An Ultra-Linear Amplifier

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Presenting a new output-stage connection in an otherwise conventional amplifier which provides a degree of listenability which is well above average.

IT HAS BEEN CLAIMED that there is no more room for improvement of power output stages since other elements of a complete sound system—particularly the electro-mechanical ones—are far inferior. There is a prevalent belief that "one good amplifier is only marginally different from another." The proponents of this line of thought imply that significant improvement in power amplifiers is extremely difficult to achieve, and with this idea the authors agree, but the authors disagree as to the *need* for further improvement. Obviously, the weaker links do need improvement, but this alone is no reason for abandoning the further development of stronger links in the chain of audio reproduction—the power amplifier and primarily the power output stage which is the prime generator of distortion in the purely electronic part of the audio system.

Present thinking is very parallel to the views of the 1935 era when it was felt that the principle need was for better program sources and that the transducers and audio amplifiers had reached a stage of near perfection which could hardly be improved. Now, what audiophile would be satisfied with the reproduction standards of sixteen years ago when playing the new LP's or high grade tape? By analogy, therefore, as well as for the never-ending search for a never-attainable perfection, we must continue to seek improvement in *every* link of the audio chain.

The old standards for evaluating amplifier quality have fallen into disrepute. It can be audibly demonstrated that a wide pass band and low harmonic content do not necessarily mean that the amplifier satisfies the critical listener. Newer criteria have been developed such as intermodulation distortion analysis and square wave testing, both of which simulate dynamic conditions to some extent and take into consideration that music and speech are not of a static nature. These new tests produce higher correlation between experimental data and listener preference. Therefore, modern amplifiers sound better than the ones of a few years ago as a general rule. However, these tests do not always separate the wheat from the chaff. Amplifiers which measure well do not necessarily sound well although an amplifier which shows up as poor on measurements will not sound well. Excellent measurements are a necessary but not a sufficient condition for quality of sound. This means that the listening test is the one of most importance—it is the most stringent test of all.

On the basis of listening tests (definitely not on the basis of measurements) the audio school has been divided into two camps—triodes versus tetrodes. There has been shifting between the popularity of the two, but there has always been a distinct cleavage. When the triode-without-feedback was judged superior to the tetrode-without-feedback, the tetrode school added feedback and reaffirmed the merits of this tube type. This was again superseded by the triode-with-feedback, but the beam tetrode still has its followers, presently in the category of a defensive minority among the audio elite.

The very fact that each tube type has ardent supporters is evidence that each has definite points of merit. Possibly the devotees of each type listen for *different* qualities of reproduction, and this causes divergence of opinion. The triode fan usually emphasizes "smoothness" or "sweetness" of sound. The beam power advocates seek "crispness" or "clean sound." Each group obviously desires sound which simulates the original, but each rejects the elusive and unmeasureable distortions which characterize the tube type preferred by the opposition camp. A new type of tube, none of which has been put on the market for many years, might be the thing which could reconcile these diverse views of listeners who all look for the same thing but seek it in different ways.

The requisites for such a new tube can be listed readily:

1. Low internal impedance, such as is offered by the triode.
2. High power sensitivity of the tetrode so as to minimize drive problems.
3. Lower harmonic and intermodulation distortion than either triode or tetrode at both high and low levels of operation.
4. Sufficiently high efficiency to permit adequate output without undue bulk or cost.

Since no such tube is available, the only recourse is to seek a mode of operation of existing type tubes to approximate the desired qualities and then to see whether the theory is justified by listening tests.

Linearizing the Output Stage

The physical difference between the triode and tetrode is, of course, the screen grid. This gives the tetrode its efficiency on the one hand, but also increases the plate resistance and contributes toward the "tetrode sound" which is so violently disliked by triode favorers. Therefore, the screen grid seems to be the element which gives the tetrode its advantages and its disadvantages compared to the triode. In fact, when the screen is connected to the plate, the resultant tube is a triode which is excellent in many respects though handicapped by limited power output and low permissible dissipation. Control of the screen is a logical step toward extracting the favorable attributes of the tube and discarding the unfavorable.

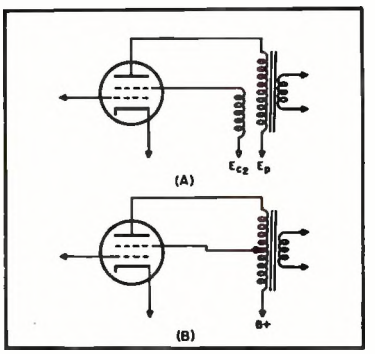


Fig. 1. Arrangements for energizing the screen grid to improve tube linearity.

Experimentally it was found that the goal of improved operation could be achieved through energizing the screen with d.c. through a special winding on the output transformer and combining the effects of both plate and screen current in the output transformer. This is illustrated at (A) in *Fig.* 1 with an alternative and simpler method shown at (B). It has been found that the screens must be fed from a low-impedance source or the benefits of this arrangement cannot be realized. This eliminates the possibility of doing the same job with resistive bridge networks or voltage dividers.

The screen load impedance is somewhat critical if optimum results are desired. As the ratio of screen load impedance varies from zero (tetrode operation) to unity (triode operation), important effects show up:

1. The internal impedance takes a sharp drop and then levels off.
2. Maximum undistorted output drops slightly at first, then decreases rapidly.
3. Intermodulation distortion at high level operation drops to a minimum and then soars upward.
4. Low level IM decreases somewhat and then holds almost level.

The situation is demonstrated graphically in *Fig.* 2 where it can be seen

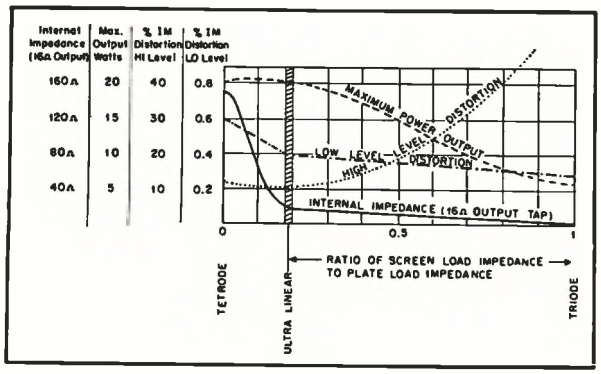


Fig. 2. Comparison of Ultra-Linear operation with triode and tetrode operation using a push-pull stage without feedback.

that over a narrow band of operation where screen load impedance is about 18.5 per cent of plate load impedance, the new arrangement provides the high power output of tetrodes with low internal impedance such as is normally obtained from triodes, while distortion figures are equal or better than the extremes of operation. We have achieved a new tube type without designing a new tube. This tube is neither triode nor tetrode, but its improved linearity over either of those types justifies the designation "ultra linear."

The Complete Amplifier Circuit

In applying the ultra-linear output arrangement to complete amplifier circuits, it was found that the simple version of (B), *Fig.* 1 could be used to advantage. By feeding d.c. to the screens through a properly placed tap on the primary of the output transformer, the operating conditions are preserved, and the close coupling between screen and plate is advantageous when feedback is carried around the stage. The disadvantage of this simpler arrangement is that screen and plate must operate at the same d.c. potential. In the particular arrangement used the screen and plate are operated at the same potential (350 volts plate to cathode) without exceeding dissipation requirements, either quiescent or at maximum output. This new output coupling arrangement reduces screen dissipation at high levels and is a safe mode of operation with respect to tube life.

A circuit arrangement has been designed to take full advantage of the ultra-linear output stage. This circuit, *Fig.* 3, takes into account the necessity for complete stability under feedback conditions so as to eliminate tendencies toward transient instability under any type of load, including the varying impedance of loudspeaker systems.

This complete circuit offers linearity of operation of a very high order. It is based around a special output transformer, the Acrosound TO-300, which is 6600 ohms primary impedance and has taps at the optimum point indicated in *Fig.* 2. A special seven-section symmetrical winding arrangement placed on a substantial grain-oriented lamination of unique shape permits a ratio of primary inductance to leakage reactance in excess of 15,000 to 1. The response of the transformer alone is within ± 1 db from 10 to 100,000 cps with extremely low phase shift and no resonances within this band.

The complete amplifier circuit is relatively simple, inexpensive, and efficient. With a 370-volt power transformer at 130-ma peak requirement, power output is almost as high as for a tetrode amplifier and twice that of a triode amplifier with cathode bias and the same power supply. No adjustments are necessary for balance either of the phase inverter or of the output-stage plate current, and there are no critical values of capacitors or resistors required. The amplifier is driven to 20 watts of output with an input of only 0.7 volt.

Feedback is carried around the complete circuit in an external loop. There are 20 db of feedback in this loop as measured under load conditions (about 30 db based on open circuit gain), and a safe margin is maintained. A small capacitor across the feedback resistor increases the feedback in the region above 100 kc to smooth the high-frequency response. This capacitor is not required to keep the amplifier stable though it does add to the stability margin.

Performance of the Amplifier

All stages of the amplifier have been adjusted for minimum intermodulation, and the IM curves based on sine-wave power output are shown in *Fig.* 4. These curves were run using frequencies of 40 and 2,000; 40 and 7,000; 40 and 12,000; 100 and 2,000; and 60 and 7,000, all mixed four to one. The IM is almost identical under all conditions of test indicating that it is completely independent of frequency, at least up to 20 watts output. This factor possibly accounts for the superlative listening quality of the amplifier.

Undistorted power, less than 2 per cent IM, is in excess of 20 watts. This power is delivered *undistorted* within 1 db over the range from 20 to 20,000 cps. This power curve (*Fig.* 5) is not a response curve run at high power level. Instead it represents *clean* power available at these frequencies. This is particularly important with today's program sources. The dynamic range of some of the best LP's is reputed to be in excess of 100 db. It is necessary to have power to handle this range, and this power is required over a wide frequency band. New standards of audio fidelity are rapidly making obsolete the five or ten watt amplifier which cannot even deliver its rated power at frequency extremes.

Another factor of considerable importance in evaluating amplifier performance cannot be seen from the curves. This is *overload characteristic*. The amplifier has been given listening tests under overload conditions with a pad on the output so as not to deafen the participants. Peaks which would require a 40-watt amplifier are transmitted without irritation even though the output can be seen to clip on the 'scope. The overload recovery is rapid and has no noticeable hangover, so a clipped peak has no time to penetrate the ear. Some amplifiers

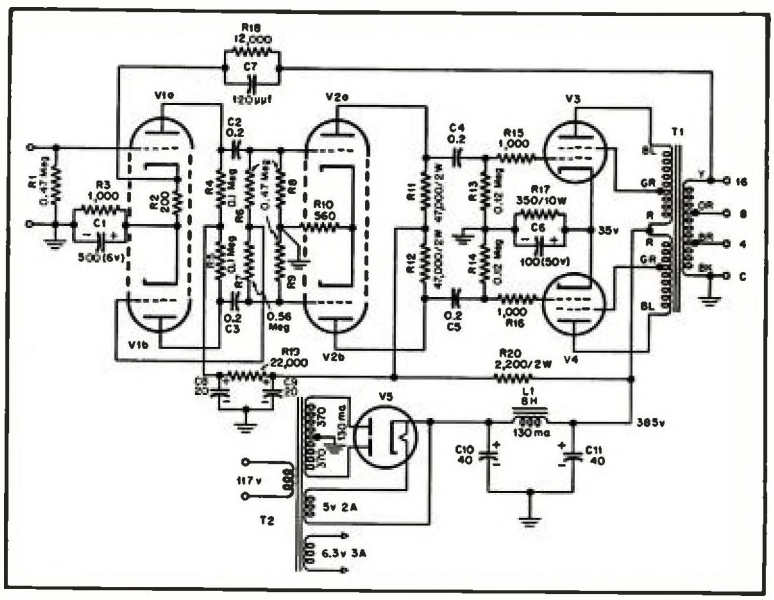
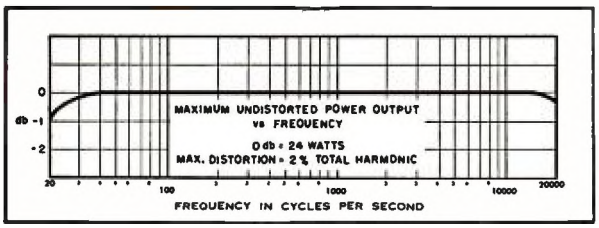


Fig. 3. Overall schematic of the Ultra-Linear amplifier and associated power supply.



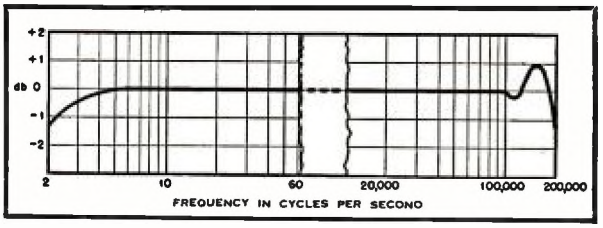


Fig. 5 (left). Undistorted power output vs. frequency. Fig. 6 (right). Frequency response, showing effects above and below the audible frequency range.

break up on a peak, and for seconds thereafter the sound is distorted badly because of poor recovery. In the ultra-linear amplifier transient instability has been eliminated—changes in amplifier characteristics caused by overload do not make the circuit unstable; and, therefore, recovery is almost instantaneous. Most feedback amplifiers fail miserably under overload listening tests.

Figure 6 shows the voltage gain versus frequency. Obviously, most present day amplifiers are flat through the audio band. However, it is the band outside of the audible region which makes some of the difference between one amplifier and another. In this circuit it is evident that smooth flat bandpass extends more than two octaves on each side of the traditional 20 to 20,000 band. This enormous band width is necessary to eliminate phase shift over the customary region and to provide good transient response.

The square wave performance of *Fig. 7* testifies to the transient response. Evidently, a circuit with response flat within 2 db for a decade on each side of the audio band should show a presentable square wave at most frequencies. However. the low phase shift, fast rise time, and insignificance of ringing in this circuit as indicated by the square waves shows that more than just the frequency response is excellent. In addition, square waves were checked on a speaker load with practically identical results, thus demonstrating that performance of the amplifier is unaffected by a load of varying impedance.

Other circuit configurations can be used with this ultra-linear output stage. However, they should have a phase characteristic permitting substantial feedback, and they should have the lowest possible distortion for the early stages. The popular Williamson circuit has been converted to this output arrangement with gratifying results. This conversion permits 30 watts of output plus the other benefits inherent in the increased linearity of the output stage.

Listening Tests

The majority of listeners agree readily to the superiority of this circuit. None felt that other equipment was better although some could not recognize differences on the program sources used. However, during the course of the tests, certain recordings were found which demonstrated differences vividly; and after this finding, even the less discriminating listeners could identify the ultra linear amplifier on "blind" tests and could recognize its superiority.

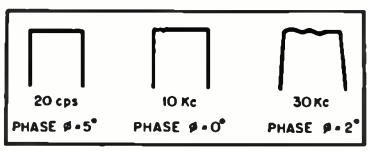


Fig. 7. Square-wave performance of the Ultra-Linear amplifier.

Listeners agree that the bass region is more articulate. better defined, and better damped than in other amplifiers. This damping is not a function of internal impedance alone but also relates to stability under dynamic conditions. For example, no low-frequency cutoff is required in the preamplifier as no ill effects are audible due to momentary overloads from turntable rumble, switching thumps, and similar disturbances. Certain types of signals such as organ pedal tones combined with rumble will cause other amplifiers to break up even at levels as low as a few watts in the mid-frequencies.

Another audible feature in the bass range is that the amplifier does not have *more* bass, but it has *lower* bass. Other amplifiers, of good quality in terms of measurements, by comparison were generating harmonics and intermodulation products. This was also apparent on scratchy "dirty" recordings which cleaned up on the ultra-linear amplifier while remaining mushy and irritating on others.

In the treble region the consensus of opinion is that the amplifier sounds "smoother." The scratch level of shellac records is less irritating while the high frequency sounds, particularly of a percussive type, cut through the scratch and seem far more prominent. This seems due to the fact that intermodulation between scratch and music is diminished, and the two assume much more pleasant proportions.

The authors believe that for sheer listening pleasure the ultra-linear amplifier represents the best that can be achieved at the present state of the art. Others who have had an opportunity to hear and try the circuit agree with this; and these beliefs will not be shaken until something comes along which *sounds* better, or at least sounds as good and can be built for lower cost.

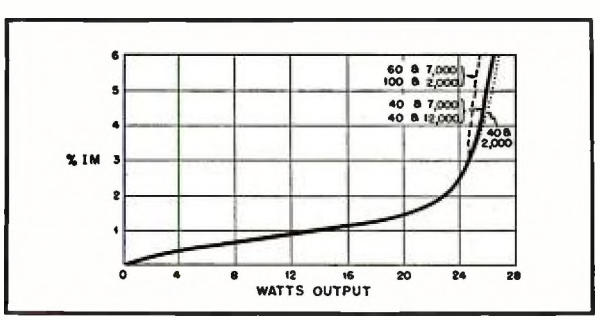


Fig. 4. Intermodulation distortion, using several test frequencies with a constant ratio of 4:1.

Parts List

C_1	500 μf, 6 v. electrolytic
C_2, C_3, C_4, C_5	0.2 μf, 600 v. paper
C_6	100 μf, 50 v. electrolytic
C_7	120 μμf, mica
C_8, C_9	20–20 μf, 450 v. electrolytic
C_{10}, C_{11}	40–40 μf, 450 v. electrolytic
R_1, R_4, R_8, R_9	0.47 meg, ½ watt
R_2	200 ohms, ½ watt
R_3, R_{12}, R_{16}	1000 ohms, ½ watt
R_4, R_5	0.1 meg, 1 watt, 5%
R_7	0.56 meg, ½ watt
R_{10}	560 ohms, ½ watt
R_{11}, R_{13}	47,000 ohms, 2 watt, 5%
R_{14}, R_{15}	0.12 meg, ½ watt
R_{17}	350 ohms. 10 watt
R_{18}	12,000 ohms, ½ watt
R_{19}	22,000 ohms, 1 watt
R_{20}	2200 ohms. 2 watt
T_1	Acro TO-300 output transformer. Primary: 6600 ohms plate – to – plate, tapped for screen; secondary: 16, 8, and 4 ohms.
T_2	Power transformer: 370–0–370 v. at 130 ma; 5 v. at 2 a; 6.3 v. at 3 a.
L_1	Filter choke, 8 Hy at 130 ma.
V_1	6SL7
V_2	6SN7
V_3, V_4	6L6
V_5	5V4