ABRIDGMENT

Transistors in Video Equipment

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Principles involved in the design of video current amplifiers for television using transistors are discussed in terms of the hybrid-pi equivalent circuit. The importance of the current gain bandwidth factor is emphasized and a design philosophy which exploits an unconventional concept of gain-bandwidth is presented. An investigation of noise with regard to camera head amplifier design gives the transistor parameters and circuit conditions necessary for maximum signal-to-noise ratio. Experimental confirmation shows transistors to be comparable with valves in this application.

Vidicon Head Amplifier

Transistor circuits can sometimes be developed using ideas directly derived from conventional valve techniques. Experience usually shows that better results can be achieved by developing new methods, suited to the special properties of transistors. Transistor video amplifiers, for example, can be built using essentially valve methods, but the results are likely to be disappointing and expensive. The purpose of this paper is to find the most economical way of using transistors to obtain the high gain, wide bandwidth and low noise required for a vidicon camera head amplifier. A vidicon camera tube is a current generator, and therefore requires a current amplifier, the gain required being about 45,000 times over a bandwidth of say 5 mc/sec.

Natural Response

Current gain is most conveniently obtained using cascaded ground-emitter stages. In this configuration the inherent low-frequency current gain of a transistor is usually in the range 20 to 200 times. At high frequencies the gain falls, closely following a simple RC-type law, in which two characteristic frequencies can be defined. The first is the natural cutoff frequency $f_{\alpha e}$, at which the current gain has fallen 3 db. Above $f_{\alpha e}$ the gain eventually falls 6 db per octave, so that the product of gain and frequency becomes a constant and defines the second characteristic frequency f_1. This is the point at which the current gain would fall to unity, if the 6 db per octave law were truly maintained down to unity gain. Since in video amplifiers we require gains well above unity, this definition of the gain bandwidth factor f_1 is valid.

Conventional Design

The stage bandwidth required for television is greater than the natural cutoff frequency of present-day transistors, so that some artificial way must be found for increasing it. With a pentode valve, gain can be exchanged for bandwidth simply by changing the coupling resistance. The product of gain and bandwidth remains constant. This would also be true in the transistor case if it were not for the extrinsic base resistance $r_{bb'}$. Figure 1 shows the hybrid-pi equivalent circuit, with a signal source represented by a current generator. Also shown is a coupling resistor R_s and a load R_L. For the moment, assume the load to be small, so Miller effect can be neglected. It will be seen that R_s reduces the effective resistance acting in parallel with the base storage capacitance, thus reducing the input time constant, and hence increasing the bandwidth. At the same time, the gain is reduced, because some of the signal input current now flows into R_s. If, for example, the stage bandwidth required were twice $f_{\alpha e}$, then the sum of R_s and $r_{bb'}$ would have to be made equal to $r_{b'e}$, but then less than half the signal current would flow into the transistor, because the sum of $r_{bb'}$ and $r_{b'e}$ would be greater than R_s. In the limit, if R_s were made zero, the bandwidth would still be finite, but the gain, zero. In other words the gain-bandwidth product falls, as the bandwidth is increased by reducing R_s. Loss of gain bandwidth in this way is inevitable when the conventional valve amplifier design method is applied to transistors, particularly when the bandwidth required exceeds two or three times $f_{\alpha e}$.

Miller Effect

It can be shown that Miller effect emphasises this loss in gain-bandwidth in two ways, firstly by a reduction in the effective value of f_1 and secondly by an increase in the adverse influence of the extrinsic base resistance $r_{bb'}$.

Cascade Loss

When stages having a simple RC-type response are cascaded, and the overall bandwidth maintained by reduction of individual-stage gains, it is well known that the overall gain passes through a maximum for a finite number of stages. The overall gain obtainable is very limited when stages having low initial gains are used.

The design calculations necessary to apply the conventional approach are formidable in any but the simplest cases. If the adverse influence of the extrinsic base resistance, Miller effect and the cascade loss are taken into account in the design of a vidicon head amplifier, for example, one would almost certainly need the services of a computer, backed up by the usual crystal ball.

New Design Method

The waste of signal current in R_s and some of the design difficulties can be avoided by a new design method. In this, the first object is to obtain all the intrinsic current gain available at the highest frequency of interest f_p. Current gain at lower frequencies is inherently larger and must be equalised by some method which does not reduce the gain at f_p.

If R_s is not to reduce the gain at f_p, it is obvious that its effective value at f_p must be made much larger than the input impedance of the transistor at that frequency. There are two ways in which this can be achieved. One is simply to use a large resistance; the other is to use a lower resistance in series with a parallel tuned circuit, resonant at f_p. A low value of real resistance may be convenient for d-c feed purposes, but a high value gives less distortion. Flexibility in the choice of coupling resistor, is one of the advantages of this design method.

Equalisation

Excess current gain at low frequencies must be equalised without reducing the

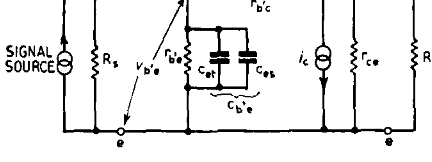

Fig. 1. Hybrid-pi equivalent circuit.

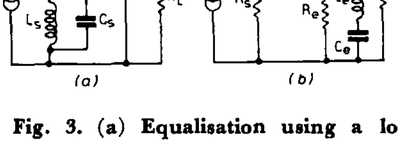

Fig. 3. (a) Equalisation using a low value R_s; (b) equalisation employing emitter circuit feedback.

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gain at f_p. If the amplifier consists of only one or two stages, the low-frequency gain per stage can be made either 3 or 1.5 db, respectively, above the high-frequency gain. But in a multistage amplifier it is better to make the low-frequency stage gain equal to that at f_p. To a rough approximation the overall gain-bandwidth is then the product of all the individual stage gains at f_p times f_p itself. It will be seen that there is no limit to the number of stages that can be used, since stage gains do not have to be reduced on cascading.

Two ways are shown in Fig. 3*, by which the low-frequency gain can be equalised. Figure 3a shows a low value R_s used in conjunction with a resonant circuit. Here R_s is chosen to give the required low-frequency gain. The optimum values for the inductance and capacitance are best found experimentally; the resonant frequency is usually just above f_p. The capacitor can be removed, with only a slight loss of gain-bandwidth. The circuit is then, of course, almost identical to the conventional one, using a shunt peaking coil, and the result can be no better. The advantage then lies only in the ease of design using this approach.

The most useful method of equalisation is shown in Fig. 3b. This uses an emitter feedback resistance R_e and a large value R_s. These, incidentally, reduce distortion. A series tuned circuit, again resonant at f_p or just above, is connected across R_e to restore the initial situation at f_p. The values of inductance and capacitance are also best found experimentally. If C_e is used alone, the gain-bandwidth product falls only a small amount, and the required capacitor value can be calculated by using the maximally flat criteria.

Figure 4 shows the use of a reactance transformer. By a proper choice of inductance and Q, the stage frequency response can be extended, while maintaining a reasonably flat response at medium frequencies.

Low-Frequency Response

Field frequency square wave response is maintained in basically the same way in both transistor and valve amplifiers. The main difference is the much lower input impedance of transistor stages, which is often comparable with the previous interstage coupling resistor. As in valve amplifiers, some low-frequency compensation can be achieved by suitable choice of the decoupling network feeding the previous collector.

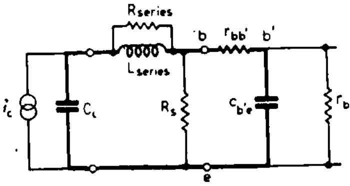

Fig. 4. Reactance transformer coupling.

Noise

Noise reduction is a major problem in camera head amplifier design. Transistors produce two types of noise, each with a characteristic spectrum. The very low frequencies are dominated by the excess or surface noise, which has a spectrum inversely proportional to frequency. In a television camera, noise at the lower audio frequencies can almost be eliminated by the usual error-correcting clamp, so excess noise can be neglected.

L. J. Giacoletto has shown (Fig. 5) that white noise sources can be represented by four uncorrelated generators. Also shown is a vidicon and its load resistor with their associated equivalent noise sources.

The extrinsic base resistance produces simple thermal noise. Shot noise is generated by the flow of base and collector current and is also associated with the transfer mechanism.

Optimum Emitter Current

To make a direct comparison of signal and total noise, it is convenient to refer each equivalent noise source back to the input of the amplifier. The expression for total noise obtained in this way shows there to be an optimum emitter current which gives minimum noise. With presently available transistors, this optimum emitter current is a function of amplifier bandwidth, current gain, transit time of current carriers through the base region, and the fixed capacitances associated with the junction barriers, and the vidicon signal electrode.

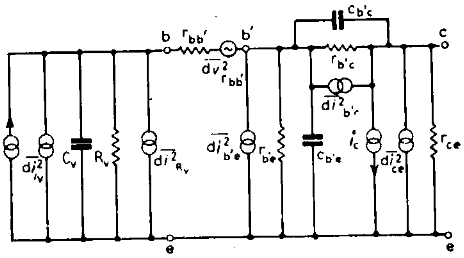

Fig. 5. First stage noise sources.

Transistor Characteristics Required

Evaluation of the terms of the resulting optimal noise equation shows that to get minimum noise, a transistor should be chosen which has small values, for base transit time, barrier capacitances, saturation currents and extrinsic base resistance. Also the circuit should be arranged to minimise stray capacitances, and the vidicon load resistance should be large compared with twice $r_{b'e}$. There also appears to be a very shallow optimum value for current gain, well above present values. In practice, normal gains in the range 30 to 100 give noise figures within 1 db of the optimum.

Amplifier Performance

An experimental amplifier using type 2N345 transistors, was built to measure noise under these optimal conditions. It was designed to give a gain of 100,000 over a 5 mc/sec bandwidth. The required 1st stage transistor parameters had previously been measured and gave an optimum emitter current of 51.8 μamp. Substitution in the noise equation predicted a signal-to-noise ratio of 42.3 db. The measured figure was 43 db. It is interesting to note that this is identical to the figure obtained with an earlier 6BQ7A valve head amplifier. Also the power consumption of this valve amplifier was 27½ w, whereas the experimental transistor amplifier consumed only 300 mw.

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* Figures 2 and 6 are omitted.