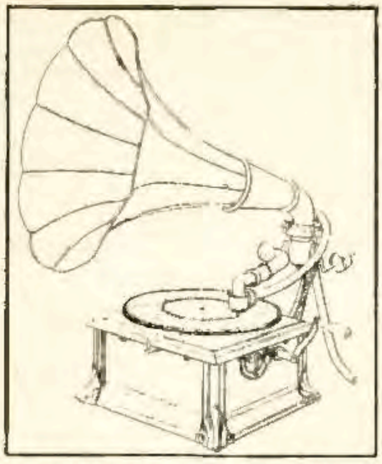

Fig. 2. The Pathé phonograph of 1905 used a compressed-air amplifier.

with a view towards developing talking motion pictures. (See *Fig.* 2.)

Another type of device, the mechanical or friction amplifier, found more favor in the United States. It was used in certain models of Columbia's cylinder "graphophone," as shown in *Fig.* 3. The reproducing stylus of these instruments, instead of being coupled directly to its diaphragm as in standard acoustical phonographs, was attached to the diaphragm via a string and friction shoe that passed over a rotating drum. When the stylus tightened up on the string, friction between the shoe and the drum was increased, and force picked up from the drum augmented the displacement of the diaphragm. When the record groove forced the stylus in the opposite direction, so as to loosen up on the string, the diaphragm returned to its original position due to spring tension. In this way the vibratory path of the diaphragm was extended by the energy of the independently driven drum, and sound output was increased.

Both of the above designs were referred to at the time as relay systems. The original stimulus was thought of as touching off latent power, like a relay runner passing the baton to his successor. These systems were the forerunners of our present-day electronic amplifiers, but they were themselves doomed to a short life. The golden age of mechanics, when the diabolical iron fingers that set printing type, tabulated sums, and rolled cigarettes were the wonders of applied science, was passing. Electronics was taking over, and the amplification of sound was destined to include an intermediary step, the temporary transformation of mechanical vibratory energy into electrical energy possessing the same characteristics in time.

Electrical amplification may be achieved (and still is, in some telephone circuits) by carbon amplifiers, which extend the principle of the carbon microphone. The carbon granules through which current is directed act as a variable electrical gate, whose resistance to current flow is controlled by the pressure of a diaphragm. Changes of pressure, such as would be created by stimulating the diaphragm with sound, create corresponding changes in the amount of current drawn from the source of electric power, and the electrical source releases energy greater in magnitude than that possessed by the input stimulus.

The Vacuum-Tube

The device which really opened up the field of amplification was the vacuum-tube. Fleming had made an electronic valve that contained two electrodes sealed in an evacuated glass chamber, a cathode emitter and an anode collector. When the cathode was heated a cloud of electrons was given off, and if the device was then connected in series with a battery, in such a way that the anode was positively charged relative to the cathode, the electrons were attracted to and entered the anode. Since electrons in motion constitute electrical current the circuit was completed through this one-way path.

The stream of electrons flowing in the empty space between cathode and anode provided an especially favorable area for sensitive control of the current drawn from the battery. The opportunity was seized by de Forest, who introduced a control element into the valve by inserting a "grid"—an open network of fine wire—across the electronic stream. De Forest's grid was a sieve mechanically, but if it was charged negatively relative to the cathode it tended to repel electrons (which are also negatively charged) and to retard current flow. A weak input "signal" voltage applied between grid and cathode, varying according to a given frequency and wave form, produced an imitative variation in the relatively heavy output current flow, as may be seen in *Fig.* 4. This output power could follow the input characteristics more closely than had been possible with any other device designed previously. The limits imposed by mechanical systems—their intractability when subjected to forced vibration in modes foreign to natural resonances, the uneven restraint of elastic suspensions, and the fact that supposedly rigid parts become flexible when subjected to vibration at high frequencies—all disappeared, and development workers found themselves operating in a dream-world of virtually massless units, where incredibly swift oscillation could be controlled and amplified without having to reckon the price of inertia, elasticity or gravity.

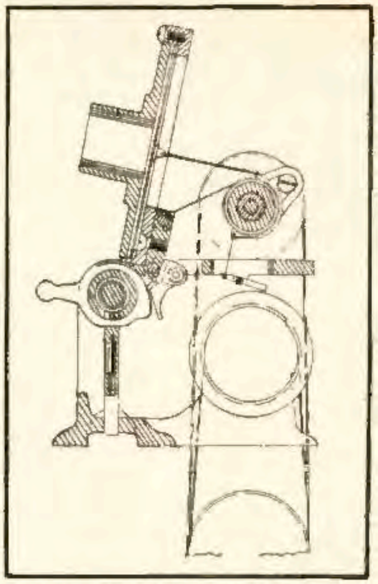

Fig. 3. The stylus of Columbia's cylinder graphophone was coupled to the reproducing diaphragm through a lever-type shank, a string, and a friction shoe that picked up extra energy from the rotating drum.

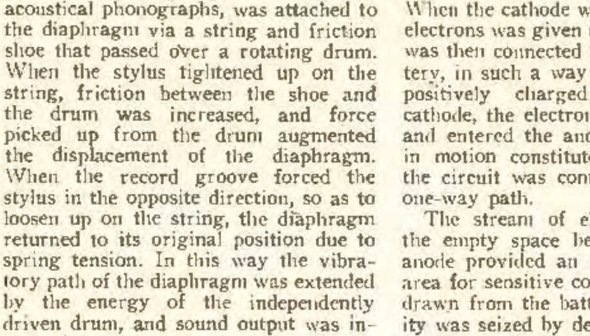

Fig. 4. Amplification of a weak electrical impulse is achieved by a vacuum-tube circuit. The input electrical stimulus has alternating polarity, while the output is in the form of pulsating one-way current. The cathode heating element is not shown.

An early application of vacuum-tube amplifiers was to the generators and receiver of radio waves. Like sound, electromagnetic radio energy is oscillatory, although at frequencies which may be millions of times higher than those of acoustical vibrations. The element analogous to the phonograph horn is the antenna, acting as a passive transducer to the "atmosphere"—and, as in the case of the horn, more efficient antennas were not enough. With transmitter output amplified, however, from a few watts to hundreds of kilowatts, and receiver sensitivity raised to the point where a few millionths of a volt at the antenna created usable reception, wireless global communication became possible. Other applications followed quickly. The recording and reproduction of sound, the detection and measurement of very small quantities of light, sound, pressure, or voltage, the myriad

Fig. 5. The junction transistor is tiny compared to the "sub-miniature" tube, the smallest type made. These are approximately full size. (Courtesy General Electric Co.)

tasks performed by calculating machines, and the sensitive control and regulation of massive machinery became part of the electronic field.

But with poetic injustice, after the vacuum-tube has served as the vehicle for the modern science of electronics, it is being prepared for the scrap-heap, at least in certain applications. The vacuum-tube has several disadvantages, foremost among which is its unreliability. Besides having too short a normal life, the possibility of failure at any time after installation must always be taken into consideration by design engineers. The unreliability of the vacuum-tube is such an accepted fact-of-life that instead of being wired permanently into the circuit, like other components of electronic apparatus, it is plugged into a tube socket to facilitate periodic replacement. In addition to this unreliability the vacuum-tube requires a separate power supply to heat its filament (diverting and wasting most of the energy taken from the independent source), it must be given a warm-up period prior to service, and it is too bulky in some applications. The feature which redeems all of these disadvantages is the superb control which may be exerted over the captive electron stream.

Without abandoning the last feature, new ways in which electrons can be made to submit to instantaneous regulation at high frequencies are being investigated. The transistor, a revolutionary experimental device a few years ago, can aready be ordered by the part number at radio dealers, and development work is also being performed on magnetic, dielectric, and other types of amplifiers.

Transistors

From the electrical point of view materials may be classified according to their resistance to the passage of current, as conductors, insulators, and semi-conductors. In an atom of a good electrical conductor the outermost electronic shell is held so loosely that its electron inhabitants are not associated exclusively with any particular parent atom. The attachment, originally weak because of the relative distance from the nucleus, disappears with the close atomic spacing typical of these materials, and the outer electrons are free to rove. These *free* electrons are able to respond to the force of an electric potential applied across the conductor, and form an electronic wind blowing across the relatively stationary atoms themselves towards the positive terminal, constituting the flow of current. Current does not flow to any appreciable extent in non-conductors because the atoms of insulators hold on grimly to their outer shell electrons, which are more numerous, closer to the nucleus and much more difficult to dislodge.

To impart motion to an electron is to give it added kinetic energy. Quantum requirements dictate that the electrons must fill certain discrete energy levels, that is, that they cannot possess a random amount of energy, and that each energy level can only accommodate a given number of electrons. Therefore the energy of an electron can only be increased or decreased by an amount which brings it into a new step level in which a vacancy exists. The quantum levels of the atoms of a conductor have vacancies, permitting electronic transfer from one level to another. The energy levels of the atoms of insulators, on the other hand, are all filled, so that the system is locked.

The energy level states of semi-conductors (substances such as germanium, selenium, silicon, and the oxides of copper and barium) form a special case. The locked system is upset by the presence of minute impurities, whose outer electronic orbits contain electrons in a number either greater than or less than the amount normal to the pure substance, and which introduce energy levels capable of releasing or accepting electrons. Where the number of outer electrons is greater than normal, excess electrons are available for current flow in the form of an electronic wind, and the substance is called a donor. Where the number of outer electrons is less than normal, the substance is called an acceptor, and vacancies are available for electronic current flow in the form of "hole" conduction (an effective migration of the unfilled spot from one atom to another, a phenomenon which has been aptly compared to the motion of an air bubble in water). These two modes of conduction occur in opposite directions and are called, respectively, *n-type* for negative, and *p-type* for positive. Hole conduction has a positive designation because the migration of holes has the same experimental effect as the transfer of positive charges.

The development of semi-conductor devices has followed the same course as that of the vacuum-tube, from two-terminal systems providing a one-way electronic path, to three-terminal systems in which the electronic flow is made subject to control from an area astride the path. Semi-conductors were used as rectifiers of alternating current long before the word transistor was coined. A potential applied in one direction across the junction of a *p*-type and an *n*-type substance will encounter relatively low resistance to current flow, but relatively high resistance if the polarity and hence the direction of current flow is reversed. This is because the electrons and holes travel towards each other for one polarity, facilitating transfer across the junction, and away from each other for the opposite polarity. The rectifying action may also be described from the point of view of energy-level states; for one polarity, electrons belonging to energy levels capable of releasing electrons are driven towards atoms containing energy levels capable of receiving added electrons, while for the other polarity the opposite effect occurs.

A *p*-type substance sandwiched between two *n*-type substances, or vice-versa, creates the basic design of one type of transistor amplifier. The conducting properties of one of the junctions for "wrong-way" current may be controlled by creating either hole or electron carriers in the sandwiched element (by means of a current through the other junction)—to put it another way, by causing a shift in the electron energy level states responsible for conduction. The pattern of variation of a small controlling current shapes the instantaneous resistance of the unit, and large currents may then be forced to follow the same pattern in time.

The transistor requires no warm up period, is smaller (see *Fig.* 5), cheaper in operating cost, and is potentially so much more reliable than the vacuum-tube that it may be wired permanently into the circuit rather than plugged into a socket. Transistor hearing aids, for example, which are already produced commercially, are smaller than their vacuum-tube counterparts, consume only a small fraction of electrical power for the same amplification (they have no *A* battery) and may ultimately be expected to require less service. The transistor has been developed to a point where it can duplicate many, although not all, of the vacuum-tube functions. One application of the transistor is illustrated in *Fig.* 6.

Magnetic Amplifiers

The electrical amplifiers that have been here described provide circuit paths whose resistance to current flow is varied by an input signal. Such a path may also be produced by an electro-magnetic rather than a resistive unit, which is called a *saturable reactor*.

The impedance of an electrical coil to alternating current is far more than would be expected from the inherent resistance of the wire. Each time that the current increases, drops to zero, and then increases in the opposite direction a magnetic field around the coil builds up, collapses, and builds up again with reversed polarity. This pulsating magnetic field cuts the wires transversely each time that it builds up and each time that it collapses, inducing current of such instantaneous direction as to oppose and reduce the original flow. This is the descriptive analysis of inductive reactance. In the magnetic amplifier the input signal controls the intensity to which the self-induced field can build up, and hence it controls the electrical impedance of the coil.

Among the factors that determine the intensity of the field are the number of turns in the coil, the size of the core, and the material of the core. None of these can be manipulated at high frequencies, but there is another, more easily controllable characteristic that can influence the coil's field strength and a.c. impedance—the magnetic condition of the core. The core will not continue to accept added magnetization indefinitely; there is a natural limit to its capabilities. As the current is increased the core begins to *saturate*, which means that a further increase of current flow through the coil will produce less than the corresponding increase in magnetic field strength.[1] The degree of this saturation may be controlled, electrically, by the input signal.

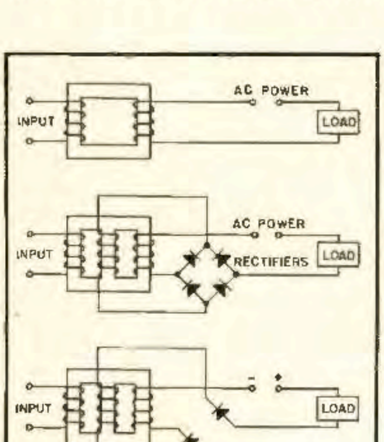

Fig. 7. The top diagram shows the essentials of a magnetic amplifier circuit. Current in the input winding controls magnetic saturation of the core, which in turn controls the impedance of the output winding to the flow of alternating current. The bottom diagram includes rectification of the a.c. power to pulsating d.c., and use of an additional "positive feedback" winding to increase power sensitivity.

A separate winding on the same core, through which the controlling input current flows, will cause the degree of saturation to increase and decrease according to the instantaneous polarity and value of the input signal. A larger current flowing in the output winding, drawn from an a.c. source of power, will then vary in step with the varying impedance.

If the input current must do all of the saturating the power gain will be low, as an appreciable amount of energy is required to saturate the core. A third winding is therefore assigned the major burden of saturation. This winding may carry direct current from a separate electrical supply, or it may carry rectified current from the output circuit. In the latter case the third winding introduces "positive feedback," because the effect of a small input current is re-introduced into the circuit in such a way as to intensify the effect on the output. Small input currents can then control very much larger output currents, and power gains of the order of 100,000 times are obtainable.

In practice it is found necessary for the independent energy source of the magnetic amplifier to supply pulsating direct current rather than alternating current, as shown in *Fig.* 7, so that the saturation effect of the current in the output winding can never oppose that of the input winding. Pure direct current in the output circuit, however, such as is used with vacuum-tubes and transistors, will not work. Direct current would remain uninfluenced by the changes in core saturation; the impedance of the coil to d.c. is entirely a matter of the resistance of the wire conductor. Thus the power that is varied by the input signal is itself a steadily oscillating quantity, but it is a relatively simple matter to separate and extract the amplified impulses from the alternations of the power source. For this purpose the frequency assigned to the power supply is made much higher than the highest-frequency input that is to be amplified.

Magnetic amplifiers are very reliable, have the ability to withstand severe shock, and require no warm-up period. They are also exceptionally efficient, because most of the impedance which they introduce into the output circuit is of a type called reactive, which does not itself absorb energy. (The resistive barrier to current flow introduced by vacuum-tubes and transistors wastes energy in heat.) Magnetic amplifiers are at present advantageously applied in circuits which must control appreciable amounts of power at relatively low frequencies—adjustable-speed motors, winding reels, automatic pilots, voltage and frequency regulators, and other automatic control apparatus. A magnetic amplifier used in servo work is illustrated in *Fig.* 8.

Fig. 6. With the transistor reducing space requirements of tubes and batteries, an electronic megaphone can contain microphone, amplifier, batteries and speaker in one independent unit. (Courtesy General Electric Co.)

Dielectric Amplifiers

In the search for new, more compact, and simple amplifier devices research is being pursued in yet another direction, that of the capacitor or dielectric amplifier. The principles of operation are quite similar to those of the magnetic amplifier, in that a circuit element with variable a.c. impedance is connected in series with an a.c. source of power. The element is not a coil, however, but a capacitor, a system of parallel plates separated by an insulating material or dielectric.

If a battery is connected across a capacitor there will be no steady-state current flow. Electrons move from the negative terminal and charge one side of the capacitor by surfeiting its plates with negative charges; at the same time electrons move from the opposite plates of the capacitor into the positive battery terminal, and leave these plates positively charged by reason of their lack of the normal number of negative charges. The process continues for a short time, until the storage "capacitance" of the device for electric charge is reached, at which point the short-

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[1] A familiar example of this phenomenon is the decrease of inductance in a choke when the current rating is exceeded.

lived current drops to zero again. If the battery is then disconnected, and the two sides of the capacitor are connected through an electrical conductor, there will be another momentary surge of current, this time in the opposite direction. The second surge is created by the capacitor's discharge, which brings the plates back to their original neutrality of charge.

Except for the initial surge, then, capacitors are non-conducting devices for direct current. In an alternating current circuit, however, they are effectively conductors. Although electrons never actually cross the dielectric bridge between plates, each side of the device alternately accepts and discharges electrons, so that as far as the a.c. source is concerned it is able to send electrons into the circuit and receive them back again. The impedance which the capacitor offers to the flow of alternating current is inversely proportional to the frequency of reversal of the electrical alternations and to the value of the capacitance.

In the dielectric amplifier control of current flow is achieved by varying the capacitance. One of the elements upon which the value of this capacitance depends is the material of the separating dielectric. The electrostatic field created by the application of voltage across the capacitor plates produces a molecular strain in this material, and potential energy is stored by the dielectric in a manner comparable to the storage of mechanical energy by a stretched spring. It is this molecular strain and storage of potential energy that makes it possible for the plates to accept and retain their unnatural charges. The amount of charge that will be accepted, and the capacitance of the system, is therefore limited by the amount of energy that can be stored in the dielectric. The quantitative index of this characteristic of the insulating material is called the dielectric coefficient.

It was discovered that the dielectric coefficients of certain materials such as the barium titanates, Rochelle salt, and tungsten trioxide are not constant, but vary significantly with the applied voltage. Since the electrical impedance of the capacitor is directly dependent upon the value of the dielectric coefficient, the latter characteristic may be used as the control element in an a.c.-power circuit, using circuits as in *Fig. 9*. A high degree of amplification may be achieved in this way, with many of the same advantages that are achieved in the case of the transistor. The same oscillating power supply that is used by the magnetic amplifier will work here, so that the dielectric amplifier is suitable for use in conjunction with magnetic amplifiers. It is cheaper than the magnetic amplifier, although not as stable, because the dielectric properties of the titanates that are currently being used are affected by temperature changes, and the gain of the amplifier tends to drift, requiring compensatory measures.

Functional Categories of Amplifiers

In the beginnings of radio an experimenter was able to buy a single type of "audion" or three-element vacuum-tube. Today the number of specialized tube types that have been designed for particular jobs runs into the thousands. Amplifiers may, nevertheless, be classified into a few basic functional categories. These concern (1) the amount of output power required, (2) the band and band-width of frequencies covered, and (3) the degree of wave form distortion to the original stimulus that can be tolerated. The total amount of amplification may be regulated by the number of amplifying stages, of whatever type, connected in cascade.

Heavy tasks, such as the radiation of sound into a room, the engraving of the undulated groove in a disc record, the control of machinery, or the radiation of radio waves by a transmitting antenna, require "power" amplifiers, so-called because of the relatively large amounts of power regimented to the appointed duty. "Voltage" amplifiers or amplifying stages do not differ in principle. They, too, increase the input power, but they are used where the primary requirement is to raise the signal voltage, without a corresponding decrease in current, and where the amount of output power needed is not very great. These conditions are normally present, for example, when the output of a stage of amplification is used to drive another amplifier, perhaps a power amplifier insensitive to weak signals, or when the ouptut is connected to a final load with modest power requirement, such as a pair of earphones.

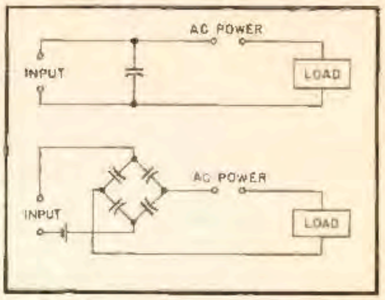

Fig. 9. The dielectric amplifier permits a small input voltage to control the dielectric coefficient of a special capacitive unit. The more elaborate circuit incorporates d.c. "bias" and a bridge arrangement that keeps a.c. power out of the input circuit.

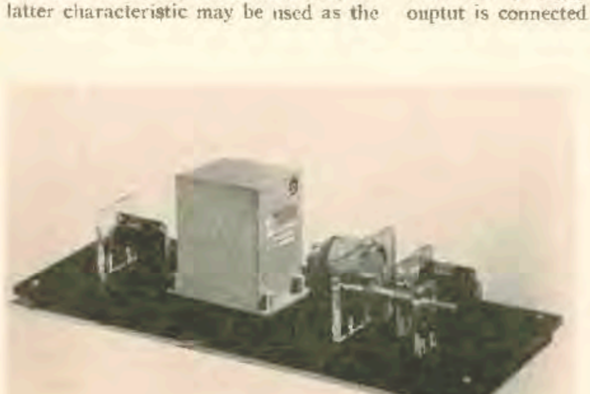

Fig. 8. This "servo" magnetic amplifier may be used to drive a mechanical positioning system. (Courtesy Magnetic Amplifiers, Inc.)

Amplifiers are designed for various frequency ranges between zero cycles (direct current) and the microwave band. The upper limit of the latter is considered to be about 100,000 megacycles, approaching the infra-red region of the electro-magnetic spectrum. Microwave amplifiers are used in radar and television-relay stations. An amplifier that can build up d.c. stimuli, or stimuli that change only slowly, is required for various types of measurement, including such medical applications as the detection of minute body potentials. Each frequency region has its own problems of amplifier design, with regard to both the amplifying units themselves and to circuitry. Microwave circuits, for example, use hollow-pipe wave guides instead of connecting wires, and the transmission lines are often referred to as plumbing because of their physical appearance. Special tubes for microwave oscillators and amplifiers—magnetrons, klystrons, and traveling-wave tubes—have been designed.

Most amplifiers cover only a small portion of the electrical frequency spectrum, but certain types of signal embrace an unusually wide band of frequencies. Video signals, for example, which represent variations of dark and light across successive strips of the picture screen, cover the range from thirty cycles to four megacycles, a ratio of better than 1,000 to 1. Amplifier stages for such signals require special design treatment. A sacrifice in gain must be made in order to achieve broad-band operation.

Increasing the magnitude of the input signal invariably involves a certain amount of wave form distortion, and amplifier stages are classified (as Class A, B, or C) according to the compromise that is made between fidelity and efficiency. A method has been found, called push-pull operation, in which most of the distortion of a compromise amplifier stage can be cancelled by a second compromise stage working alongside.

The degree of output inaccuracy in a high-quality audio amplifier is ordinarily less than the degree of hearing

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discrimination for such inaccuracy. The main sources of distortion in sound reproducing systems are the electro-mechanical and electro-acoustic transducers—pickups and loudspeakers—but even here amplification helps matters. When the efficiency requirements of the passive transducers are reduced by virtue of the amplifier it is easier to subdue annoying mechanical resonances, a step that improves performance considerably.

The possibilities of securing amplification from new types of devices have by no means been exhausted. nor have current amplifying devices been fully covered here. Research in basic amplifier units and in applied circuitry is continually going on. The amplification of oscillatory or otherwise variable stimuli occupies a central position in modern applied physical science. Although the popular drama of nineteenth century gadgets may be missing, revolutionary work is being performed.