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Magnetic Audio Frequency Fundamentals

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Challenging the electron tube in its well established position as the basic amplifier component, the magnetic principles invoked offer a promising field of new development.

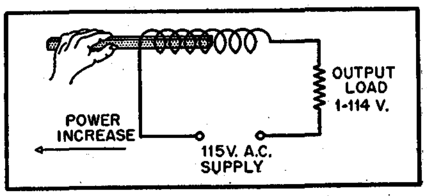

Fig. 1. Basic principle of controlled reactance. The position of the core in the coil is varied.

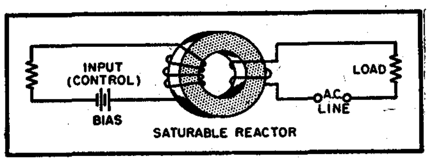

Fig. 2. In the saturable reactor, the core remains stationary, but its permeability is varied by a control circuit in which d.c. flows.

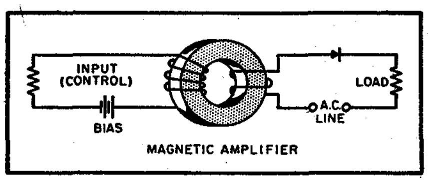

Fig. 3. The addition of a rectifier in the load circuit improves performance by eliminating self-saturation.

Summary: A brief history of magnetic amplifier development is given, with a preliminary description of the operating principles. Comparisons between electron-tube amplifiers and magnetic amplifiers are made, and a number of basic circuits are shown. The advantages and disadvantages with respect to conventional tube amplifiers are listed, with indications of future advances in the art.

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Electronic engineers are beginning to accept the fact that competitors to the electron tube are not only a reality but are here to stay. The Bureau of Ships is interested in these devices primarily because of their reliability and long life compared to that of the electron tube.

The most formidable competitors to these tubes are transistors, magnetic and dielectric amplifiers, and more recently, the promising resistance or crystal amplifier (a semi-conductor responding resistively to magnetic fields).

The transistor has been thoroughly described in numerous publications. Dielectric amplifier fundamental data has recently been assembled and published in the Bureau's monthly periodical *"Electron."* Material is now being prepared on the resistance or crystal amplifier.

A considerable amount of material has been published on magnetic amplifiers, most of which pertained to servo and other electro-mechanical control applications. Very little data is available on high-speed applications, with the possi-

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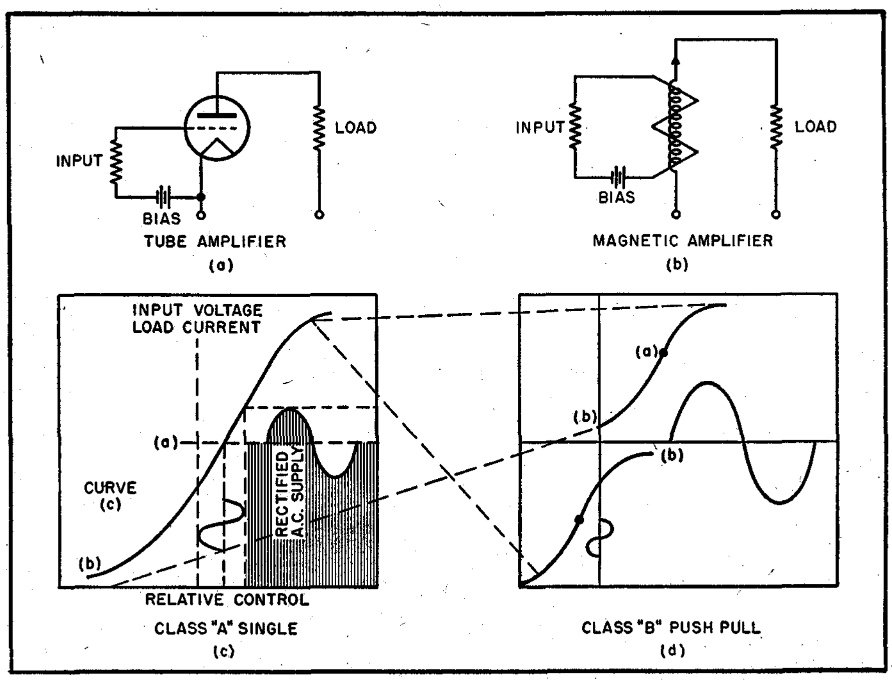

Fig. 4. (a) Simplified tube amplifier, and (b) simplified magnetic amplifier; (c) characteristic, Class A showing operation on linear portion of curve; (d) characteristic converted for push-pull operation.

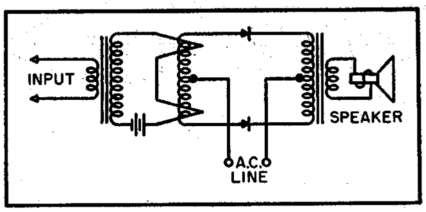

Fig. 5. Simplest form of audio amplifier employing magnetic principles.

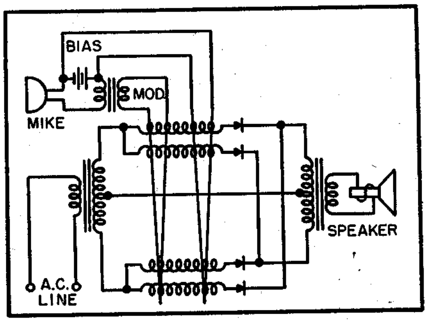

Fig. 6. Single-stage audio amplifier capable of gains up to several hundred.

ble exception of some special magnetic computer circuits, responding to impulses up to 400 kc. Only minor exploratory tests have been made with magnetic circuits at audio and radio frequencies. These tests showed that gains of over 100 per stage can be obtained at audio frequencies and at radio frequencies up to 200 kc. These experiments were made primarily to demonstrate the feasibility of using the device at these frequencies. Reasonable amplification fidelity was obtained, but with low efficiency. Before any attempts were made to improve the efficiency, the developments were terminated in favor of more pressing demands in the computer field. Research in this field was considered more important due to the greater number of tubes involved.

It is believed no further efforts have been made towards developing magnetic audio amplifiers in this country, although it is understood a 500-watt magnetic audio unit was designed for a European airport, showing excellent response up to 7000 cps. The carrier power supply in this instance was 20 kc. This installation, however, required hot-cathode rectifiers.

Recent improvements in core material, rectifiers, and circuitry have elevated the magnetic amplifier, within its limitations, to a reasonably competitive position with the tube amplifier.

Description

For those not familiar with the basic principles of the magnetic amplifier itself, the following description and figures may be helpful.

Figure 1 shows a coil of wire surrounding an iron core. With the core completely within the coil, the reactance to a.c. will be high, restricting the flow of current to the load; with the core removed the impedance drops to about that of the d.c. resistance of the wire; intermediate positions of the core vary the power to the load accordingly. Since it would be difficult to move the core rapidly to follow an audio frequency, a separate winding is used to control the saturation of a stationary core, as shown in *Fig. 2.* This would be satisfactory as an amplifier except that the power sensitivity would be relatively low since the control ampere-turns must be equal to the load ampere-turns, plus sufficient ampere-turns to control the core.

In *Fig.* 3, a rectifier is inserted in series with the load circuit. This eliminates the negative output-winding current pulses that drive the core away from saturation which would require a greater cancelling control-winding current. This is referred to as self-saturation. Self-saturation is not the inclusion of positive feedback, but the elimination of negative feedback whereby the control current for a given output voltage is made independent of the output current. Because of the increased power sensitivity, self-saturation circuits are usually considered for audio applications.

In order to understand the principles involved in audio frequency, a rough analogy between a tube and a magnetic amplifier should be made. Any attempt

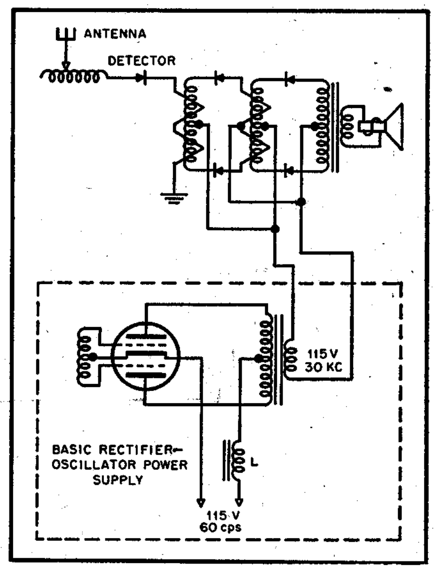

Fig. 8. Typical arrangement for radio receiver use, employing magnetic amplifier circuits throughout.

to analyze the magnetic amplifier in direct relation to a tube requires that certain assumptions be made, as this amplifier differs considerably from those using electron tubes. However, since the input saturation-control voltage vs. load current of an iron core can be made to follow almost precisely that of a tube, a theoretical analysis can be made on the straight portion of the curve.

Analysis of Operation

Figures 4 (a) and (b) are sketches of a tube and magnetic amplifier; (c) is a curve showing magnetic saturation vs. impedance in a magnetic amplifier. Since this curve almost duplicates that of certain type tubes, operating characteristics of both can be plotted on the same curve. For a fair comparison the "plate" supply of both amplifiers must be a.c., for a magnetic amplifier will not control d.c. If this amplifier is to be used to amplify audio frequencies, the supply frequency should be above audibility—at least three times the highest frequency to be controlled. Since both amplifiers are single ended, they must be operated as class A, half way up the slope, as shown in curve (c), point *a*. The operation analysis then follows along the lines of a class A tube amplifier.

These amplifiers working as class A would not only be inefficient, but provisions would have to be made to separate the carrier from the voice frequencies; consequently they would be normally operated class AB push-pull. With this connection the carrier can be biased out, as indicated by point *b* in (c). This makes it possible to use coils and rectifiers of lower capacity. (In machinery applications, control is usually effected near the upper end of the saturation curve, near the point of abrupt saturation. This results in greater power sensitivity.) With push-pull connection the "plate" supply rectified pulses are also doubled and smoothed out. *Figure* 4 (d) shows idealized push-pull transfer curves.

Figures 5 and 6 show further developments of push-pull amplifiers. *Figure* 6 is a single-stage amplifier capable of gains up to several hundred. Control and bias winding are shown as two single loops; actually they consist of four individual coils wound aiding and opposing to cause an alternate high and low impedance in each pair of load reactors. This results in a rather low efficiency, necessitating relatively large reactors and rectifiers, but does result in improved fidelity when using components not specifically designed for the purpose. *Figure 7* shows another circuit developed for audio frequencies, and *Fig.* 8 outlines the general application as a whole. Although these schematics are

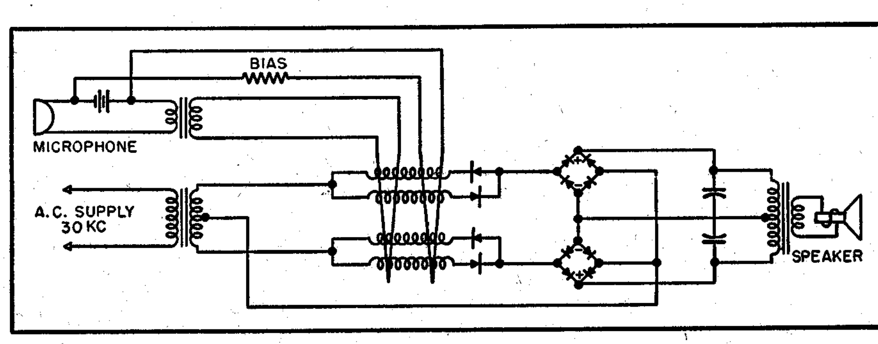

Fig. 7. Further steps in development of suitable circuit for audio applications.

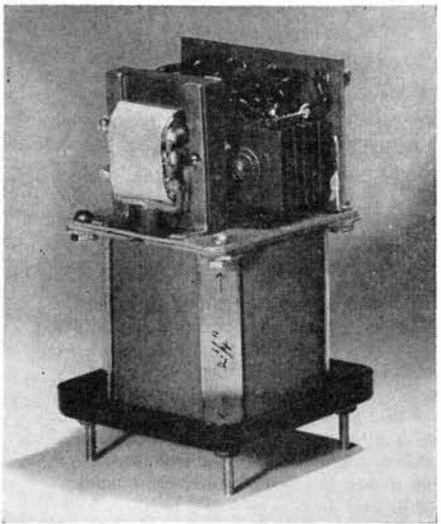

Fig. 9. Production model of 400-cps, 10-watt control amplifier—approximately same size as that required for a 5-watt audio unit. For audio use a different core material and higher-frequency carrier would be used. Photograph courtesy Magnetic Amplifiers, Inc.

possibly too simplified, they illustrate the operating principles. Design specifications would call for a better oscillator power supply. In addition, the amplifiers would include inverse feedback, bridge rectifiers, padding, filtering, and so on. *Figure* 9 shows a production model of a 400-cps, 10-watt control amplifier. The manufacturer indicates a 5-watt audio component would be comparable in size and weight.

Performance

Figure 10 is an oscillogram of the output waveform of a 100-watt magnetic amplifier built two years ago to determine the capabilities of the device at audio frequencies. The circuit used was that of *Fig. 6*; *Fig.* 11 shows the response curves. A 10-kc motor-generator was used as a power supply, and the 10-kc ripple can be noted on the peaks of the signal frequency.

The curves indicate remarkably good reproduction, considering the fact that ordinary machinery-type reactors and rectifiers were used in the amplifier.

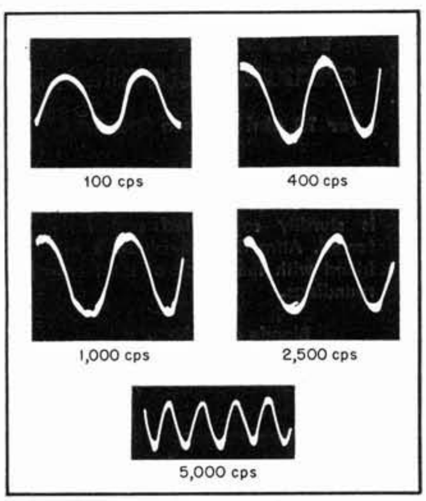

Fig. 10. Output waveforms for various frequencies. These cuts were made from actual oscillograms made from a 100-watt magnetic amplifier.

Oscilloscope patterns indicating the response of magnetic core material triggered by 1-mc pulses are shown in *Fig.* 12. Although only remotely related to audio applications, they are included to show that the response of a magnetic amplifier is adequate for any radio requirements.

The core material used to obtain the above patterns was 4-79 molybdenum steel tape 1/8-mil thick and 3/32-in. wide; the ratio of inductance from zero to maximum saturation was 4:1; the power supply was 3 mc at 20 volts. Indications are that the response of steel tape core material is superior to the currently available ferrite cores at this frequency.

According to two British investigators, Williams and Noble, it is possible to amplify control signals of 10^{-18} watts at a bandwidth of 10 cps in a special magnetic amplifier having a basic limitation of 4×10^{-20} watts due to thermal noise. Barkhausen effects in the same magnetic amplifier are equivalent to a signal input of 10^{-19} watts for a bandwidth of 1 cps. Drift is the major limiting factor in low-input applications.

From the above investigations it is apparent that the low-level limits of the amplifier are adequate to meet normal requirements. It has already demonstrated its ability to amplify relatively pure sine waves well into the r.f. spectrum.

Indications are that magnetic amplifiers have several advantages over equivalent tube amplifiers, namely:

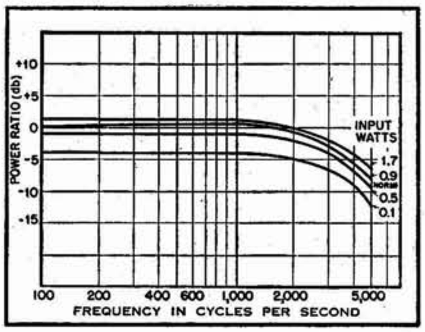

Fig. 11. Response curves for 100-watt amplifier used in making oscillograms of Fig. 10.

1. Reliability. The rectifier is the life-determining factor. Selenium rectifiers currently in use have a normal life expectancy of around 60,000 hours. Modern crystal rectifiers have a similar life, with a much higher efficiency, but are limited, at the present stage of development, to a forward current of about 500 ma, and an inverse peak voltage of 400.
2. Require no warm up time.
3. Power consumption (with push-pull class B connection) during standby periods is low.
4. Fewer components.
5. Rugged; practically indestructible.
6. Will withstand considerable overloads.
7. Unbalanced effects in balanced circuits, due to cathode emission changes, are less, because the stability of a rectifier is greater than that of a hot cathode.
8. Relatively unaffected by fungus, moisture, and heat.

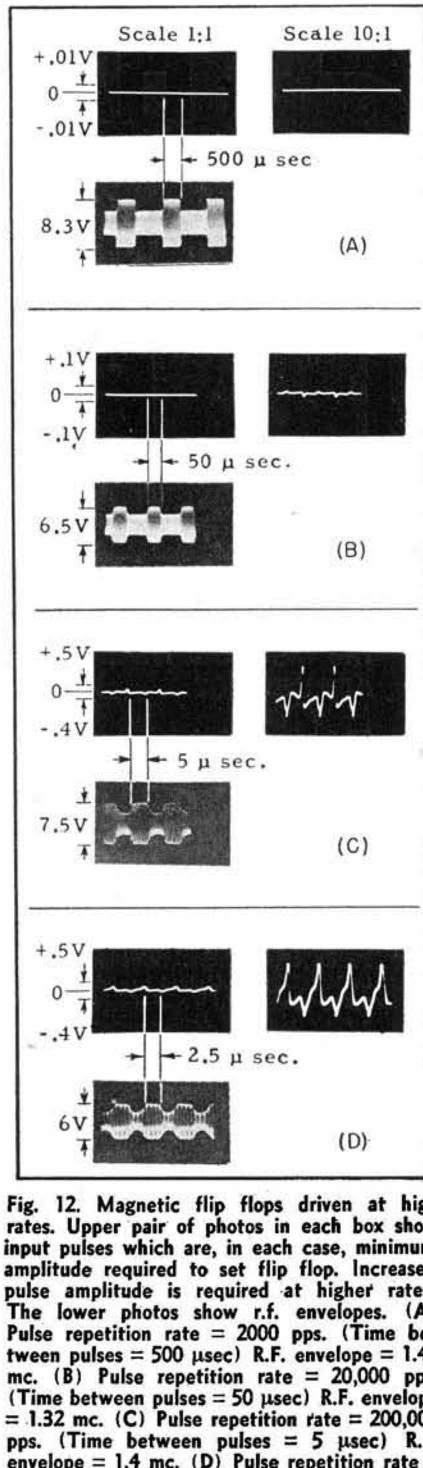

Fig. 12. Magnetic flip flops driven at high rates. Upper pair of photos in each box show input pulses which are, in each case, minimum amplitude required to set flip flop. Increased pulse amplitude is required at higher rates. The lower photos show r.f. envelopes. (A) Pulse repetition rate = 2000 pps. (Time between pulses = 500 μsec) R.F. envelope = 1.42 mc. (B) Pulse repetition rate = 20,000 pps. (Time between pulses = 50 μsec) R.F. envelope = 1.32 mc. (C) Pulse repetition rate = 200,000 pps. (Time between pulses = 5 μsec) R.F. envelope = 1.4 mc. (D) Pulse repetition rate = 400,000 pps. (Time between pulses = 2.5 μsec) R.F. envelope = 1.5 mc.

The disadvantages are:

1. Currently, until mass production of core material and rectifiers is established, these amplifiers will cost more.
2. No suitable static r.f. power supply is available. This makes it necessary to use a tube oscillator as a power supply. This is not a serious disadvantage, however, when one considers that an electron

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tube amplifier also requires a power supply (rectifier-filter) to convert the 60-cps a.c. to d.c. A similar tube to convert 60-cps to 30 kc would be comparable in size. Tube manufacturers indicate that this oscillator tube can be made with a life expectancy of 10 years, ruggedized for proximity fuse applications if desired.

3. Until more efficient rectifiers and improved circuitry are developed, this amplifier will be less efficient and possibly larger than equivalent tube units.

From the small efforts made toward magnetic audio amplifiers, it appears that there may be tremendous possibilities in this field, especially in high-power applications.

NOTE: Most of the material used in this article was obtained from a Bureau of Ships pamphlet, NAVSHIPS 900, 172, titled "Magnetic Amplifiers, A Rising Star in Naval Electronics," published several months ago to stimulate interest in the magnetic amplifier. This material has not as yet been evaluated by the Bureau Engineers.