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VAC Technical Monograph 90-8 - Classes of Amplification

[printed copies available from VAC]

Introduction

VAC Technical Monographs are provided to help anyone interested in vacuum tube electronics to better understand the issues involved in the design of truly "high end" amplifiers. They are a direct response to the (unintentionally) inaccurate impressions created by the marketing arms of manufacturers, as well as recent "reference" books fraught with misunderstanding and outright inaccuracies regarding basic concepts of tube electronics, laws of physics, operation of circuits, measurement standards, and historical attribution. It is our intention to create an unambiguous and accurate reference for many of these issues. As such, these Monographs should prove valuable not only to individuals who are just becoming aware of these issues, but also to many experienced audiophiles who are awash in the competing claims.

To ensure accuracy and provide the reader with a source for even more information on these topics, extensive reference will be made of authoritative works in the electronics field. Thus, the thoughts presented herein are not merely the random musings and recollections of one designer, but a condensation of the accumulated wisdom of a great many authorities.

Naturally, no one work is ever exhaustive, so the reader may encounter an omission, or even spot an error (hopefully only typographical in nature). We are anxious to clarify any fuzzy points and correct any inaccuracies. As such, we encourage all interested readers to correspond with us on such points. After all, the goal here is to enlighten, not to confuse!

Readers with little electronics background will probably wish to check into some of the introductory sources contained in the "Recommended Readings" at the end of this Monograph.

Finally, remember that in audio electronics there is never one uniquely and absolutely correct way to design an amplifier. Design always entails compromise. The real question is which parameters are compromised and to what degree. The best way to judge audio equipment remains familiarity with live acoustic music. Listen, and let the sound be your guide.

The Linear Region of the Vacuum Tube

For any given type of vacuum tube operating at a particular plate voltage, we can derive a curve of grid voltage vs. plate current, commonly called the dynamic characteristic curve. In essence, this is the transfer function of the tube, and shows how an input signal will be treated by the tube. The designer must select a point on the transfer curve to work from (the bias point) and the distance that the audio signal will the allowed to traverse this curve (the maximum amplitude of input signal voltage). These choices determine the nature and quantity of distortion in the output signal. They also define the class of operation for an output stage. For those interested, Appendix A demonstrates how this transfer curve is constructed from the more commonly published (on tube data sheets) static plate family curves.

The historical standard of examining the effect of changes in grid voltage on plate current rather than plate voltage may at first seem counter-intuitive. This analysis is appropriate, however, and particularly so for the output stage of a power amplifier. The device fed by the output stage is usually an output transformer. Transformers are current actuated devices. The flow of current in the primary winding induces a magnetic flux in the transformer core, which in turn induces a current in the secondary winding of the transformer. For other stages with standard resistance coupling, the relationship between voltage and current is as predictable as the quality of the load resistor, and the current is thus practically identical to the drive voltage presented to the next tube in the circuit.

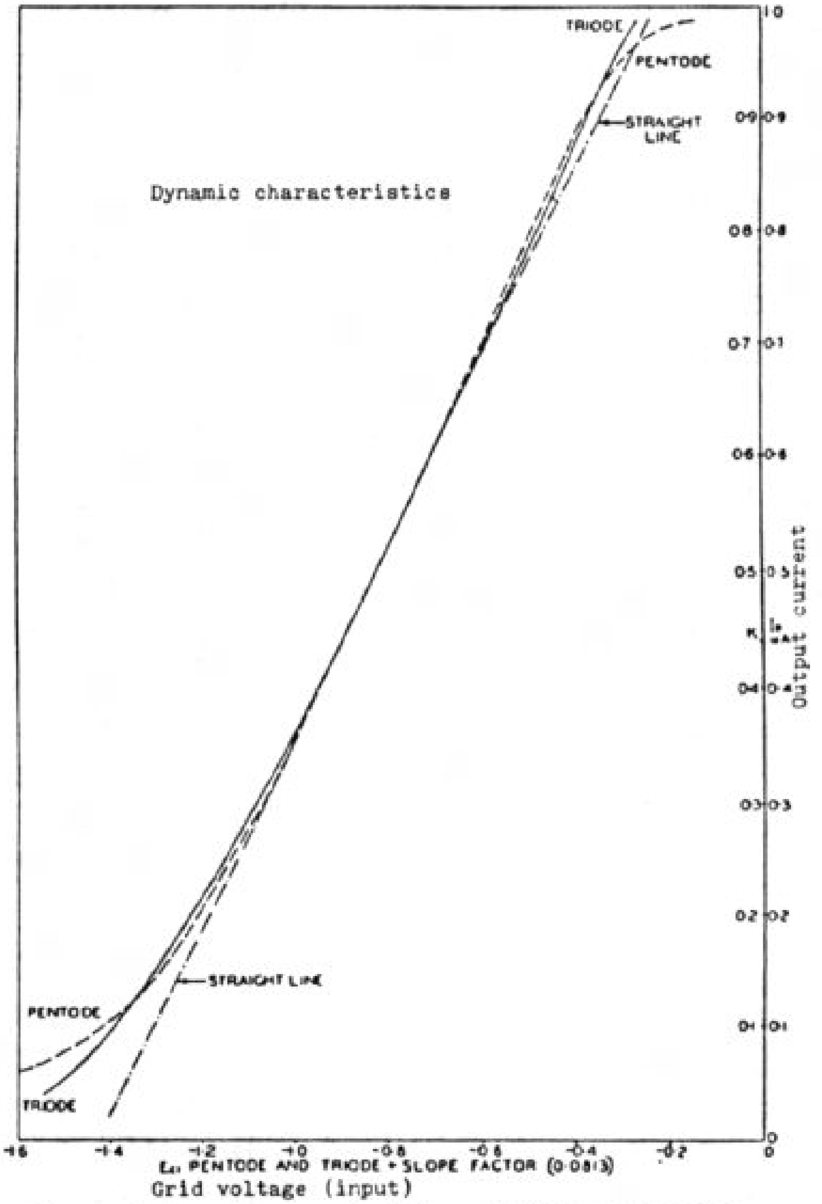

Figure 1. Dynamic characteristics of 6SJ7 connected as Pentode and Triode.

Figure 1 presents typical grid voltage/plate current characteristics for triodes and pentodes, along with a straight line representing perfect linearity (example tube is type 6SJ7 with 250 volt plate supply connected as triode and as pentode). The horizontal axis represents input drive voltage applied to the grid of the tube, while the vertical axis shows the resulting plate current output. It can be seen that neither type of tube is strictly more linear than the other. Both have sections over which they outperform the other. Each type also has other inherent characteristics (such as gain, plate resistance, etc.) on which a designer may develop a preference for a particular application. The choice is often based on the intuitive "feel" that a designer develops with experience, as virtually all choices involve a compromise between conflicting performance goals for the circuit. The relative merits of triodes and pentodes will be addressed in a future VAC Technical Monograph.

Limits of Linearity: Grid Current and Cut-Off

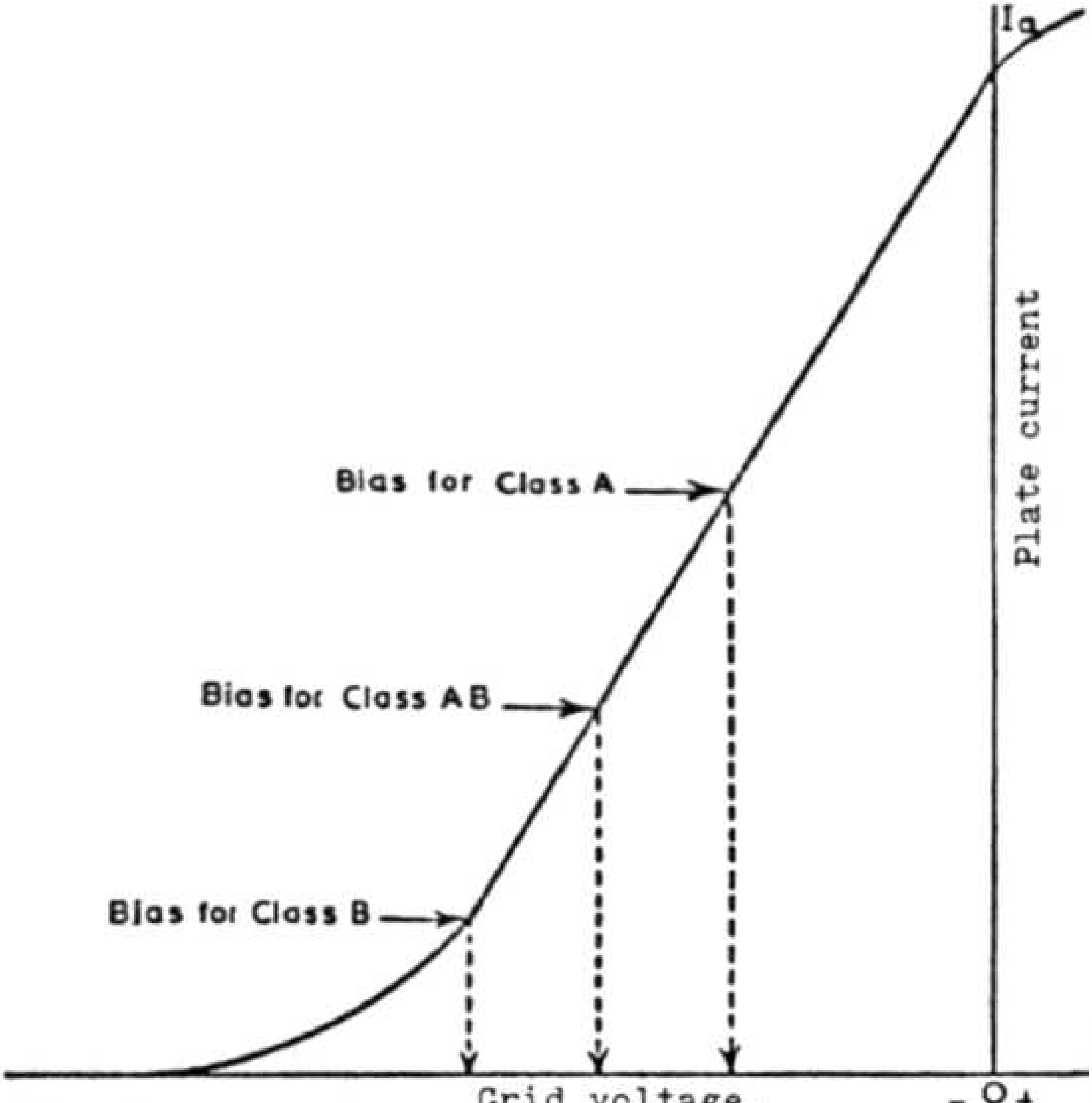

Figure 2. Generalized dynamic characteristic.

Extending the grid voltage/plate current curve beyond the boundaries of Figure 1 generally results in an "S" shaped curve, such as that of Figure 2. With some tubes, the upper portion of the curve begins to flatten out to the right of the point that represents 0 grid voltage. Others will continue to be rather linear for a bit even to the right of this point. This point where the signal applied to the grid of the tube becomes positive is the point at which grid current is drawn (i.e., the driving stage must provide power, not just voltage). It is difficult to obtain low distortion performance in the grid current region even when it appears to be linear, and this generally represents the most positive drive voltage used in high fidelity equipment.

The lower end of the transfer curve also flattens out. In this region the tube reaches a point at which it simply ceases to conduct current. When this occurs, the tube is said to have reached cut-off. The portion of an audio signal near the cutoff region (the negative swing of the drive voltage) will be seriously compressed (rounded). An audio signal driven into cut-off is simply not passed, resulting in a flat space on the output waveform.

So, the grid voltage/plate current dynamic curve can be thought of as a mirror of sorts, projecting the input grid signal onto the plate, enabling us to gain a feel for tube performance graphically. Consider the dynamic characteristic in Figure 3. Assume that in the absence of any alternating audio signal there is a DC voltage on the grid. This is the bias voltage, and implies an idle current (quiescent current) as read from the vertical axis. An alternating audio signal (shown here as a sine wave) superimposed on the DC grid voltage will result in the output signal shown.

It now becomes clear how the choice of bias voltage can effect the linearity of the transfer. In Figure 4 we see a more negative bias voltage. Here, we can see that the tube has been driven into a highly non-linear region, such that the most negative portion of the input signal is heavily compressed (distorted) in the output. Engineers say that the tube has been driven to cut-off. Similarly, Figure 5 shows a still more negative bias voltage, such that approximately 50% of the signal has been cut-off.

As mentioned earlier, at the opposite end of the dynamic curve from cut-off we encounter an area in which grid current is said to flow or be drawn. Grid current is drawn whenever the grid bias voltage and audio signal voltage combined become positive. Figure 6 shows an audio signal driven to both cut-off and grid current. Some tubes can continue to provide increasing plate current well into the grid current region, but to do so requires that significant power (current as well as voltage) must be applied to the grid by the driving stage. Thus, the driving stage must supply significant amounts of current and cope with a load that varies significantly at different points on the wave form to be amplified, which is much the same problem that a Class AB or B output stage faces. Designers working in this region must consider the driver and output stages as a single composite stage.

Classes of Operation

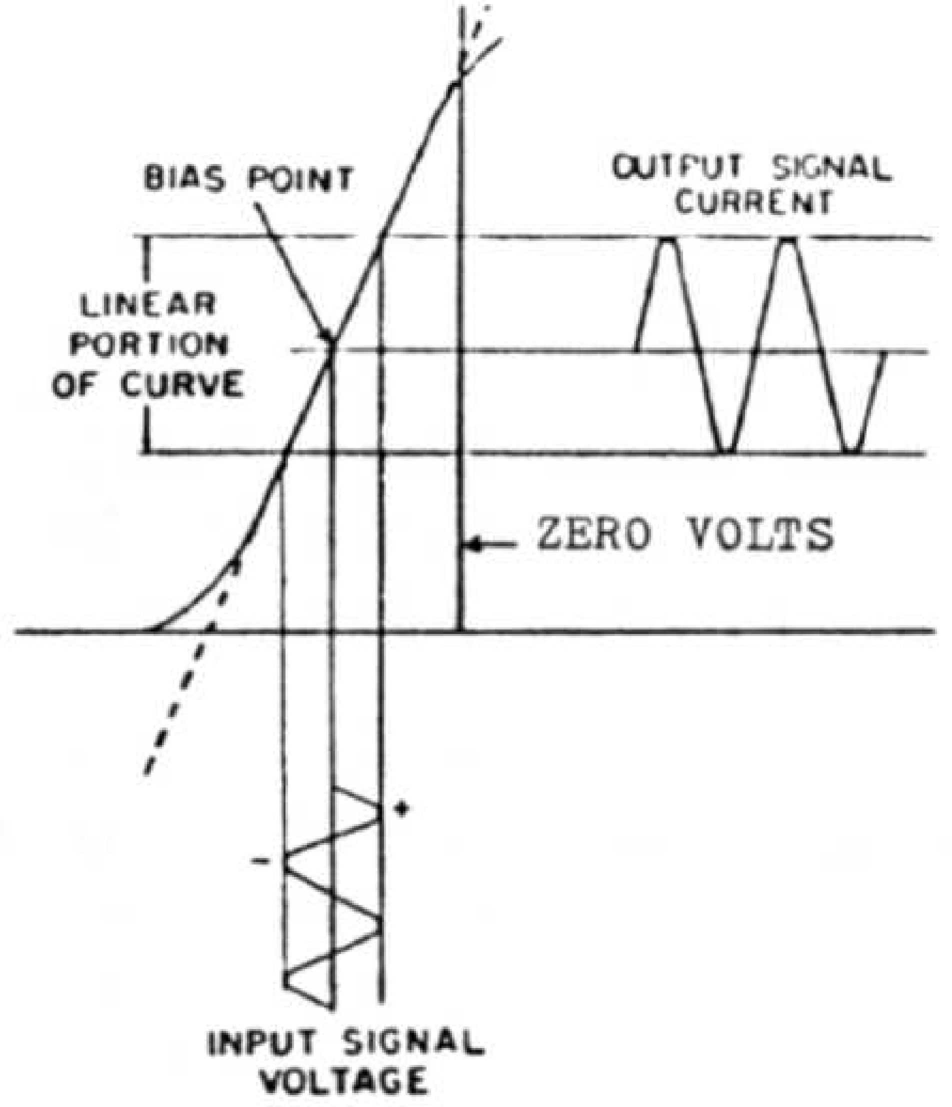

Figure 3. Class A operation.

We can now apply class labels to our figures. In Figure 3 we see a bias condition in which the maximum signal output will just touches cutoff at the negative swing and grid current at the positive swing. This is called limiting Class A. This is a useful condition, as it allows for the greatest possible signal excursion without great strain on the driver stage or severe distortion in the output. In general, Class A operation occurs when a tube is operated such that the tube never reaches cut-off at any time at any level up to the maximum at which it will be operated.

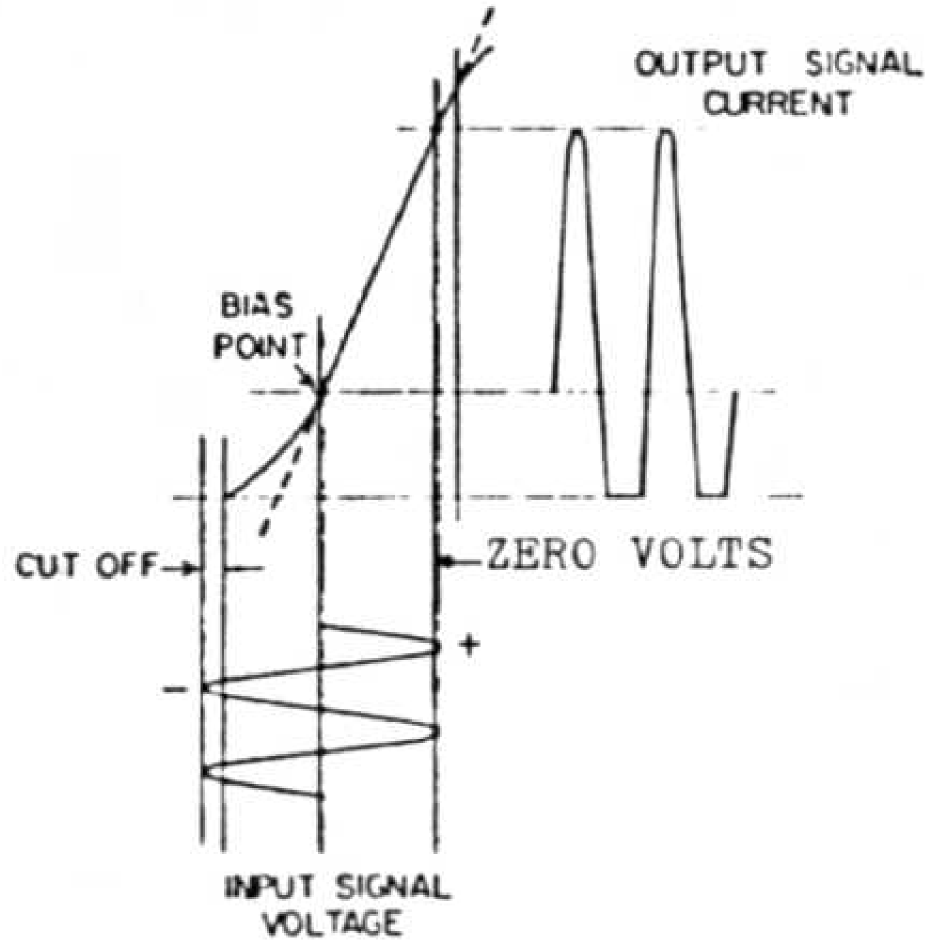

Figure 4. Class AB operation.

In Figure 4 we see that a significant portion of the input cycle (but less than 50%) is cut-off. This is Class AB operation. In Figure 5 approximately 50% of the input cycle is cutoff, which represents Class B operation.

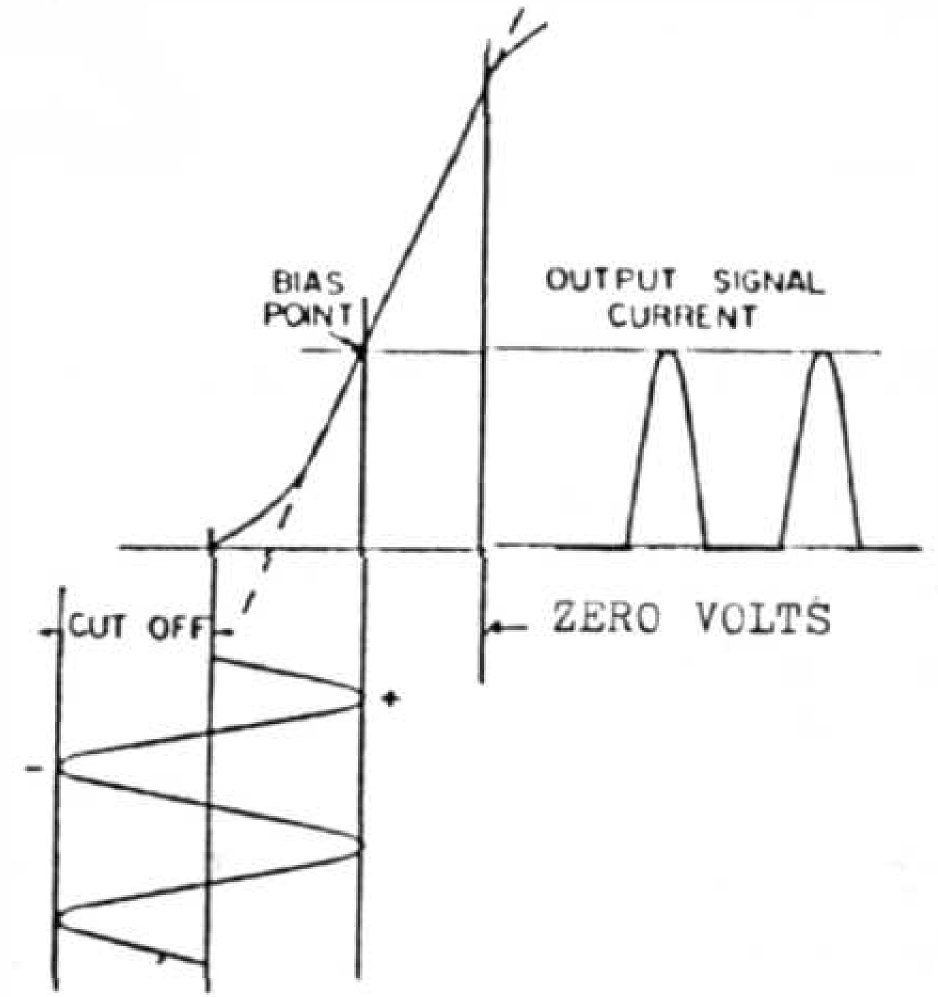

Figure 5. Class B operation.

There is also a number subscript associated with class of operation. A "1" following class indicates that the grid of the tube is never driven to a positive voltage (combination of bias and signal) at any time, while a "2" indicates that a positive grid voltage can occur. This is important, because a positive grid voltage indicates the onset of grid current. Figure 4 shows Class AB1 operation (driven to cut-off but not grid current), while Figure 6 shows Class AB2 operation (driven to cut-off and grid current drawn).

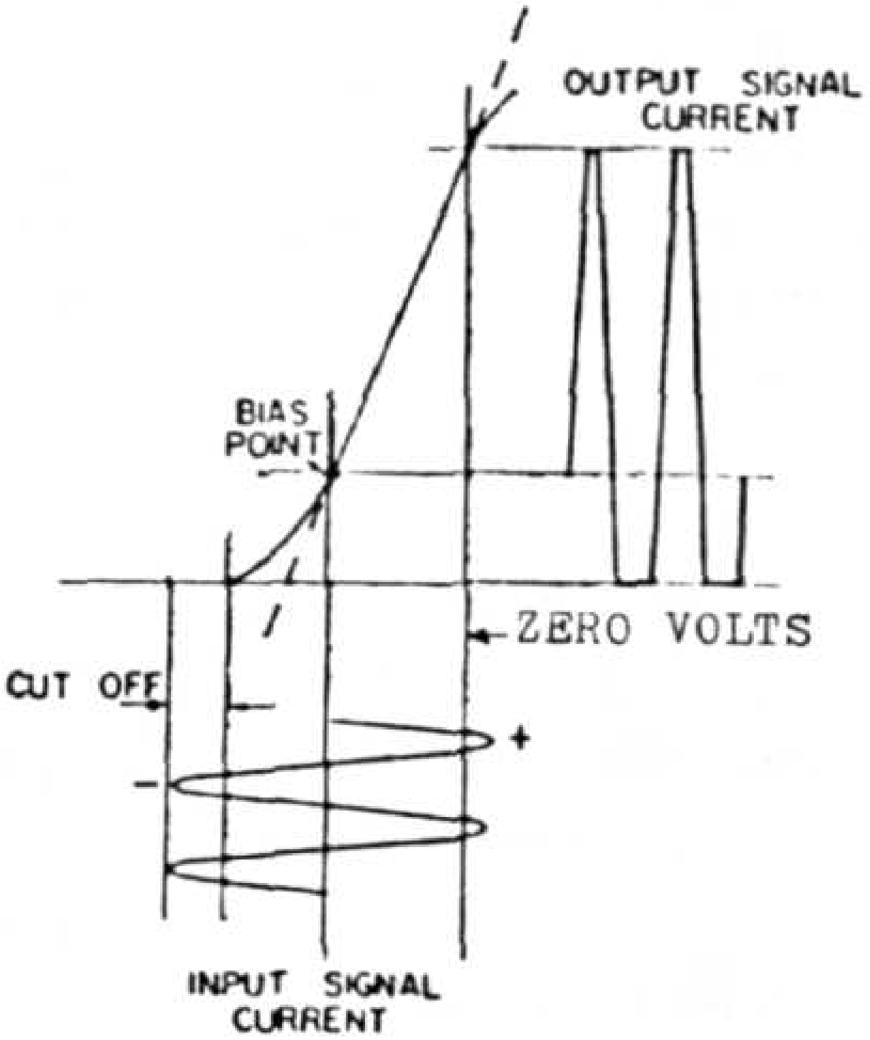

Figure 6. Class AB_2 operation.

Any class of operation may be combined with grid current. For example, there is both Class A1 (Figure 3) and A2. We often see class A without its numeric subscript because few designers choose to draw grid current with Class A, and we can generally assume that it is Class A1. Similarly, we often see Class B without its subscript, but most such designs are Class B2.

It is important to note that in all cases the class of operation is determined by the character of the output at maximum power output. It is therefore inaccurate to refer to an amplifier as operating in Class A up to X watts and class AB above X watts; this is really a Class AB amplifier where cut-off first occurs at a level of X watts.

High Fidelity in Spite of Cut-Off

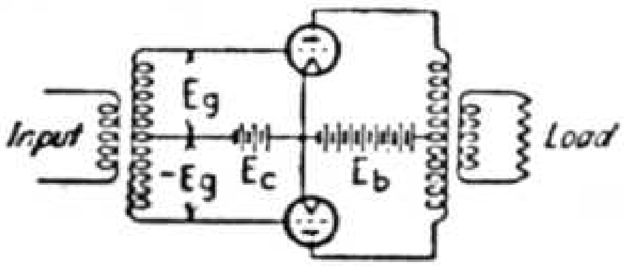

Figure 7a. Basic push-pull circuit.

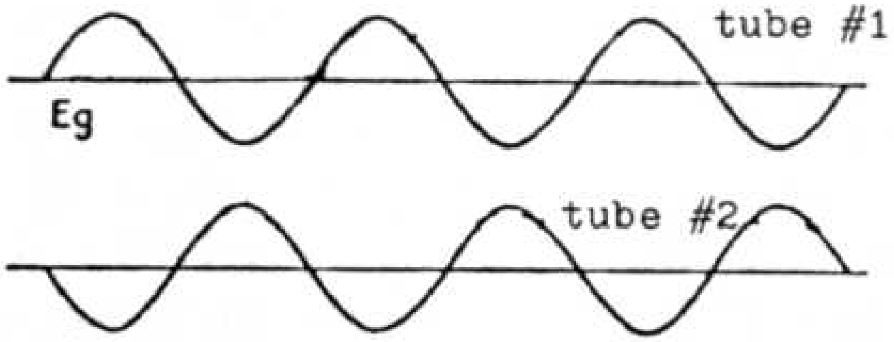

Figure 7b. Grid input signals.

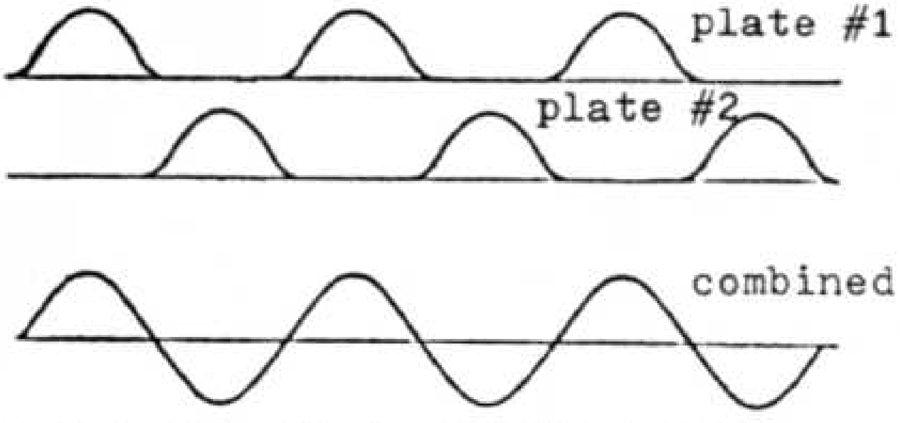

Figure 7c. Plate output signals.

Obviously, those classes in which cut-off occurs are unsuitable for use with a single tube, as severe distortion occurs on at least one side of the waveform. To produce a usable result the output is obtained from two tubes (or multiples of two) in push-pull configuration. In this arrangement, shown in Figure 7a, the grid voltage of one tube increases as the other's decreases, and vice versa, such that the two tubes see mirror images of the same signal (Figure 7b). The drive signals are said to be 180 degrees out of phase with each other. As a result, one tube's plate current will increase as the other's decreases, and vice versa. So, as one tube reaches cutoff, the other continues to conduct (Figure 7c illustrates Class B operation). We now have a situation in which at least one tube is conducting at all points of the input signal, and both conduct for some parts of the input cycle. The output of both tubes is combined through the output transformer to be a reasonable facsimile of the original waveform (Figure 7c).

Implications of the Classes of Amplification

The best push-pull results occur in Class A. With both tubes always conducting, but in opposite directions on their dynamic curves, some nonlinearity is averaged out, particularly even order harmonics. In classes AB and B, both tubes do not always conduct and distortion cancellation can not take place over the full waveform. Also, the sudden start and stop of current flow in a tube at cut-off (Class AB and B) creates a transient in the output transformer that results in crossover or notch distortion. However, Class AB is more efficient than Class A: two tubes in Class AB can produce more output power that two tubes in Class A. Class B is more efficient still, but its high distortion (particularly odd harmonics at low signal levels) generally precludes its use in a high fidelity circuit.

Class A1 operation is also easier on the power supply of an amplifier. This is because each output tube is always conducting. Further, since the current flow in one tube decreases by about the same amount that the current flow in the other tube increases, the current demand is essentially constant and unvarying, even under the most demanding musical transients. Thus, the power supply is not coping with sudden changes in load (demand for current), and it is easier for it to maintain an unvarying voltage on the plates of the output tube (i.e., power supply regulation is less critical). However, a power supply for Class A operation must be robust, capable of withstanding the stress of supplying full power continuously.

Summary

Class A offers the lowest distortion, compatibility with simple (but rugged) power supply designs, and the lowest power output from a particular tube compliment (lowest efficiency). Class B offers the greatest power output, the highest distortion, and the most stringent requirements for power supply regulation if good performance is to be obtained. Class AB offers moderate power output, moderate distortion, and stringent power supply regulation requirements.

An indication of the power level at which cut-off occurs in a Class AB amplifier is given by the manufacturer's stated idle current. For the popular EL34/6CA7 Power Pentode, Class A operation typically occurs with an idle current around 70 milliamperes per tube. RCA and Amperex engineering sheets considered 60 milliamperes to be a normal idle current for Class AB1. Class B is generally considered to start at an idle current in the vicinity of 30 milliamperes per tube or less.

Loose Ends

There are also some unusual and seldom used circuit types that represent attempts to improve efficiency and reduce distortion simultaneously. Most have justly faded into history, but a few are interesting. For example, it is possible to arrange a circuit where two tubes are driven with an in phase signal (unlike push-pull) such that as one tube starts to draw grid current the other tube is just beginning to conduct. This concept was embodied as follows: make the first tube a triode, and the second a pentode, tetrode, or beam power tube. Now, arrange a pair of such arrangements in a push-pull circuit. In theory, low power levels were provided entirely by the (low distortion) push-pull Class A triodes, while higher power levels were derived mainly from the (efficient) pentodes. Of course, the transfer function has an interesting compound curvature (nonlinearity) to it, suggesting high order distortion products. Also, the selection of a correct output transformer ratio is difficult. This type of operation was termed extended Class A, although one can argue that the name is misleading. This basic circuit has recently resurfaced commercially with a name more correctly suggesting the combination of triode and tetrode elements of operation, and independent test results of this product revealed distortion levels of around 2% even at power levels as low as 15 watts.

Other legitimate classes of amplification exist, but are rarely suitable for high fidelity applications. For example, a tube can be biased such that more than 50% of the input waveform is cut-off. This is known as Class C. Even with two tubes in push-pull the distortion levels are huge. Class C finds a home mainly in radio frequency applications driving tuned resonant circuits.

The careful reader will have noticed that we have spoken of a negative bias voltage applied to the grid of the tube. This is called fixed bias. It is also possible to set the bias point with no voltage on the grid and a positive voltage on the cathode of the tube. This can be done with a simple resistor between the cathode and ground, and as such is called self bias or cathode bias. Fixed bias is usually reserved for output stages where it allows for higher output power (some plate voltage is used to set the bias point and is thus unavailable for output power). This will undoubtedly be addressed in a future Monograph.

BIBLIOGRAPHY

Recommended Background Reading

McIntyre, Bob, Vacuum Tube Fundamentals, Part I. The Audio Amateur, 2/86, pages 26-36. (contains an excellent reference list)

McIntyre, Bob, Vacuum Tube Fundamentals, Part II. The Audio Amateur, 2/87, pages 25-29.

Moir, James, High Quality Sound Reproduction. Macmillan, 1958.

RCA Staff, RCA Receiving Tube Manual (RC-26). RCA, 1968. Pages 3-10, 13-14, 25-37.

References Used In Preparation of Monograph 90-8

Langford-Smith, F. (Editor), Radiotron Designer's Handbook. RCA, 1953 (Fourth Edition). Chapters 1, 2, 12 and 13.

Millman, Jacob, Vacuum-tube and Semiconductor Electronics. McGraw-Hill, 1958. Chapter 16.

Terman, Frederick Emmons, Radio Engineering. McGraw-Hill, 1947 (Third Edition). Chapter 6.

Tremaine, Howard M., Audio Cyclopedia. Howard W.Sams, 1969. Pages 543-544, 604.

Graph Credits

Figure 1 after Langford-Smith, page 509 (pages varies in some 4th eds.)

Figure 2 after Moir, page 281.

Figure 3 through 6 after Tremaine, pages 543-544.

Figure 7 after Terman, page 305.

Figure 8 after Millman, page 404.

APPENDIX A

The dynamic characteristic of the tube may be constructed from the static characteristics of a tube, which are commonly found in tube manuals. While we do not propose to describe this procedure in detail, Figure 8 should suffice to communicate the concept to those fairly familiar with the design of tube electronics.

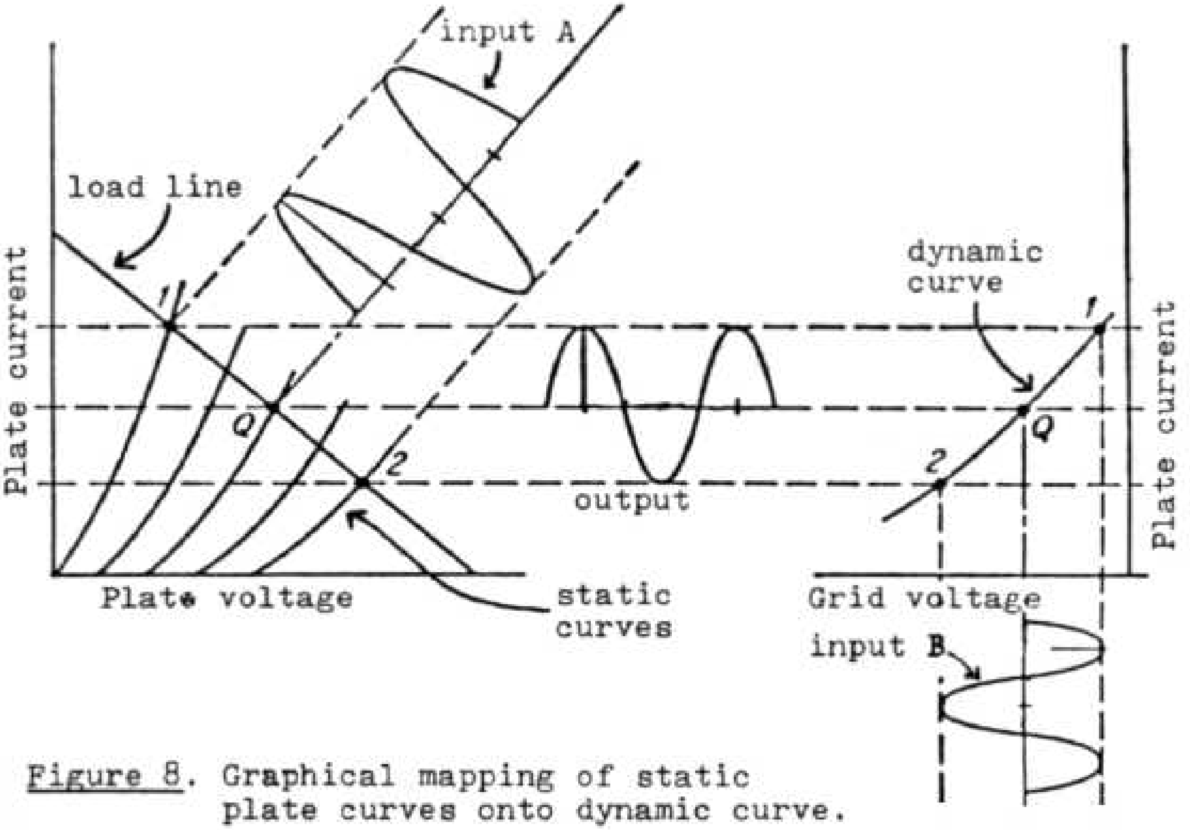

Figure 8. Graphical mapping of static plate curves onto dynamic curve.

The left portion of the figure shows the static plate curves, with a load line defined by the voltage/current changes in a specified resistance.

Each individual curve in the static plate curve family results from a different grid voltage. The difference in grid voltage between each curve is the same (e.g., each successive curve results from a 1 volt reduction of grid voltage). Point Q represents the bias point.

The reflection of an input waveform (input A) and the resulting output signal are shown.

The corresponding dynamic characteristic is mapped at the right of the figure. Input B is the same waveform as input A, but applied to the dynamic characteristic curve. The resultant output signal is the same, but drawn to the left of the dynamic curve rather than to the right as done elsewhere in this Monograph.

Thus, the output waveform in the center of the figure is the correct output as derived from either the static or dynamic curves.

The dynamic characteristic for a particular tube and load may also be derived directly by measurement. Tube manuals have chosen not to do this, owing to the vast permutation of operating conditions that a designer may select from. The static curves are unaffected by such choices, and the resultant dynamic conditions may be derived from the static curves if necessary.

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