Decade amplifier and pre-amplifier. These units are designed to provide a wide range of accurately known voltage amplification with low distortion and noise level.

A Flexible Decade Amplifier

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Describing an audio amplifier having exceptionally fine characteristics for exacting laboratory test purposes.

THE AMPLIFIER to be described was developed primarily for use in measurements of noise, frequency response, distortion, etc., on experimental magnetic recording systems. Although this use appears to be somewhat specialized, there is no feature of the amplifier which limits it to this particular application. Its flexibility and performance are such as to recommend it for a wide variety of work at audio frequencies. However, since it was developed for use in conjunction with magnetic recording systems, it will be described in terms of the requirements imposed by this application.

The design objective was an amplifier having highly stable gain adjustable over a wide range of known values. Exceptionally low distortion and noise, and uniformity of gain over a wide frequency range were also required. In addition, it was desired to make the unit flexible, convenient to use and to service, and to use standard components wherever possible.

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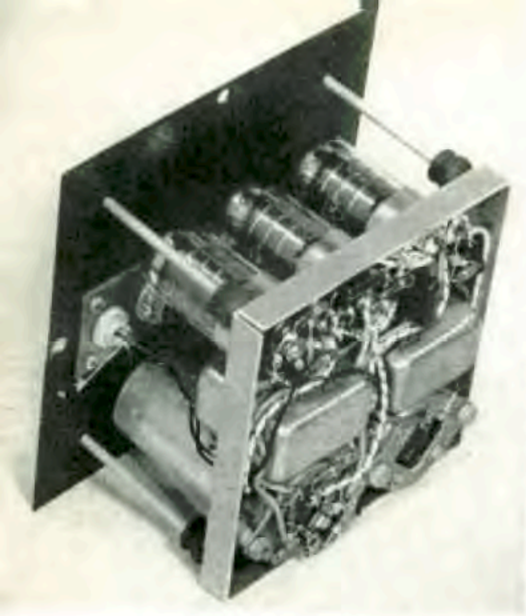
General Description

The design which has finally evolved consists of two units; a pre-amplifier in a small box which can be placed within a short distance of the reproducing head of a magnetic recording system, and the main amplifier and power unit. The pre-amplifier gives a nominal voltage gain of 100 with a one-step attenuator at the input, which reduces the gain to 10. The main amplifier gives an additional voltage gain of 100 with a similar attenuator at its input. In addition, there is an accurately calibrated potentiometer-type attenuator in the main amplifier so that intermediate values of gain are readily available. Both input and output leads of each unit are brought out to terminals so that the two units can be used separately, in cascade, or with an equalizer or filter between the pre-amplifier and the main amplifier. The input impedance of each unit is of the order of 500,000 ohms. The output impedances are comparatively low, for voltage amplifiers, and a wide range of load impedances can be used. Either unit can be used with such loads as a Ballantine voltmeter, oscilloscope, headphones, the usual recording head circuits, or the input to a power amplifier stage.

Rear view of chassis of main unit of decade amplifier. Power supply components are at the back of the chassis and the amplifier stages at the front. The potentiometer on the front panel is an accurately calibrated gain control.



View of pre-amplifier chassis showing manner of supporting entire unit from front panel.

Mechanical Construction

The pre-amplifier is housed in a sheet metal box 6" x 6" x 4". It consists of three type 1280 tubes with their associated circuit components mounted on a small chassis bent up from a sheet of 1/16" aluminum. The chassis is supported at each corner by a rubber shock-mount. The chassis is supported entirely from one panel of the box and all external connections and the attenuator switch are mounted on the same panel. Thus the pre-amplifier can readily be removed from its box for inspection or testing. The leads from the chassis to the panel are made with flexible wire to minimize transmission vibration to the chassis. External connections are made through standard microphone connectors and shielded leads, thus making possible complete electrostatic shielding of the pre-amplifier and all leads to it.

The main amplifier is built on a standard 10" x 12" x 3" chassis and is housed in a sheet metal box 10½" x 14" x 8". The power supply is built across the rear of the chassis and the amplifier stages across the front. A sheet metal partition underneath the chassis provides electrostatic shielding between the power supply and the amplifier stages. The controls provided are an on-off switch, a 10 to 1 attenuator switch, a calibrated gain control, and a switch to connect the two amplifiers in cascade or to bring the output of the pre-amplifier and the input of the main amplifier to the front-panel terminals.

Space was provided in the main amplifier unit for the addition of a flexible low-frequency equalizer and two additional stages of amplification should these become desirable at some later date.

Electrical Design

The pre-amplifier consists of two resistance-coupled pentode stages and a cathode follower as shown in the circuit diagram, *Fig. 1*. Feedback is taken from the output of the cathode follower to the cathode of the input stage through an adjustable resistance. This resistance permits presetting the gain to a value of 100. A pentode is used for the input stage in order to keep the input capacitance low. A cathode follower is used for the output stage in order to provide low output impedance.

The main amplifier consists of a cathode follower, two resistance-coupled pentode stages, and another cathode follower, as shown in the circuit diagram, *Fig. 2*. The first cathode follower is used as an impedance transformer between the high-impedance input and the relatively low-impedance calibrated gain control. The output from the pre-amplifier is normally connected to the input terminals by means of a shielded cable. The double-pole, double-throw switch S is normally in the down position. However, if it becomes desirable to insert a filter, an equalizer, or any other similar device between the pre-amplifier and main amplifier, the switch S can be placed in the up position and the auxiliary terminals A and B will then be available for the insertion of such a device. The remainder of the circuit is similar to that of the pre-amplifier.

The power supply is unconventional in that all tubes except the rectifier and voltage regulator are heated by well-filtered direct current. In order to keep the power supply from being too massive and unwieldy, tubes having 150 ma heaters were used. Since high voltage was not required for a power stage, a standard power transformer designed for high current output at a relatively low voltage was used. The output from the rectifier is heavily filtered to insure a wide margin of safety from troubles due to power supply ripple. Heater current is taken from the output of the filter through an adjustable resistance. Plate voltage for all stages is also taken from the output of the filter, and is regulated by a VR150 tube.

PERFORMANCE DATA

Intermodulation Distortion—In making measurements of non-linear distortion on magnetic recording systems, it was anticipated that measurements would be made of distortion components having amplitudes well below one per cent of the amplitude of the applied signal. If an amplifier is to be used between the reproducing head and a wave analyzer, this imposes the requirement that the amplifier shall deliver a few volts output with harmonic distortion of the order of 0.1 per cent or less. In terms of intermodulation as measured on an Altec-Lansing intermodulation analyzer, this would be about 0.4 per cent intermodulation, or less.

Fig. 3 shows curves of per cent intermodulation versus output voltage (as read on a Ballantine voltmeter) for the pre-amplifier unit and for the main amplifier unit, output being expressed in decibels above one volt. The frequencies used in these measurements were 60 and 7000 cycles per second. The load was a 10,000

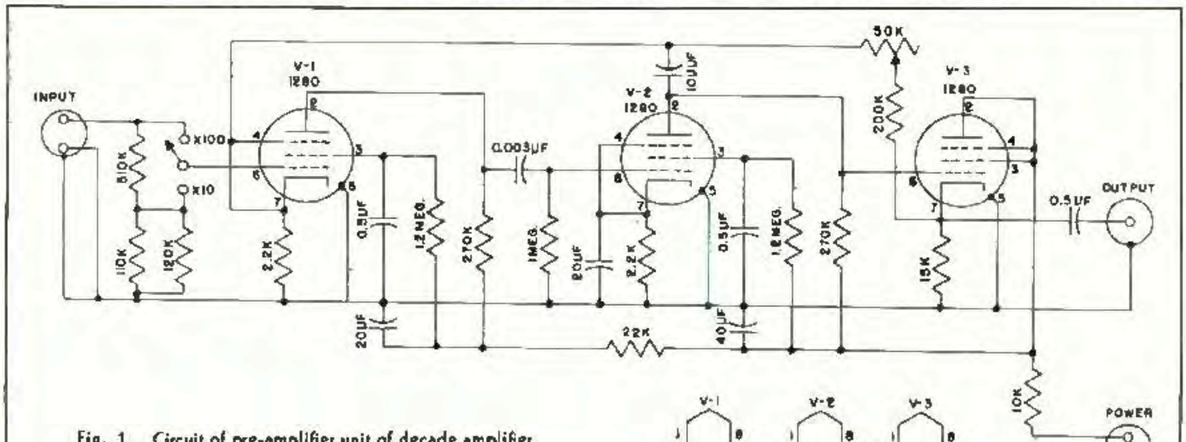


Fig. 1. Circuit of pre-amplifier unit of decade amplifier.

ohm resistance in series with the 600 ohm input to the intermodulation analyzer. Measurements were also made at all other combinations of frequencies available from the intermodulation analyzer signal generator. These were 40, 60, and 100 cycles per second for the low frequency, and 2000, 7000, and 12,000 cycles per second for the high frequency. There was no appreciable difference between any of these measurements and those plotted in *Fig. 3*. There was no significant difference between the intermodulation measured with the main amplifier alone and that measured with two units in cascade, each set for a gain of 10.

The measurements represented by the dashed portions of the curves are influenced by noise, and become increasingly inaccurate as the output decreases. For this reason the slight rise in intermodulation distortion with decreasing output indicated by the curves is considered to be an error in measurement rather than a real effect. The only information available from the measurements in this region is that the intermodulation distortion is less than, or at most equal to, the values indicated by the curves.

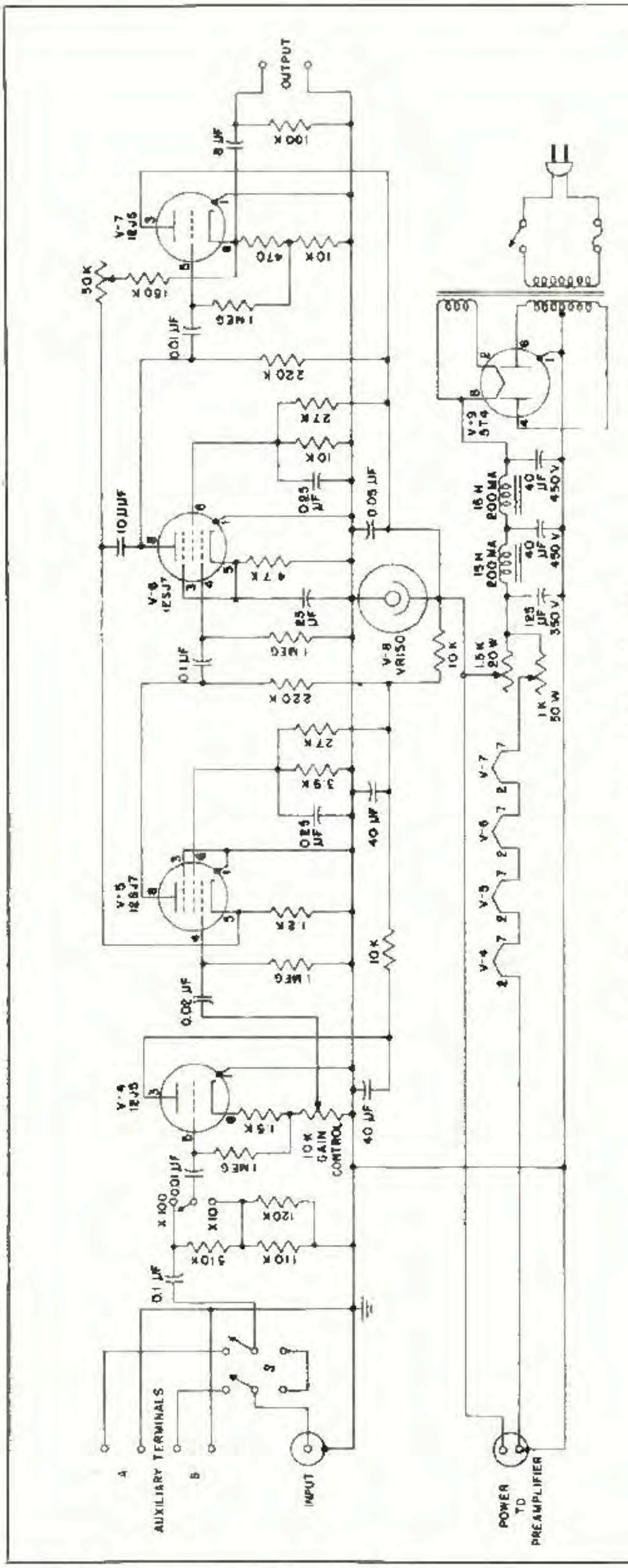


Fig. 2. Circuit of main amplifier unit of decade amplifier.

Output Voltage

It is evident from the curves that either amplifier will deliver an output voltage 16 or 17 db above one volt before the intermodulation distortion exceeds 0.4 per cent. This is equivalent to about 11 or 12 volts peak, or about 8 or 9 volts rms, for a single sine wave. The Ballantine meter reads practically the same with a low-frequency signal alone, and with a low-frequency signal upon which is superimposed a high-frequency signal of one-fourth its amplitude. The latter is the combination used in making the intermodulation measurements. Thus, a voltage reading on the Ballantine meter should be multiplied by 1.25 to take this effect into account, and then by 1.4 to find the peak value of the wave.

Several measures were employed in achieving the low values of distortion indicated by the measurements. By far the most potent single measure is the use of inverse feedback directly from the output of each unit to the cathode of the first amplifier stage. It is estimated that the feedback used amounts to about 40 db in each loop; i.e., the gain with feedback is about 40 db less than without feedback. Avoiding the use of transformers or reactors whose impedance changes rapidly within the frequency range of interest insures that the feedback will be effective throughout the range and that the distortion will not change radically within this range. In addition to using feedback in the main amplifier for low distortion, it was found that considerable improvement could be made by adjustment of the voltages on the elements of the second 12SJ7 and of the bias of the cathode follower output stage. This necessitated the use of a coupling condenser between the two stages in order to obtain independent control of the grid bias voltages. The distortion of the pre-amplifier was initially low and no attempt was made to improve it further by adjustment of voltages.

Gain and Frequency Range—It was anticipated that there would be occasion for making measurements at frequencies from about 20 to about 20,000 cycles per second. It is obviously desirable to have the gain of the amplifier as uniform as is practically possible within this range at any setting of the attenuators. It is also desirable to have the gain independent of signal-source impedance and of load impedance over a wide range.

Fig. 4 shows the gain of each of the two units versus frequency, with the attenuators set for maximum gain. These measurements were made using two Ballantine voltmeters, one reading the input voltage and the other the output voltage of the unit under test. Variation of gain over the frequency range of interest is less than one decibel for either unit, most of the variation occurring between 20 and 30 cycles per second. Measurements of gain were also made with other attenuator settings, with only slight variation in the shape of the curves. For instance, with the attenuator switch of the pre-amplifier set for a gain of 10, the gain at 100,000 cycles per second was down five db from that at 1000 cycles per second, while, with the switch set for a gain of 100, the corresponding figure was 4 db. The difference in shape below 20,000 cycles per second for the same conditions was negligible.

Uniformity of gain over the desired frequency range was attained by several means. Using adequate coupling and bypass capacitors and avoiding the use of transformers tends to reduce variation of gain with frequency. Inclusion of as much as possible of each amplifier circuit in a feedback loop further reduces variation of gain in the frequency range of interest. In addition to these obvious methods of securing uniform gain, several other expedients were used. For one, the input capacitance of the pre-amplifier was made low by using a pentode input stage, and by using mechanical construction such that the unit can be located near the reproducing head of a magnetic recording system, thereby keeping the connecting cable short and its capacitance small. It had been found in previous experimental setups that the capacitance of the cable and of the amplifier input were large enough to resonate with the inductance of a high-impedance reproducing head, thereby introducing an error into frequency response measurements. Keeping the input capacitance of the pre-amplifier low was an attempt to reduce this error.

Another expedient is the use of a cathode follower as an impedance transformer at the input of the main amplifier. This permits a high-impedance input and the use of a relatively low-impedance gain control. The gain control is a 10,000-ohm potentiometer calibrated with an accuracy of plus or minus one per cent plus or minus one-half dial division, with a total of 50 dial divisions. Use of the low-impedance gain control reduces the effect of shunting capacitances to a negligible value, and insures uniform gain over the desired frequency range at any setting of the gain control.

Still another expedient is the use of a cathode follower as the output stage of each unit. This, together with the large amount of inverse feedback, makes the impedance looking back into either unit very low. Thus, the capacitance of the cable connecting the two units does not appreciably affect the gain at high frequencies. Furthermore, the variation of gain with load impedance is undetectable for any load above 10,000 ohms, thus eliminating variations of gain when using reactive loads.

Above 20,000 cycles the gain is deliberately made to fall off by use of a 10 $\mu\mu f$ capacitor from the plate of the second 12SJ7 to the cathode of the first, and similarly in the pre-amplifier. This eliminates regeneration at about 200 or 300 kc which tends to produce a large increase in gain in that region, or even oscillation.

Noise—The lowest noise measurements that we have made up to the present time on magnetic recording systems show minimum values of noise of about 5 or 6 microvolts from a system using a high impedance reproducing head having good frequency response, a nda recording speed of 24 inches per second. In order to be able to make accurate measurements and to provide for possible lower noise levels it is obviously necessary to have the noise generated in the amplifier as much lower than this as it is practicable to make it.

The noise level finally achieved is equivalent to about 1.5 to 2 microvolts at the input to the pre-amplifier, with the input shortcircuited and with a pass band equivalent to a 10,000 cycle rectangular band. This is not quite the ultimate that can be achieved, but any substantial improvement would have required the use of a high-mutual-conductance triode as the input stage, the sacrifice of the low input capacitance attainable with a pentode, the use of batteries or a much bulkier power supply, and the provision for more elaborate shock mounting of the pre-amplifier.

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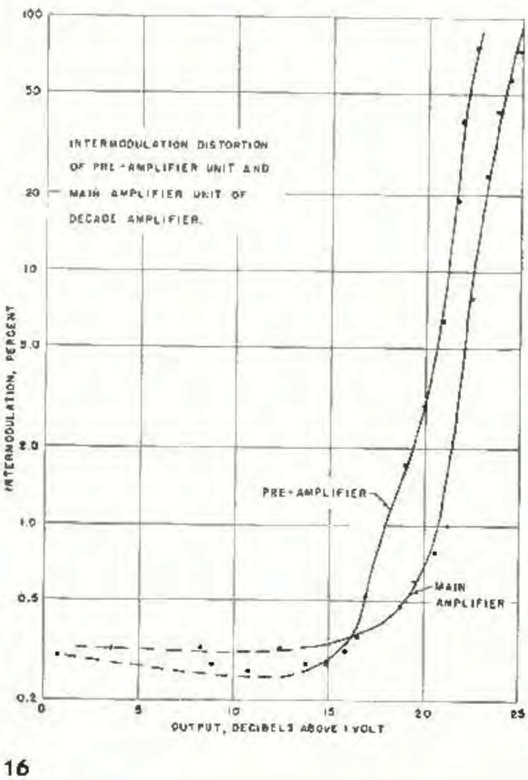
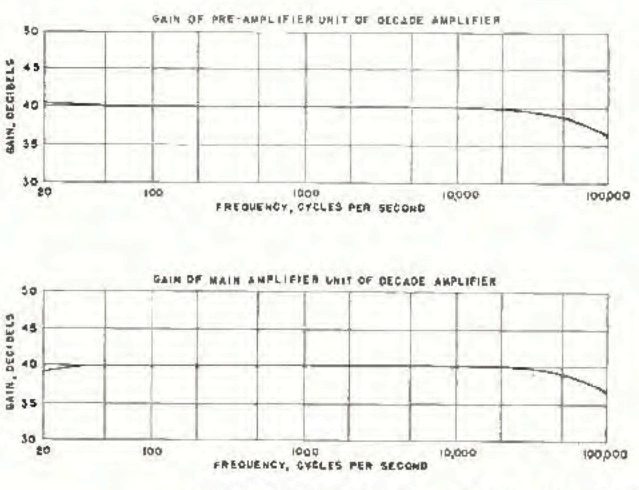


Fig. 3. Per cent intermodulation versus output voltage for pre-amplifier and main amplifier unit.

Fig. 4 (below). Gain vs. frequency curves.



Decade Amplifier

[from page 16]

The noise level of the main amplifier is somewhat higher than that of the pre-amplifier but is not a limitation for any ordinary use. The noise voltage read at the output of the main amplifier with the gain control at zero is at times barely detectable on the 0.01 volt scale of a Ballantine voltmeter, which reads down to 0.001 volt.

Rather elaborate means were employed to obtain this low noise level. One obvious source of trouble was effectively abolished by heating all tubes except the rectifier and voltage regulator with well-filtered direct current. This made it unnecessary to carry any a-c power into either amplifier compartment. The result is that the hum component in the noise is not detectable when observed on an oscilloscope.

The noise was minimized in other ways by using selected "non-microphonic" tubes in the pre-amplifier, shock mounting the pre-amplifier, restricting the frequency range, and using complete electrostatic shielding of the pre-amplifier and associated wiring. Of the several types of "non-microphonic" tubes available, the 1280 was chosen because it apparently is the only type with a 150 milliampere heater. This feature is desirable for the sake of economy and minimum power supply bulk when using direct current from a rectifier and filter for heating the tubes. The tube for use in the first stage of the pre-amplifier was selected from six available for lowest noise. Three of the six were found to be suitable for use in the first stage.

Restricting the frequency range is useful in reducing noise because thermal-agitation noise voltage varies as the square root of the bandwidth. Further restriction of any desired degree can be employed by inserting a simple resistance-capacitance filter between the pre-amplifier and the main amplifier.

Stability—In order for an instrument of this type to be most useful in everyday laboratory work, it is necessary that there be a minimum of critical adjustments, and that its characteristics be essentially independent of aging, changing tubes, or varying line voltage.

The only critical adjustments are the potentiometers in the feedback circuits which vary the gain over a small range. These potentiometers are set to make the voltage gain of each unit equal to 100, and should not require frequent adjustment. The one-step attenuators were made up to accurate attenuation values from selected five-percent resistors.

Use of a large amount of inverse feedback makes the characteristics of the amplifier essentially independent of small changes in circuit component values, in tube characteristics, or in supply voltage. Changing tubes results in a variation of gain of one or two per cent, or less, and negligible variation of distortion. Variation of the a-c supply voltage from 130 volts to 110 volts results in a change of gain of about plus or minus two per cent from that at 120 volts.

One form of instability usually encountered in a new design of a high gain amplifier is a tendency toward oscillation. This one was no exception, each unit originally oscillating by itself and, after this was overcome, oscillating when the two were used together. Oscillation in the pre-amplifier was due to phase shift at high frequencies which caused the feedback to become positive in the neighborhood of 200 or 300 kc. The phase shift was due to the shunting effect of stray and tube capacitances. The 10-$\mu\mu$f capacitor from the plate of the second 1280 to the cathode of the first completely eliminated any tendency to oscillate in this region. A similar capacitor was included in the main amplifier because it was regenerative in this region, although it did not actually oscillate there.

Oscillation in the main amplifier was due to phase shift at low frequencies in by-pass and decoupling networks. Use of voltage dividers of fairly low impedance rather than series resistors to supply screen voltages completely eliminated any tendency toward oscillation in this region.

Oscillation when the two were used together was due to coupling through the B + lead to the pre-amplifier at frequencies of 20 or 30 kc. This was effectively eliminated by by-passing the voltage regulator tube with a small capacitor.

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