

IMPROVING THE WILLIAMSON AMPLIFIER

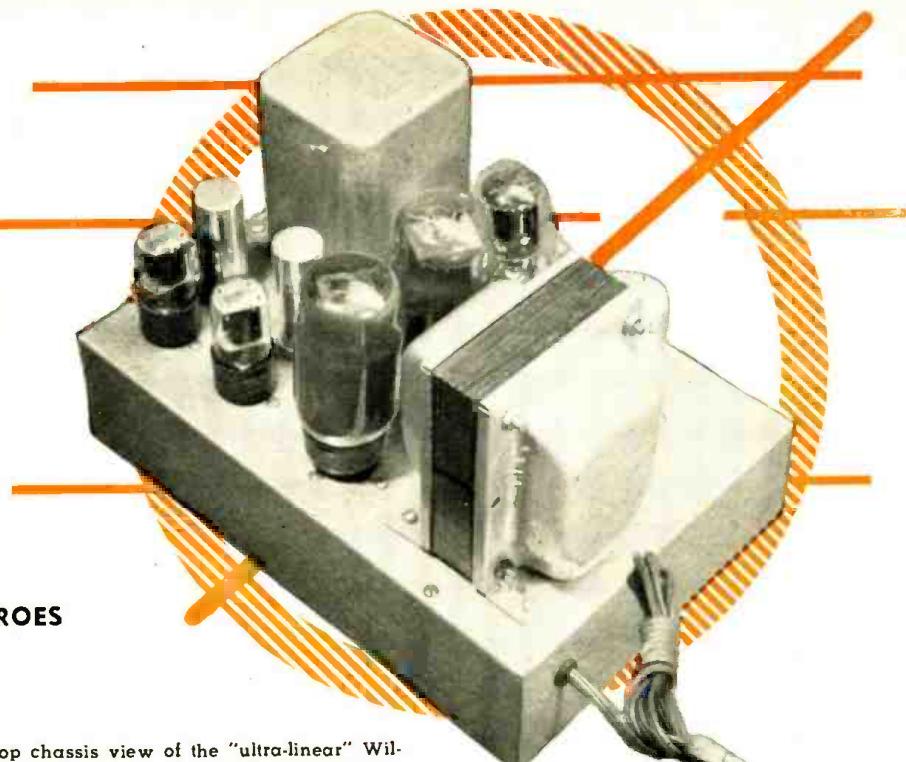
By

DAVID HAFLER and HERBERT I. KEROES
Acro Products Company

THE Williamson amplifier circuit is undoubtedly the most popular amplifier circuit ever developed for high quality audio reproduction.¹ It has become famous throughout the world, and its popularity is certainly justified. It provides amazingly clean, clear reproduction of a quality which sets a new standard of performance against which all newer circuits have been judged. The circuit permitted the home constructor or experimenter to achieve audio quality surpassing that which was commercially available at the time.

The high quality of the amplifier is due to several design principles. All stages are designed for minimum distortion and maximum bandpass. Class A triodes are used throughout. A push-pull, resistance-coupled driver stage is used to provide adequate signal at low distortion to the push-pull output stage. This stage consists of triode connected tetrodes which furnish a very important advantage over conventional low mu triodes. They require grid signal voltages of approximately 40 volts for full output as contrasted with 60 or 70 volts for triodes of the 2A3 and 6B4 type and 80 to 90 volts for a tube like the 6AS7G. In many triode amplifiers, there is more distortion generated in the attempt to drive the output stage than there is in the output stage. In the Williamson circuit there is sufficient drive available, and the limiting factor is the distortion inherent in the output stage. This is kept to low levels through the use of a feedback loop encompassing the entire four-stage circuit, including the output transformer.

These distinctive features of the amplifier make for a truly high grade circuit. The basic principle of the design is that there is no skimping. For example, Mr. Williamson stipulated design specifications and operating



Top chassis view of the "ultra-linear" Williamson amplifier. A specially-designed output transformer is required in this circuit.

A variation on the Williamson circuit which provides "ultra-linear" operation and a minimum of distortion.

parameters for the output transformer to be used to insure that this critical component had frequency response far in excess of the audio band and could handle 20 watts of undistorted power even though the power rating of the complete circuit was less than 15 watts.

This combination of attributes makes an outstanding amplifier with frequency response from 10 cps to 100 kc. (a wide bandpass provides good transient response) and intermodulation distortion of less than 1% at 10 watts of output. It has the elusive quality of "presence" which cannot be reflected in measurements but only in listening tests.

Improving the Williamson circuit is obviously a difficult task. It seems that conventional designs using conventional components are unlikely to excel the Williamson either in listening quality or in laboratory tests.

However, a recent *unconventional* circuit development has made possible a simultaneous reduction in distortion and increase in efficiency in the output stage of the Williamson (and many other circuits). This new circuit arrangement, on which patents are pending, is termed "ultra-linear"² operation—a name chosen because the circuit represents the most linear possible mode of operation of a pair of output tubes. It is neither triode nor tetrode tube operation but borrows the advantages of both without the disadvantages of either.

"Ultra-Linear" Operation

Arguments concerning triodes *versus* tetrodes have been carried on for many years without any definitive conclusions. Each tube type has its advantages and its disadvantages, and those who favor either will find many reasons to justify their choice while disparaging the other type. The present status of the battle seems to be that the tetrode advocate is in the minority. The triode with feedback, such as is used in the Williamson circuit, has surpassed it in popularity among home constructors and custom builders of audio equipment although not among commercial manufacturers. The commercial interests are motivated by the fact that the efficiency of tetrodes is higher than triodes, and the distortion of a tetrode amplifier can be made lower over a greater operating range than can be done with triodes.

Since there are arguments on each side, the choice between the two must be based on the relative weights of the various factors by which they differ. One person prefers triode low impedance; another likes tetrode power sensitivity. Similarly, the triode proponent likes the sound of triodes; the tetrode man likes tetrode sound. Each rejects the elusive and minute distortions which characterize the other tube type.

The basic cause of the whole argument seems to be that neither tube type is close enough to perfection.

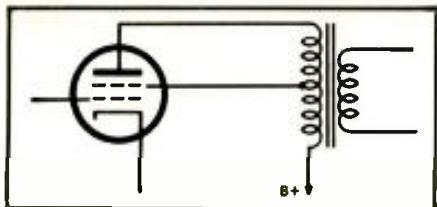


Fig. 1. "Ultra-linear" connection of a tetrode.

Each has its faults. Conventional tubes are essentially nonlinear circuit elements. As such, they generate audible distortion. Acceptance of one type is not necessarily because of its quality—often it stems from rejection of the other type. Choice resolves to the lesser of two evils. The remedy for this basic situation can only come from either a new tube type or from a new method of operating existing tube types.

The tetrode output tube can be operated as a triode by connecting screen to plate as is done in the Williamson circuit. If the screen is partially connected to the plate, we have what is effectively a new type of tube. This can be accomplished by connecting the screen grid to a point on the primary winding of the output transformer as is illustrated in Fig. 1. If the primary tap is at the top of the winding, we have a triode tube with plate characteristic curves concave upward. If the tap is at the low end, the "B plus" point, we have a tetrode with plate characteristic curves concave downward. At a critical intermediate point, we obtain a plate characteristic which is essentially a straight line. This is the point of "ultra-linear" operation and the point of minimum distortion.

Fortunately, the "ultra-linear" point also has several additional operating advantages. It maintains the full efficiency and power sensitivity of the tetrode along with its high power capabilities. Simultaneously, it has low internal impedance like the triode. It combines the most advantageous features of each and has lower harmonic and intermodulation distortion than either of the two basic tube types.

Fig. 2, for example, shows a comparison of the intermodulation distortion of a push-pull stage without feedback for triode connection, "ultra-linear" connection, and tetrode connection. These curves show that the triode cannot handle high powers while the tetrode has relatively high distortion at lower operating levels. The "ultra-linear" stage obviously is an improvement over either of the others over most of the useful power range. Evidently, with other things held equal, an "ultra-linear" output stage must make a better amplifier than can be realized with any triode or tetrode circuit.

One of the more subtle advantages of "ultra-linear" operation lies in the inherent regulation of this type of output stage. There is practically no change in tube current drain from

quiescent operation up to full output. This permits the use of a minimum power supply. With other operating arrangements there is a loss of low frequency power handling capacity if the power supply regulation is inadequate.

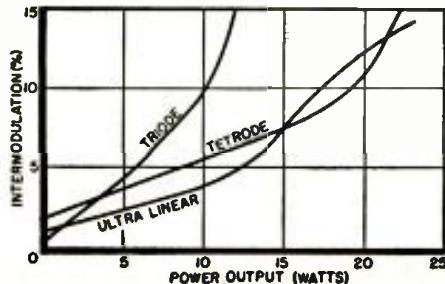
"Ultra-linear" tube operation cannot be utilized with standard output transformers. It is necessary to have a tapped primary winding, and the conventional units of multiple impedance have taps at positions which do not give optimum results. The primary tap for tube types such as are commonly used in the Williamson circuit must be at a point so that the load impedance in the screen circuit is 18.5% of the load impedance in the plate circuit. In order to carry through the optimum conditions, a special transformer, the *Acrosound* TO-300, has been developed to be used for "ultra-linear" operation of beam power tubes of the 6L6, 807, 5881, and KT-66 type. It is a unit which has a tapped primary of 6600 ohms total impedance with the screen-to-screen load impedance 1220 ohms—the ratio of plate-to-screen load which provides most linear tube characteristics. The transformer also has a frequency characteristic of plus or minus 1 db from 10 cps to 100 kc. and the ability to handle 40 watts of audio power over a very wide frequency range.

The specifications of this transformer exceed those stipulated by Mr. Williamson. The operating conditions of the output stage exceed those of his triode-connected tubes. Therefore, since the Williamson circuit using the "ultra-linear" output stage will have a more linear characteristic in that portion of the amplifier which is its weakest link and the prime source of distortion, the combination of "ultra-linear" stage and the Williamson circuit can be expected to be an improvement over the original. Actually, the power output of the "ultra-linear" Williamson is about doubled for the same distortion as compared to the triode Williamson and auditory quality is also improved.

Combining the Two Circuits

Fig. 3 shows the complete circuit of the Williamson amplifier with the "ultra-linear" output stage. Several minor changes have been made from the original circuit for optimum integration of the two circuits. All of the changes from the original circuit are

Fig. 2. Comparison of distortion characteristics of triode, "ultra-linear," and tetrode stages. See text for full details.



shown within dotted lines on the schematic. The change in the output transformer is the major change. The other deviations from the original involve only a few condensers and resistors. These changes readjust the feedback to maintain it at the desired 20 decibels, and they also improve on the stability margin of the original circuit.^{3, 4}

The circuit requires a power supply furnishing between 425 and 450 volts at 130 to 140 ma. This is obtained most simply by using a standard 400 volt, 200 ma. power transformer with 5V4G rectifier and condenser input. Operation of the power transformer at the lower drain provides higher-than-rated output voltage along with cool operation. The input filter condenser should have at least a 500 working volt rating while the later condensers can be 450 or 475 volt types. The use of a cathode-type rectifier limits the initial voltage surge so that higher rated condensers are not required.

In order to get equal output signals from each half of the phase inverter, the plate and cathode resistors should be matched to within 1%. If equipment for measuring this closely is not available, the use of 1% deposited carbon resistors (made by *Continental Carbon, IRC, or Wilcor*) is suggested. This also applies to the plate load resistors of the push-pull driver stage which should be matched so that the drive to the output stage is equal on both sides.

The output tubes can be 807's, 5881's, WE350A's, or the British KT-66's. All of these can take the recommended voltage without exceeding tube dissipation. Though the difference in performance is not substantial, the authors have found that the KT-66 provides the lowest distortion at low power levels (around one or two watts), and its power capabilities are somewhat better than the others.

It is highly recommended that, as shown, the output cathode resistors be bypassed with a condenser in excess of 100 μ fd. This avoids third harmonic distortion and consequent intermodulation distortion particularly under conditions of high level dynamic operation.¹

Negative feedback is carried around the output transformer and all four stages. This negative feedback reduces distortion, hum, noise, and output impedance by a factor of 10. In connecting the feedback loop, the color coding of the plate and screen leads of the output transformer should be observed. As indicated on the schematic, the plate and screen leads marked with a white tracer should be paired and connected to the lower output tube; this tube is on the side of the circuit which is energized from the cathode of the phase inverter. The other plate and screen leads go to the side of the circuit which comes off the plate side of the phase inverter. In this way, feedback phasing is correct, and there will be no oscillation of the amplifier at either high or low fre-

quencies if the remainder of the circuit has been wired correctly.

The feedback connection is made from the 16-ohm tap irrespective of the tap used to connect the speaker. This arrangement saves having to reconnect the output winding and change the feedback resistor should a speaker of different impedance be connected to the amplifier.

A bias balancing network is shown in the cathode circuit of the output stage. This cannot compensate for badly mismatched tubes, but it does permit adjusting for normal variations from tube to tube. A milliammeter should be inserted in each cathode circuit at the points marked "X", and the cathode currents should be balanced by adjusting the potentiometer. Each tube should draw in the neighborhood of 60 ma. if the plate supply voltage is 450 volts. If the plate voltage is 400 volts, the current drain will be approximately 50 ma.

Amplifier Performance

Maximum undistorted output of the "ultra-linear" Williamson amplifier is about 30 watts. This output is achieved with an input signal of one volt. In the triode Williamson, close to two volts of drive are required, and maximum output is not over 15 watts.

The comparative intermodulation data for the triode and "ultra-linear" Williamson is shown in Fig. 4. It can be seen that the "ultra-linear" circuit provides about double the power before the distortion becomes serious. At levels of one or two watts, the intermodulation is in the vicinity of .06%. At 13 watts of output, it is only .3%, and it reaches the 1% point at about 20 watts.

The high power handling capacity of the amplifier is well demonstrated by the power curve of Fig. 5. It represents the maximum *undistorted* power available at various frequencies. The amplifier puts out 25 watts at 20 cps and nearly 30 watts past 20 kc. This power curve is *not* a response curve. It would be possible for response to be flat and for power to be down considerably at the ends of the frequency spectrum. The *undistorted*

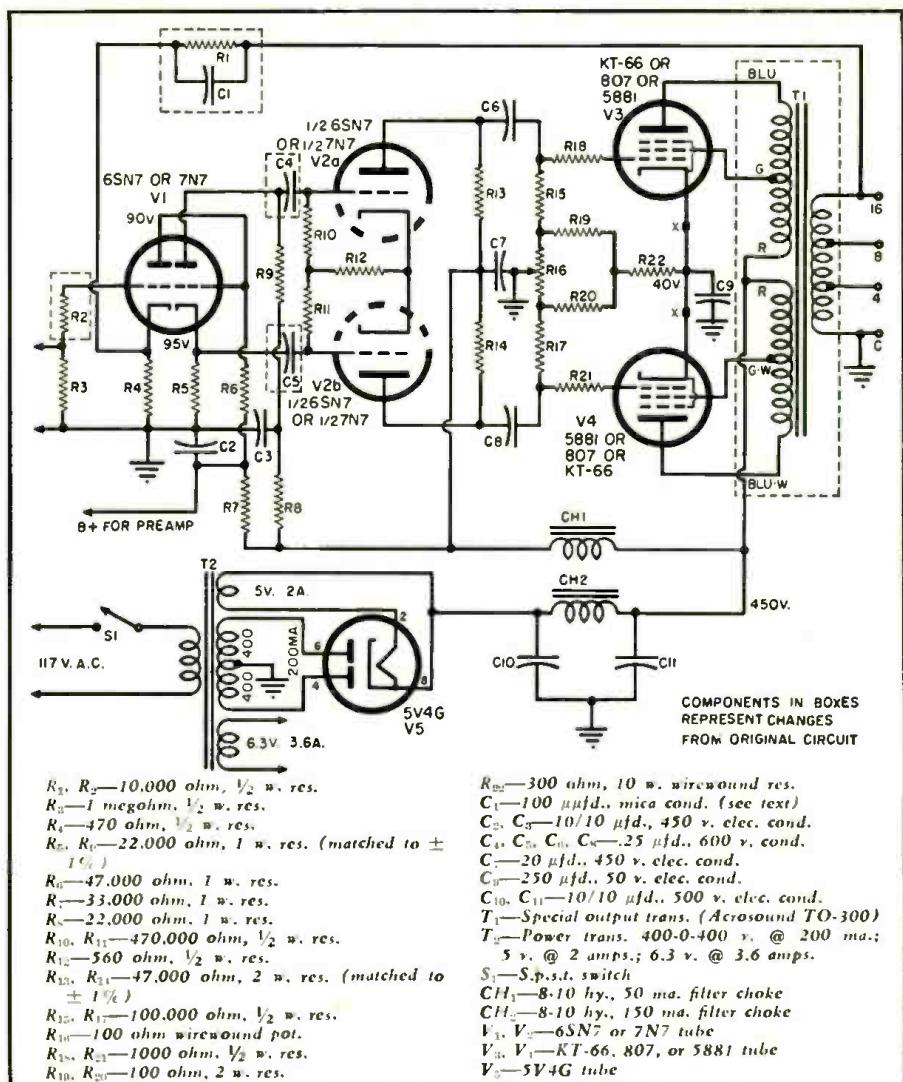


Fig. 3. "Ultra-linear" Williamson circuit. Dotted sections are changes from original.

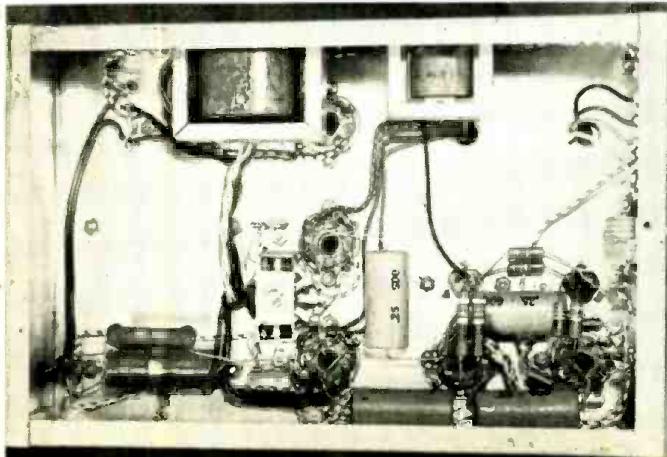
power measurement is a much more rigid test of amplifier performance than a response curve run at a 25 watt level where the distortion is ignored. Little publicized data makes the distinction between a true power curve of undistorted power and a high level response curve.

Fig. 6 shows the response curve which is broad beyond normal re-

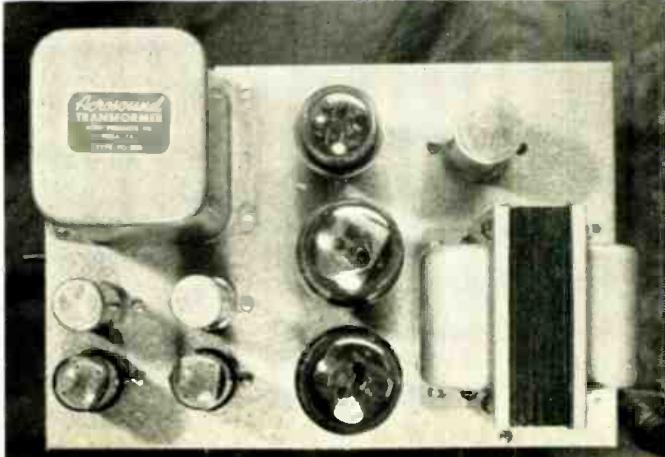
quirements. The response of plus or minus 1 db from 2 cps to 200 kc. is required to minimize phase shift in the audio band since very small variations in gain are correlated with comparatively large variations in phase even at points far removed from where the response is first observed to vary. In this circuit, the response is flat from

(Continued on page 98)

Underchassis view of the "ultra-linear" Williamson amplifier.



Top chassis view showing specially-designed output transformer.



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"Ultra-Linear" Amplifier (Continued from page 45)

20 eps to 20 kc. within much less than .1 db. Maximum phase shift over this band is about 3 degrees.

The very wide frequency band and low phase shift permit excellent transient response as attested by the square wave oscillograms of Fig. 7. The slight ringing visible on the high frequency square waves could be removed by introducing roll-off in the circuit above 100 kc. This expedient, however, would lessen the steep rise and round the upper left-hand corner. The designer always has to compromise between damping of the square wave and loss of high frequency response. In this circuit, the Williamson principle of maximum bandpass was preserved, and the resulting square wave is still better damped than that of most other high quality equipment.

Those who have actually tested amplifiers with square waves on scopes capable of showing details of the performance without distortion, will appreciate the extremely short rise time and rectangular corners of these oscilloscopes.

The transient response of the circuit undoubtedly makes a substantial contribution to its listening quality.

Listening Tests

Many AB listening tests have been made comparing the "ultra-linear" Williamson with the triode Williamson and with other circuits. A variety of speakers and speaker systems have been utilized in these tests, and many different program sources have been included. Results were almost invariably the same—the "ultra-linear" circuit was accepted as the most realistic. On bass passages, drum rolls, and musical climaxes, the ability of the circuit to handle large power without distortion and with no tendency to transient instability shows up to advantage.

At the high-frequency end of the spectrum, the low phase shift maintains the correct harmonic structure of complex transients; and the percussive sounds of triangles, cymbals, tambourines, and other instruments come through with a naturalness and crystal clarity which is audibly evident to the untrained ear. String instruments have the natural "gutty" quality; and with a high grade speaker, it is possible to differentiate between the metal "E" string of the violin and the gut "A" string even

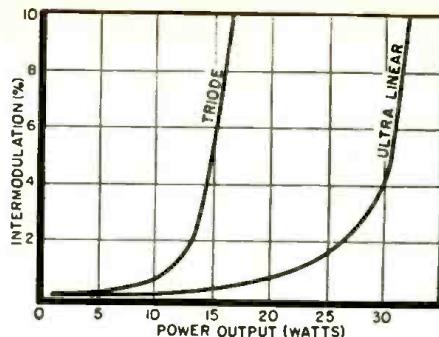


Fig. 4. Intermodulation distortion for triode and "ultra-linear" operation at 40 and 2000 cps mixed in a 4 to 1 ratio.

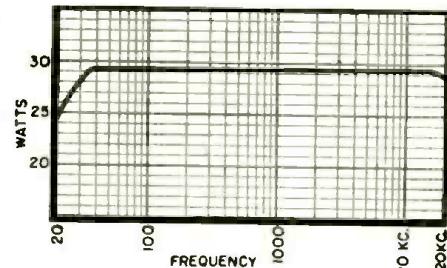


Fig. 5. Undistorted power vs. frequency.

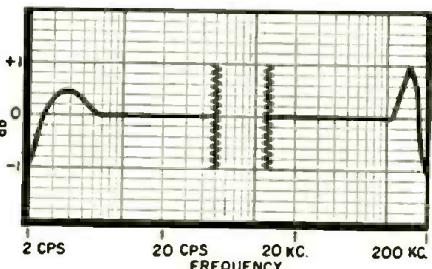


Fig. 6. Frequency response of the amplifier.

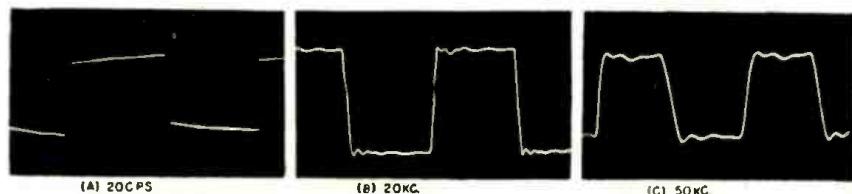
though a tone of the same frequency may be played on either.

The scratch of phonograph records is less noticeable and less irritating on the "ultra-linear" Williamson than on other amplifiers. Scratch and noise have a high transient energy content and tend to intermodulate with high frequency signals if the amplifier cannot handle considerable power at the high-frequency end of the musical spectrum.

The low intermodulation content of the amplifier is evident in the crisp definition of the music. There is no blurring, no shrieking. The slip of the violin bow against the bridge, the breathing of the singer, the cough in the audience; all are audible while the music plays. The various instruments are distinguishable individually rather than as a conglomeration of sound.

The increased power handling ca-

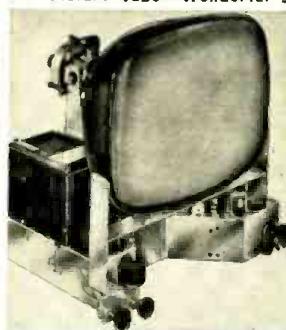
Fig. 7. Square-wave performance at (A) 20 cps, (B) 20 kc., and (C) 50 kc.



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pability of the "ultra-linear" Williamson shows up to audible advantage. The newest LP records, tape, and live FM cover very broad dynamic ranges, and it takes power to do them justice. The ten-watt amplifier cannot reproduce the climaxes of today's program sources, as is evidenced by comparison with a higher power unit such as the "ultra-linear" Williamson. New developments in program sources are forcing new ideas in amplifiers.

For some applications, even higher powers may be required. Just as can be done with the triode Williamson, the "ultra-linear" circuit can be operated in push-pull parallel, and the performance specifications can be maintained within a 60-watt rating. Experimental work is also being carried out with high power transmitting tubes to investigate the feasibility of using the same circuit arrangement in amplifiers of more than 100-watt capacity.

Thus the "ultra-linear" Williamson circuit offers a distinct improvement over the original. It also offers the possibility of still further extension into the higher power ranges.

Many articles have appeared which describe amplifiers in terms of "best we ever heard." Such descriptions do not furnish a basis for the reader to judge the quality of the circuit. In this article the authors have attempted to provide the theoretical justification for an improved amplifier circuit. Theory and specifications cannot substitute for the listening tests which, in the end, are the only ones which count. The dubious reader, therefore, will wait until he hears it before accepting the "ultra-linear" Williamson as the best around. However, when he does hear it, he will find that, to coin a phrase, "hearing is believing."

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