and the local peculiarities of the earth's magnetic field, then it must either have an extraordinary differential sensitivity to any e.m.f. produced by movement of its small flippers, or some different type of mechanism must be considered.

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DISTORTION IN LOW-NOISE AMPLIFIERS

IN his otherwise informative article on distortion in transistor amplifiers (August 1977 issue), Mr Taylor is incorrect in stating that the equation

$$\exp\left|\frac{eV}{KT}\cos\omega t\right| = a_0 + a_1\cos\omega t + a_2\cos 2\omega t + \ldots \quad (1)$$

cannot be solved analytically. The required mathematical identity is [1,2]

$$\exp(\lambda\cos\theta) = I_0(\lambda) + 2\sum_{n=1}^{\infty} I_n(\lambda)\cos(n\theta) \quad (2)$$

where the coefficients $I_n(\lambda)$ are n^{th} order, modified Bessel functions whose values may be found in standard tables [2,3]. Thus the amplitude of the n^{th} harmonic relative to the fundamental is given by

$$A_n/A_1 = I_n\left(\frac{eV}{KT}\right)/I_1\left(\frac{eV}{KT}\right) = \frac{1}{n!}\left(\frac{eV}{2KT}\right)^{n-1} \quad (3)$$

where the last expression is an approximation, correct for small values of eV/KT. The exact value of t.h.d. may be easily calculated since successive coefficients are of rapidly decreasing value.

However, for approximate calculations neither tables not computers are required. Equation (3) shows that the second harmonic distortion level in per-cent is roughly given by

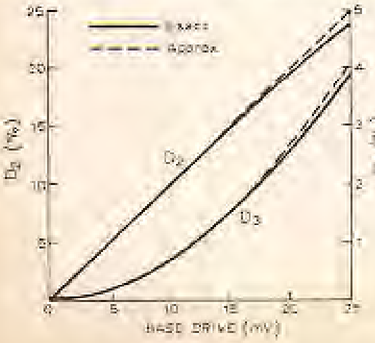
$$D_2 = \frac{100}{2}\left(\frac{eV}{2KT}\right) = 25\frac{eV}{KT} \quad (\%) \quad (4)$$

Further, since the t.h.d. is predominantly second harmonic, and since KT/e is 0.025 volts at room termperature, we find the remarkably simple numerical approximation.

$$D = V \quad (5)$$

where D is the t.h.d. in percent and V the base drive in millivolts. As Mr Taylor noticed from his numerical calculations, the distortion is 1% at 1mV drive and is 10% at 10mV!

To see the degree of approximation involved, the accompanying figure compares



the approximate and exact values of the second and third harmonic components D_2 and D_3 (note different scales) using equation (3). One can show numerically that the t.h.d. curve lies between the exact and approximate D_2 curves. Thus equation (5) is accurate to 1% up to 15mV base drive and is less than 3% high at 25mV.

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References
1. G. N. Watson, A treatise on the theory of Bessel functions, 2nd ed., 1958, (Cambridge University Press).
2. M. Abramowitz and I. A. Stegun, Handbook of Mathematical functions (Dover Publications).
3. British Associates for the Advancement of Science, Bessel functions, Mathematical Tables Vol. VI (1950) and Vol. X (1952), Cambridge University Press.

Dr Taylor replies:

It is evident from Mr Edgley's letter that I should have been more cautious in my choice of words when I stated that the Fourier Series expansion for the exponential base-emitter characteristic of a transistor could not be solved analytically. Mr Edgley is quite correct in pointing out that a table of modified Bessel Functions allows an analytical solution. Unfortunately it is normally necessary to resort to recurrence relations to determine the higher order functions (see for example Mr Edgley's ref. 2) and again the solution becomes laborious. The repetitive nature of the calculations to determine t.h.d. as a function of input signal amplitude is ideally suited to a numerical computing technique which, with a minor programme modification, also allows the distortion performance of the long tailed pair input stage to be calculated.

I would now like to reply to the comments made by Mr Dytch and Mr Bishop in their letter in the November 1977 issue.

When the design of this pre-amplifier was initiated some time ago I consulted a well known cartridge manufacturer to determine whether the input bias current would damage the cartridge and was informed that it would not. It seems unlikely that 100nA of bias current will have any effect on the performance of a magnetic cartridge and recently Shure have been kind enough to conduct tests with their V15 Mk III cartridge and confirm that this in in fact so. If however the amplifier is adapted for use with a moving-coil cartridge it would perhaps be advisable to a.c. couple the input to prevent damage to the cartridge.

I have received some correspondence concerning the accuracy of the RIAA equalisation, typically −2.5 dB at 20Hz and +2.5dB at 20kHz with my original circuit. The discrepancy at low frequencies is primarily due to the 10μF capacitor and 1kΩ resistor in the input circuitry giving a low frequency roll off at 16Hz. Increasing the capacitor to 47μF brings the equalisation to within 1.0dB of the RIAA characteristic with the preferred values of components used in the equalisation network. Correct high frequency equalisation of a series feedback pre-amplifier presents certain problems because it is not possible to obtain a gain of less than unity. These problems become more severe as the sensitivity is reduced and therefore, for a particular amplifier design, the accuracy of equalisation is related to the overload capability. The high frequency equalisation of my original circuit can be improved, however, to within 1.0dB of the RIAA characteristic at 20kHz by shorting out R_3 and increasing C_1 to 75pF to maintain closed loop stability. As yet I have not made any measurements with this circuit modification but cannot see any reason why it should significantly effect the distortion performance of the amplifier.

Eric F. Taylor.

DIRECT SENSING OF RADIO WAVES?

MR DONALD WOOD, who writes in the December issue concerning the direct perception of electromagnetic waves, might be interested to learn of some experiments carried out by A. F. Collins in 1902. These were aimed at verifying "the casual observations long since made that approaching electrical storms manifested their presence in persons afflicted with certain forms of nervousness and other pathological conditions, though the storm influencing them might be many miles beyond, or even below, the horizon. To accomplish this task it was necessary, of course, to decide conclusively that electric waves exercised some behaviour or produced a change, molecular or otherwise, on the brain cells."

Collins' technique was to insert two electrodes into the brain to see if it would act as a "coherer" – i.e. to search for a decrease in resistance under the influence of electromagnetic radiation. He experimented initially with a dead mammalian brain obtained from a slaughter-house, and with the brain of a live cat which, in Collins' own words, "willingly lent itself to the subject for the investigations to be made on brain matter in the living state". Coherence was obtained, and also some twitching of the base of the brain was seen in response to the application of the electromagnetic stimulus.

Encouraged by these results, he repeated the experiments on a human brain from a recently deceased person, and found that the rust-red material in the cerebellum showed the greatest response. Finally, he carried out some measurements of resistance to determine the effect of 24 hours brain deterioration, but found that his instruments were behaving very erratically, the galvanometer needle jumping all over the scale. "This state continued for a few minutes, when a peal of thunder awaked me to the actual cause. A storm was approaching.... As the storm approached, the deflections grew more and more pronounced, the needle quivering at either end of the scale alternately as though endowed with life. The very phenomenon I sought to verify with a 2cm spark coil was here produced by the lightning itself.....In these tests I was favoured with circumstances which, with me, might never occur again, for the reason that a fresh human brain was necessary, and that an electrical storm should be in progress when all was in readiness was quite remarkable".

Some other relevant remarks were made by the editor of the journal *The Electrician* in 1913. He was commenting on the experiments performed by Prof. Lefeuvre of Rennes,[2] and verified by H. R. B. Hickman.[3] In these, the sciatic nerve of a frog's leg was connected to an aerial (via a rectifier) and to earth. The incoming c.w. telegraphy signals were then read from the Galvanic twitchings