AVERAGE EFFICIENCY OF CLASS-G POWER AMPLIFIERS

Frederick H. Raab, Senior Member, IEEE
Green Mountain Radio Research Company
50 Vermont Avenue, Fort Ethan Allen
Winooski, Vermont 05404

Abstract

Class-G operation is an inexpensive and yet effective means of increasing the efficiency of audio power amplifiers (PAs) and amplitude modulators. A class-G PA consists of two or more parallel-connected class-B PAs with different supply voltages. Low-voltage segments of the signal are amplified by the low-voltage component of the amplifier, thus reducing power dissipation and increasing efficiency. The average efficiency of a class-G PA depends upon both the supply-voltage transition point and the amplitude distribution of the signal. Average efficiencies are computed for a number of signals that occur in AF amplification, full-carrier amplitude modulation, and envelope modulation of a linear RF PA. For typical peak-to-average ratios, an ideal, two-voltage class-G PA has average efficiencies in the range of 60 to 70 percent, in contrast to the 35 to 40 percent of an analogous class-B PA.

1. Introduction

The class-G power amplifier (PA) is a combination of two (or more) class-B PAs with different supply voltages. In the simplified AF PA of Figure 1, Q_1 and Q_2 comprise the high-power class-B component and operate from the full supply voltages of $\pm V_{DD}$. Transistors Q_3 and Q_4 comprise the low-power class-B component and operate from the reduced supply voltages $\pm\alpha V_{DD}$.

Signals whose peak amplitudes are smaller than αV_{DD} are amplified exclusively by the low-power class-B component. Since the instantaneous efficiency of a class-B PA is proportional to the ratio of its output voltage to its supply voltage, the efficiency is higher by a factor of $1/\alpha$ than it would be if the high-power class-B component were used to amplify the signal.

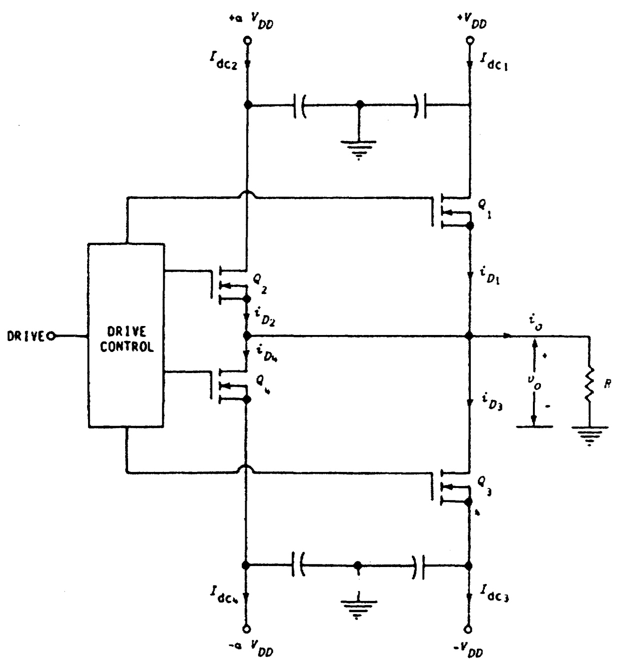

Figure 1. Simplified class-G power amplifier.

For signals of larger amplitudes, the drive is switched from the low-power component to the high-power component when the instantaneous signal amplitude exceeds αV_{DD} (Figure 2). The high-amplitude segments of the signal waveform are amplified with the efficiency of an ordinary class-B PA, since the full supply voltage must be used. However, the low-amplitude segments are amplified with an efficiency of $1/\alpha$ times that of a full-power class-B PA, hence the average efficiency of a class-G PA exceeds that of a class-B PA at all signal levels.

A second supply voltage is readily available when batteries are connected in series. Alternatively, the equivalent of a second supply voltage can be achieved by adding taps to an audio output transformer. Consequently, class G is often an easy means of increasing the efficiency of power amplifiers in portable audio and radio equipment.

Class-G operation requires transistors to be switched on and off at the signal frequency, and the switching occurs at times when the drain or collector current is nonzero. Consequently, class-G is best suited for audio-frequency applications. Its most widely publicized use is in consumer stereo equipment [1 - 3]. However, class-G PAs have also been used in sonar power amplifiers [4], modulators for AM broadcast transmitters, and other AF applications [5, 6].

The instantaneous efficiency is easily related to the output voltage and power-supply voltage-transition ratio α. However, most real audio signals contain a variety of different amplitudes. The average efficiency of a class-G PA is therefore dependent upon both the voltage transition(s) and the type of signal being amplified [8]. The signal-amplitude characteristics are vested in the probability-density function (p.d.f.) of the signal [9].

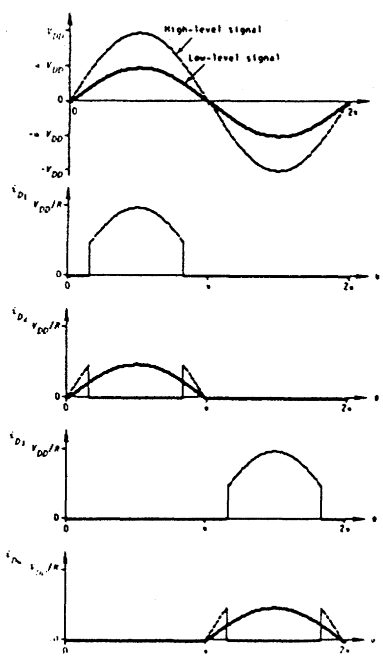

Figure 2. Waveforms of class-G PA.

Contributed Paper.
Manuscript received April 7, 1986.

This paper determines the average-efficiency characteristics of both two- and three-voltage class-G PAs with a variety of signals, including:

- Sinewave,
- AF signals for music and speech,
- AM envelopes for sinewave, music, and speech modulation, and
- SSB/SC envelopes for multicarrier and speech signals.

The results presented here enable the design engineer to determine the benefits of using a class-G PA in a given application, and to select a supply voltage to maximize its efficiency. To simplify the analysis, ideal transistors are assumed; however, the results are easily scaled to include the effects of nonzero saturation voltage or resistance.

2. Configurations

The class-G PA can be implemented in both bipolar and monopolar forms. The bipolar form shown in Figure 1 is used for AF PAs in which the output voltage has both positive and negative excursions. The monopolar form (Figure 3) is used for series-pass amplitude modulation of RF PAs, which requires only a positive output voltage. For full-carrier AM, the input to the class-G PA is the modulation voltage with a bias selected to produce the desired carrier level. For SSB/SC, the envelope-elimination-and-restoration (EER) technique [7, Chapter 16] is used and the input to the class-G PA is the envelope of the RF signal.

To simplify the driving circuits, the class-G PA is usually implemented in a complementary (totem-pole) emitter-follower or source-follower configuration [1, 3]. The equivalent of multiple supply voltages can be achieved by the addition of taps in a transformer-coupled PA. Most class-G PAs use either two positive supply voltages or two positive and two negative supply voltages. However, three or more different supply voltages can be used. The circuits are straightforward extensions of those for two supply voltages.

3. Instantaneous Efficiency

The *instantaneous efficiency* is the efficiency of the PA for a given dc (constant) output voltage. The PA of Figure 1 can be modelled as four independent, controllable current sources, with only one current source producing nonzero current at a given time. For an output voltage v_o, the output power and current are

$$P_o = v_o^2 / R \quad . \tag{1}$$

and

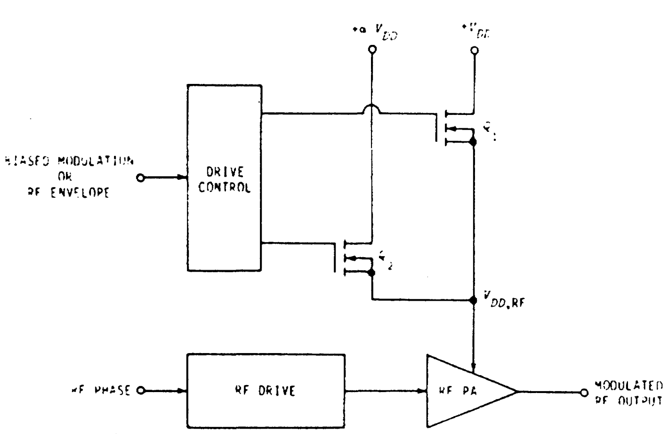

Figure 3. Class-G modulator for RF PA.

$$i_o = v_o / R \quad . \tag{2}$$

Class B

A class-B PA has only the full-voltage component of the class-G PA of Figure 1. The instantaneous power input and efficiency for such a PA are

$$P_i = V_{DD} \, |i_o| = V_{DD} \, |v_o| \; / \; R \tag{3}$$

and

$$\eta = P_o \; / \; P_i = |v_o| \; / \; V_{DD} \quad . \tag{4}$$

As v_o increases from zero its maximum value of V_{DD}, the power input and efficiency increase linearly as shown in Figure 4. The maximum instantaneous efficiency of 100 percent is not in disagreement with the well known value of 78.5 percent, which applies to a sinewave rather than dc [7, Chapter 12].

Class G

The class-G PA effectively reduces the supply voltage from $\pm V_{DD}$ to $\pm \alpha V_{DD}$ whenever the signal magnitude is less than αV_{DD}. The instantaneous input power and efficiency for class-G operation are therefore

$$P_i = \begin{cases} \alpha V_{DD} \, |v_o| \; / \; R, & 0 < |v_o| < \alpha V_{DD} \\ V_{DD} \, |v_o| \; / \; R, & \alpha V_{DD} < |v_o| < V_{DD} \end{cases} \tag{5}$$

and

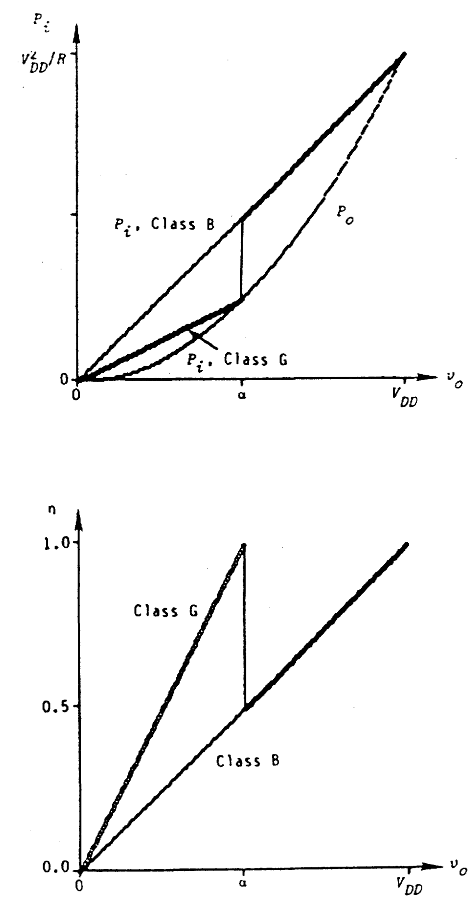

Figure 4. Instananeous power and efficiency.

$$\eta = \begin{cases} |v_o| \,/\, (\alpha V_{DD}),\ 0 < |v_o| < \alpha V_{DD} \\ |v_o| \,/\, V_{DD},\ \alpha V_{DD} < |v_o| < V_{DD} \end{cases} \quad . \tag{6}$$

As shown in Figure 4, the instantaneous input power is reduced by a factor of α, and the instantaneous efficiency is increased by a factor of $1/\alpha$ when the signal level is below the transition voltage.

Effects of Saturation Voltage and Resistance

Real transistors have nonzero saturation voltage (BJTs) or on resistance (FETs) that reduces the efficiency below the ideal values given above. However, inclusion of the effects of saturation voltage or on-resistance not only complicates the equations, but necessitates four separate sets of equations.

These problems are eliminated by using an effective supply voltage [7] in place of the true supply voltage when computing output voltage, current, and popower. The effective supply voltage is obtained by reducing the true supply voltage by the saturation-voltage drop(s) or the on-resistance voltage drop(s), hence

$$V_{eff} = \begin{cases} V_{CC} - V_{sat},\ \text{BJTs} \\ V_{DD}\, R \,/\, (R + R_{on}),\ \text{FETS} \end{cases} \quad . \tag{7}$$

Input power is computed using output power and the true supply voltage.

4. Average Efficiency With Sinewave

A single-frequency sinusoid of arbitrary but constant amplitude is commonly used as a test signal for AF PAs. The envelope of the two-tone test signal commonly used with SSB/SC radios is a full-wave rectified sinusoid, which has equivalent efficiency characteristics. Since the sinewave is a deterministic signal, the average PA efficiency is more readily calculated from the waveforms than from the p.d.f.

The output voltage and current waveforms (Figure 2) for a single-frequency sinusoid are represented by

$$v_o(\theta) = V_{om} \sin\theta \tag{8}$$

and

$$i_o(\theta) = I_{om} \sin\theta \quad , \tag{9}$$

where V_{om} is the amplitude, $I_{om} = V_{om}/R$, and $\theta = \omega t$ for convenience. The output power is

$$P_o = V_{om}^2/(2R) < V_{DD}^2/(2R) \quad . \tag{10}$$

The dc input power is the sum of the dc input power of each of the four transistors; i.e.,

$$P_i = P_{i_1} + P_{i_2} + P_{i_3} + P_{i_4} = 2\,P_{i_1} + 2\,P_{i_2} \quad , \tag{11}$$

where

$$P_{i_1} = V_{DD}\, I_{dc_1} \quad ; \tag{12}$$

and

$$P_{i_2} = \alpha\, V_{DD}\, I_{dc_2} \quad . \tag{13}$$

The transition between high-voltage and low-voltage components occurs when

$$\alpha\, V_{DD} = V_{om} \sin\theta_T \quad , \tag{14}$$

hence

$$\theta_T = \begin{cases} \pi/2,\ V_{om} < \alpha\, V_{DD} \\ \arcsin(\alpha\, V_{DD}/V_{om}),\ V_{om} > \alpha\, V_{DD} \end{cases} \quad . \tag{15}$$

To facilitate subsequent computations, it is convenient to note that

$$\cos^2\theta_T = \begin{cases} 0,\ V_{om} < \alpha\, V_{DD} \\ 1 - \alpha^2\, V_{DD}^2/V_{om}^2,\ V_{om} > \alpha\, V_{DD} \end{cases} \tag{16}$$

The dc input current to the two low-voltage sections is therefore

$$I_{dc_2} = I_{dc_4} = (I_{om}/\pi) \int_0^{\theta_T} \sin\theta\, d\theta = (I_{om}/\pi)(1 - \cos\theta_T) \quad . \tag{17}$$

Similarly, the dc input current to the two high-voltage sections is

$$I_{dc_1} = I_{dc_3} = (I_{om}/\pi) \int_{\theta_T}^{\pi/2} \sin\theta\, d\theta = (I_{om}/\pi)(\cos\theta_T) \quad . \tag{18}$$

The total dc power input is therefore

$$P_i = (2\, I_{om}/\pi)[V_{DD} \cos\theta_T + \alpha\, V_{DD}\, (1 - \cos\theta_T)] \tag{19}$$

$$= (2/\pi)(V_{om}\, V_{DD}/R)[\alpha + (1 - \alpha)\cos\theta_T] \quad . \tag{20}$$

Consequently, the efficiency of the class-G PA with a single sinusoid is

$$\eta = P_o/P_i = (\pi/4)(V_{om}/V_{DD})/[\alpha + (1 - \alpha)\cos\theta_T] \quad . \tag{21}$$

When $\alpha = 0$ or $\alpha = 1$, then (21) reduces to the $(\pi/4)$ (V_{om}/V_{DD}) efficiency of a class-B PA with a sinusoidal output.

The impact of transition voltage upon efficiency for a maximum-amplitude sinusoid is shown in Figure 5. A maximum efficiency of 0.857 is obtained with α = 0.707. The efficiency can be further increased to 0.892 if three supply voltages are available by setting α_1 = 0.56 and α_2 = 0.82, as shown in the next section. In any case, the impact of the choice of transition voltage(s) is not great.

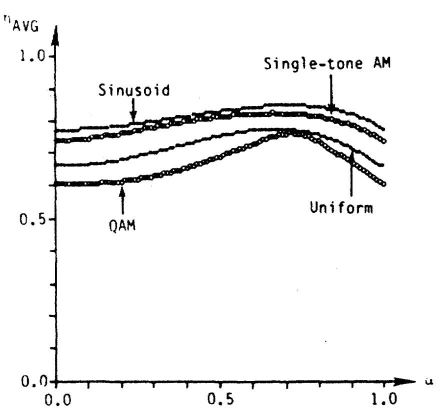

Figure 5. Average efficiency with selected signals.

The variation of efficiency with sinewave amplitude is shown in Figure 6 for several values of α. For low-amplitude signals, a properly selected value of α can produce a significant increase in efficiency.

5. Random Signals

Most signals encountered in the actual use of a power amplifier are random, in contrast to the deterministic signals commonly used for testing. The relative likelihood of the different amplitudes in a given signal is given by its probability-density function (p.d.f.) [9].

Average efficiency [8] is defined *not* as the average of the instaneous efficiency, but as the ratio of average output and input powers:

$$\eta_{AVG} = P_{oAVG} \; / \; P_{iAVG} \quad . \tag{22}$$

For convenience, a normalized voltage V is defined by

$$V = v_o \; / \; v_{omax} \tag{23}$$

so that $0 < V < 1$. If $p(V)$ is the p.d.f. of the signal of interest, the average output and input power are given by

$$P_{oAVG} = \int_0^1 V^2 \, p(V) \, dV \tag{24}$$

and

$$P_{iAVG} = \int_0^1 P_i(V) \, p(V) \, dV \quad . \tag{25}$$

The variations of average efficiency with the transition voltage(s) are calculated for both two- and three-voltage class-G PAs with a number of commonly encountered p.d.f.s [8]. The results (obtained by numerical integration) are discussed in this section and summarized in Table 1.

Audio-Frequency Amplification

Music and mixed sound typically have Gaussian p.d.f.s, which are the result of the addition of a large number of independent random variables. The variation of the average efficiency of a two-voltage class-G PA is shown in Figure 7. For low peak-to-average ratios (ξ), the choice of α is not critical and the improvement in efficiency is modest. However, as the peak-to-average ratio increases, the choice of α becomes much more critical and the improvement in efficiency much greater. For typical peak-to-average ratios of 10 to 15 dB, the average efficiencies of a class-B PA are only 39.2 and 22.3 percent, respectively, which are well below the well known 78.5 percent for amplification of a sinewave. A two-voltage class-G PA with the proper values of transition voltage (Table 1) increases the average efficiencies to 61.1 and 50.4 percent, respectively. A three-voltage class-G PA further increases the average efficiencies to 71.4 and 64.3 percent.

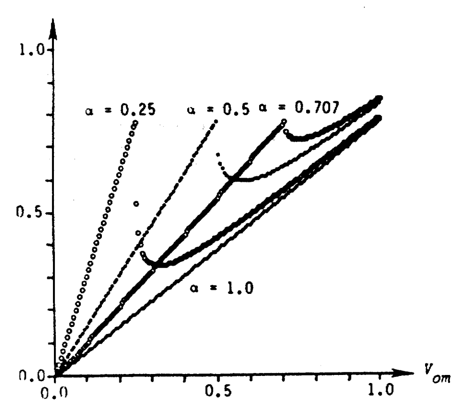

Figure 6. Variation of efficiency with output for sinusoid.

PDF	ξ, dB	η_{AVG} class-B	Two-Voltage Tracking max η_{AVG}	Two-Voltage Tracking α	Three-Voltage Tracking max η_{AVG}	Three-Voltage Tracking α_1	Three-Voltage Tracking α_2
Sinusoid	3.0	0.782	0.857	0.71	0.892	0.56	0.82
1-tone AM	4.3	0.747	0.834	0.66	0.875	0.50	0.79
Uniform	4.8	0.667	0.783	0.67	0.838	0.52	0.78
QAM	4.8	0.616	0.771	0.71	0.831	0.57	0.76
Gaussian	5.0	0.561	0.719	0.60	0.791	0.45	0.72
Gaussian	6.0	0.536	0.703	0.58	0.780	0.44	0.70
Gaussian	7.0	0.505	0.684	0.57	0.766	0.42	0.68
Gaussian	8.0	0.470	0.662	0.55	0.750	0.40	0.66
Gaussian	9.0	0.432	0.637	0.52	0.732	0.38	0.64
Gaussian	10.0	0.392	0.611	0.50	0.714	0.36	0.61
Gaussian	11.0	0.352	0.585	0.48	0.696	0.34	0.58
Gaussian	12.0	0.315	0.561	0.45	0.680	0.31	0.55
Gaussian	13.0	0.281	0.540	0.42	0.665	0.29	0.51
Gaussian	14.0	0.250	0.521	0.39	0.653	0.27	0.48
Gaussian	15.0	0.223	0.504	0.37	0.643	0.24	0.44
Gaussian	16.0	0.199	0.489	0.34	0.634	0.22	0.41
Gaussian	17.0	0.177	0.476	0.31	0.626	0.20	0.38
Gaussian	18.0	0.158	0.464	0.29	0.619	0.18	0.34
Gaussian	19.0	0.141	0.453	0.27	0.613	0.17	0.32
Gaussian	20.0	0.125	0.443	0.24	0.608	0.15	0.29
Rayleigh	5.0	0.579	0.738	0.63	0.808	0.50	0.73
Rayleigh	6.0	0.538	0.714	0.61	0.791	0.48	0.71
Rayleigh	7.0	0.493	0.688	0.58	0.773	0.45	0.68
Rayleigh	8.0	0.446	0.660	0.55	0.754	0.42	0.65
Rayleigh	9.0	0.400	0.634	0.52	0.736	0.39	0.61
Rayleigh	10.0	0.357	0.610	0.49	0.721	0.36	0.57
Rayleigh	11.0	0.318	0.588	0.45	0.708	0.33	0.53
Rayleigh	12.0	0.283	0.570	0.42	0.697	0.30	0.49
Rayleigh	13.0	0.253	0.554	0.39	0.688	0.28	0.46
Rayleigh	14.0	0.225	0.540	0.36	0.680	0.25	0.42
Rayleigh	15.0	0.201	0.527	0.33	0.673	0.23	0.39
Rayleigh	16.0	0.179	0.516	0.30	0.667	0.20	0.35
Rayleigh	17.0	0.159	0.506	0.28	0.662	0.18	0.32
Rayleigh	18.0	0.142	0.496	0.25	0.657	0.17	0.29
Rayleigh	19.0	0.127	0.488	0.23	0.653	0.15	0.27
Rayleigh	20.0	0.113	0.480	0.21	0.648	0.14	0.24
Laplacian	5.0	0.511	0.684	0.55	0.765	0.40	0.68
Laplacian	6.0	0.491	0.671	0.53	0.756	0.38	0.67
Laplacian	7.0	0.470	0.657	0.52	0.745	0.37	0.65
Laplacian	8.0	0.446	0.641	0.50	0.734	0.36	0.64
Laplacian	9.0	0.420	0.624	0.48	0.721	0.34	0.62
Laplacian	10.0	0.393	0.605	0.47	0.707	0.32	0.60
Laplacain	11.0	0.364	0.585	0.45	0.692	0.31	0.58
Laplacian	12.0	0.335	0.564	0.43	0.676	0.29	0.56
Laplacian	13.0	0.305	0.542	0.41	0.660	0.27	0.53
Laplacian	14.0	0.276	0.520	0.39	0.643	0.25	0.51
Laplacian	15.0	0.249	0.498	0.37	0.627	0.24	0.49
Laplacian	16.0	0.223	0.477	0.35	0.612	0.22	0.46
Laplacian	17.0	0.199	0.457	0.33	0.597	0.20	0.43
Laplacian	18.0	0.178	0.439	0.31	0.584	0.19	0.41
Laplacian	19.0	0.159	0.423	0.29	0.572	0.17	0.38
Laplacian	20.0	0.141	0.407	0.27	0.561	0.16	0.36
Gaussian AM	5.0	0.608	0.756	0.66	0.821	0.54	0.76
Gaussian AM	10.0	0.549	0.744	0.65	0.820	0.54	0.72
Gaussian AM	15.0	0.516	0.776	0.62	0.855	0.53	0.66
Gaussian AM	20.0	0.505	0.831	0.58	0.900	0.52	0.61
Laplacian AM	5.0	0.579	0.758	0.63	0.825	0.54	0.73
Laplacian AM	10.0	0.542	0.761	0.62	0.835	0.54	0.70
Laplacian AM	15.0	0.516	0.789	0.59	0.864	0.53	0.65
Laplacian AM	20.0	0.505	0.883	0.57	0.902	0.52	0.61

Table 1. Maximum average efficiencies and transition voltages.

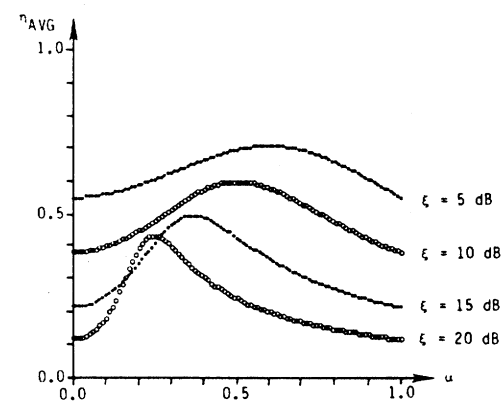

Figure 7. Average efficiency with Gaussian signals.

Pure speech is characterized approximately by the Laplacian or exponential p.d.f. The dependence of the average efficiency upon α (Figure 8) is similar to that for a Gaussian p.d.f. For a typical 10-dB peak-to-average ratio, the 39.3-percent efficiency of class B is increased to 60.5 percent by two-voltage class G and to 70.7 percent by three-voltage class G.

Signals such as triangle and sawtooth waves have uniformly distributed amplitudes. Since the peak-to-average ratio for these signals is relatively high, the

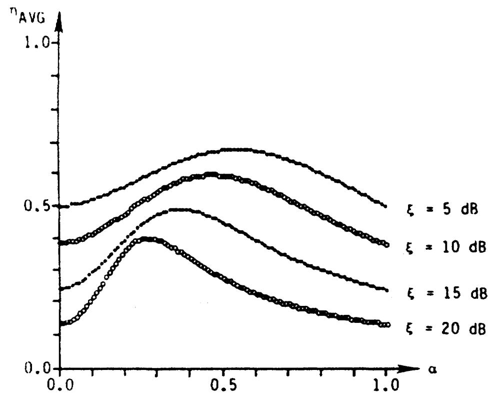

Figure 8. Average efficiency with Laplacian signals or envelopes.

corresponding variation of average efficiency with α is similar to that for amplification of a sinusoid (Figure 5).

Amplitude Modulation

Full-carrier AM radio transmitters are generally tested by single-tone modulation. For series-pass modulation [7, Chapter 15], the modulating signal consists of a dc bias (corresponding to the carrier) and a sinusoid, which spends most of its time at relatively high and relatively low amplitudes. Its variation of average efficiency (Figure 5) is similar to that of a sinewave.

Amplitude modulation by music and speech produce, respectively, Gaussian and Laplacian p.d.f.s with means (dc biases) corresponding to the carrier level. The variation of average efficiencies with α are shown in Figures 9 and 10. For typical modulation peak-to-average ratios, the 51 - 55 percent average efficiency of class B is increased to 76 - 78 and 83 - 86 percent by two-voltage and three-voltage class G.

Envelope Modulation for Linear RF PA

The envelope-elimination-and-restoration technique [7, Chapter 16] treats a bandlimited signal as a carrier with simultaneous amplitude and phase modulation. The phase-modulated RF carrier is amplified efficiently by class-C, -D, -E, or -F PAs. The envelope is restored by amplitude modulation of the final RF PA by an efficient series-pass audio PA.

The envelope produced by SSB/SC modulation by speech is approximately Laplacian-distributed, hence

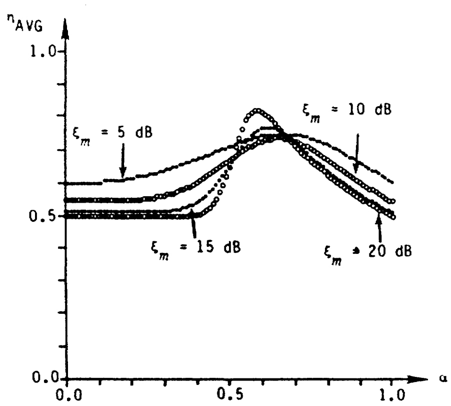

Figure 9. Average efficiency with Gaussian modulation.

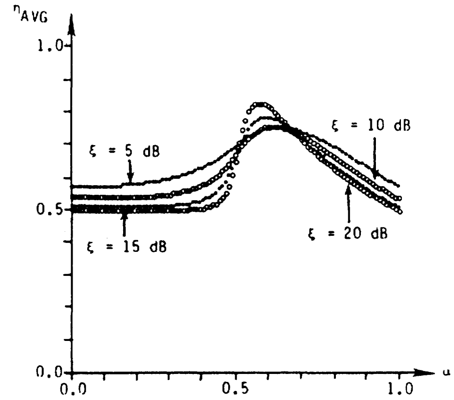

Figure 10. Average efficiency with Laplacian modulation.

the average-efficiency characteristics are those shown in Figure 8. Simultaneous amplification of Gaussian noise or a number of independent carriers produces a Rayleigh-distributed envelope, whose average-efficiency curves are shown in Figure 11. For a typical 10-dB peak-to-average ratio, the use of a two- and three-voltage class-G PA as the envelope modulators increases the average efficiency from the 39.3 percent of a class-B PA to 60.5 and 70.7 percent, respectively.

Quadrature amplitude modulation (QAM) is being used with increasing frequency because of its effectiveness in utilizing the available bandwidth for data transmission. Figure 5 includes a curve for the limiting case in which both the I and Q channels have infinite numbers of levels. The behavior of the average-efficiency curves is similar to those of the sinusoid and other low-peak-to-average ratio signals.

Maximum Average Efficiency

The maximum attainable average efficiencies for class-B and two- and three-voltage class-G PAs are shown in Figures 12, 13, and 14, respectively, for peak-to-average ratios from 5 to 20 dB. It is, of course, not possible to relate the maximum average efficiency to the peak-to-average ratio without specifying the type of signal. However, the inclusion of curves for Gaussian-, Laplacian-, and Rayleigh-distributed signals in these figures should enable the design engineer to obtain some insight into the range of average efficiencies that might be expected from a signal of a given peak-to-average ratio.

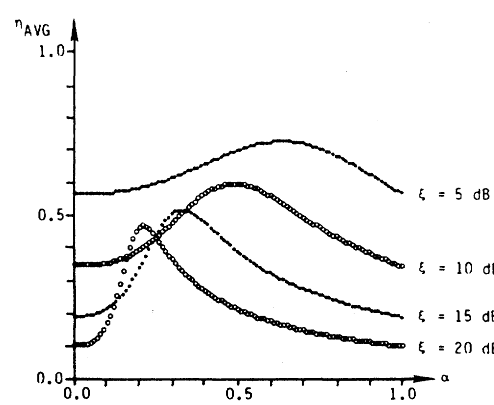

Figure 11. Average efficiency with Rayleigh envelope.

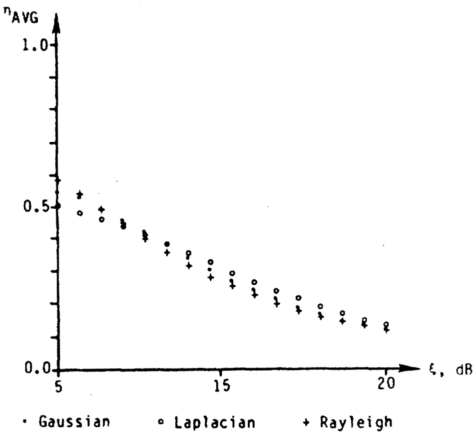

Figure 12. Maximum average efficiency of Class-B PA.

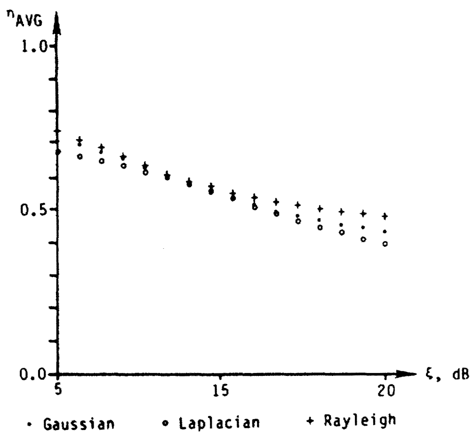

Figure 13. Maximum average efficiency with two supply voltages.

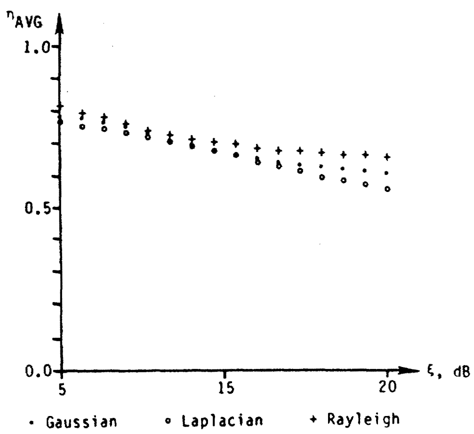

Figure 14. Maximum average efficiency with three supply voltages.

6. References

1. T. Sampei and S. Ohashi, "High efficiency and high fidelity class-E audio amplifier," *Transactions of Institute of Electronic Communications Engineering (IECE) of Japan*, vol. 75, no. 231 (EA75-70), 1976.

2. L. Feldman, "Class G high efficiency hi-fi amplifier," *Radio Electronics*, pp. 47 - 49, 87, August 1976.

3. T. Sampei, S. Ohashi, Y. Ohta, and S. Inoue, "Highest efficiency and super quality audio amplifier using MOS power FETs in class G operation," *IEEE Transactions on Consumer Electronics*, vol. CE-24, no. 3, pp. 300 - 307, August 1978.

4. J. L. Veranth, "Final study and development report of high efficiency sonar transmitters," Report no. 1303-002F (AD-901,236), Bose Corporation, Natick, MA, June 1972.

5. V. N. Nogin, "Push-pull power amplifiers with stepped supply voltage and antiparallel connection of the arms," *Telecommunications and Radio Engineering*, part 2, vol. 19, no. 7, pp. 76 - 88, July 1974.

6. J. Leiner, "Demand-switched supply boosts amplifier efficiency," *Electronics*, vol. 51, no. 23, pp. 114 - 15, November 9, 1978.

7. H. L. Krauss, C. W. Bostian, and F. H. Raab, *Solid State Radio Engineering*, New York: John Wiley and Sons, 1980.

8. F. H. Raab, "Average efficiency of power amplifiers," *Proceedings of RF Technology Expo '86*, Anaheim, CA, January 30 - February 1, 1986.

9. P. Beckmann, *Probability in Communication Engineering*, New York: Harcourt, Brace & World, Inc., 1967.

Biographical Sketch

Frederick H. Raab (S'66, M'72, SM'80) was born in Fort Crook, Nebraska on February 4, 1946. He received B.S., M.S., and Ph.D. degrees in electrical engineering from Iowa State University in 1968, 1970, and 1972, respectively.

Since starting Green Mountain Radio Research in 1980, Dr. Raab has been involved in RF power-amplifier design and simulation, target transfer using GPS and JTIDS, adaptive noise cancellation, proximity warning, VLF propagation prediction, spacecraft rendezvous/docking systems, and in-plant training seminars. From 1975 to 1980, he was with Polhemus Navigation Sciences, Inc. and was involved with terrestrial use of Loran-C, trapped-miner location systems, and special-purpose position-finding systems. From 1971 to 1975 he was with Cincinnati Electronics and was involved in using OMEGA and GPS for search and rescue and transmitter design.

Dr. Raab is coauthor of *Solid State Radio Engineering*, has authored or coauthored over thirty technical papers, and holds four patents. He is a member of the Institute of Navigation, International Omega Association, Wild Goose Association, Canadian Aeronautics and Space Institute, Eta Kappa Nu, and Sigma Xi.