Reducing crossover distortion

Michael McLoughlin presents the undistorted facts on why the amplified diode has had its day

Several disadvantages dog reduction of crossover distortion in Class B amplifiers where a separate output transistor is used for each direction of current. The classical solution is to use an amplified diode — a potentiometer with its three terminals connected to the three leads of a transistor — as a voltage source hung between the bases of the two output transistors.

As a result, these transistors continue to operate fairly well during crossover. But this arrangement needs initial adjustment, which can go wrong, and the circuit hovers on the brink of thermal runaway. Preventing runaway can involve an over-large heat sink. However before looking at alternative methods of reducing crossover distortion we should consider its measurement.

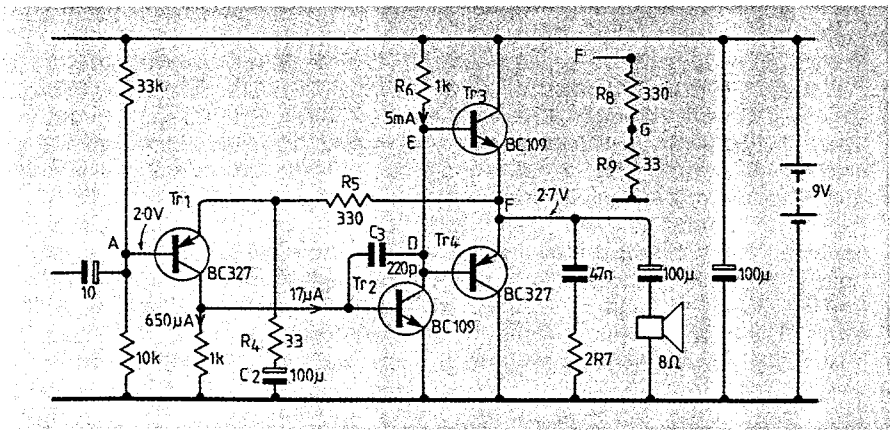
Measurement methods

Harmonic analysis is not a good method of displaying crossover distortion, because it conceals the causes. Better results are achieved by filtering out the fundamental, or by using the subtraction method.

To use the latter, attenuate the amplifier output until it is reduced to the size of the input signal, and display the difference. For example, in **Fig. 1,** connect R_8 to F, find the voltage difference between A and G, and multiply by 11 — the amplifier gain.

Whatever method is used, the distortion is more easily revealed if the output signal is small. So it seems sensible to take all measurements with an output signal of 1V peak. (1V RMS is a nuisance on the oscilloscope!)

Fig. 1. Basic Class B amplifier without the amplified diode. At switch-on A jumps to 2.0V and F rises rapidly to 2.7V, leaving quiescent currents as marked (assume a median gain of 300 for the BC109).



10kHz seems to be a sensible test frequency, as crossover distortion is worse at higher frequencies. At an alternative of 20kHz many loudspeakers offer an impedance of more than twice their nominal figure, reducing output current and crossover distortion. So the standard signal for measurement should be a sinusoidal output of 1V peak at 10kHz. All oscillograms in this article follow this standard.

Trace A. Unmodified distortion: The output from point F (**Fig. 2** top trace), clearly shows crossover distortion. All further traces rely on the subtraction method as described above and for Fig. 1 this gives trace A. In fact the crossover distortion of trace A appears with some fundamental, due primarily to the imperfect matching of the potentiometer (R_8 and R_9) to the amplifier gain. But the crossover distortion is easy to pick out and draw, because of its shape and its agreement in time with the jumps of the top trace.

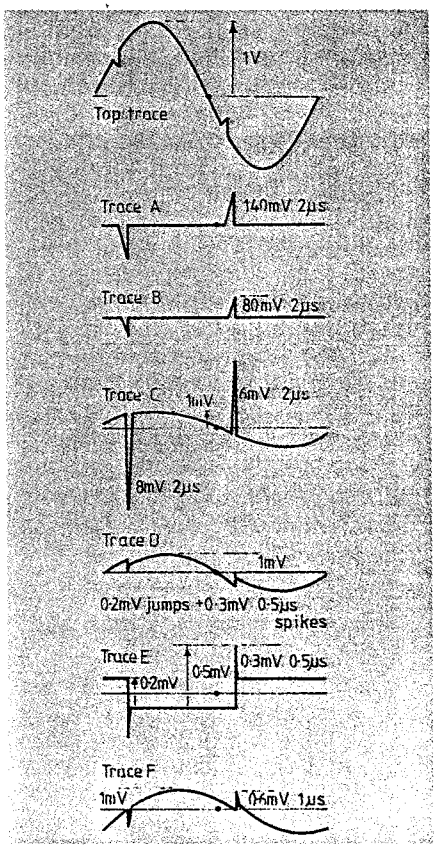


Fig. 2. Crossover distortion. The duration of any spike measured at 10% of its height is marked in μs. The top trace shows output volts. The other traces align in phase.

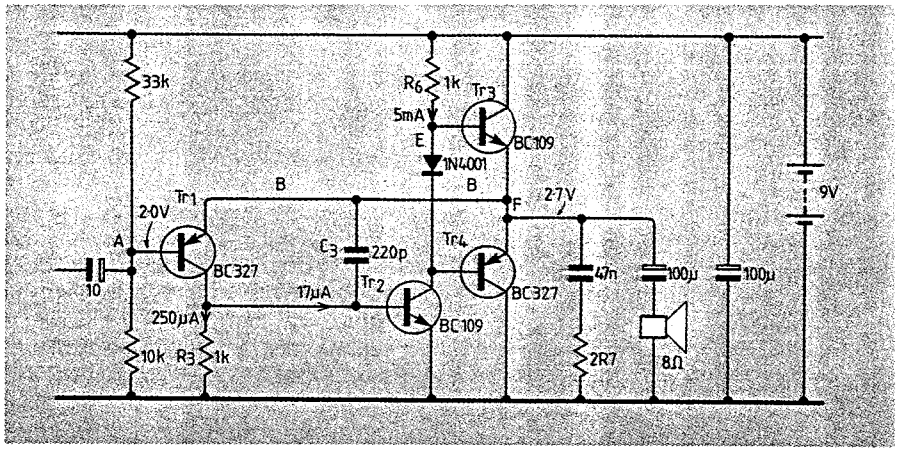


Fig. 3. Class B amplifier with low crossover distortion (trace E). High gain in the feedback loop means leads must be kept short to avoid 4MHz oscillation; lead BB is particularly sensitive. The 47n and 2Ω7 also help with stability. While experimenting display output from F to check for HF oscillation.

Trace B. Single diode: A voltage jump of 1.4V or so is needed at DE to effect crossover. This jump can easily be halved by inserting a silicon diode between D and E, halving the amplitude of the crossover distortion.

Trace C. Negative feedback: The normal way to reduce distortion is to increase feedback. Remove the feedback network R_5-R_4-C_2, and join Tr_1 emitter directly to F. This provides 100% voltage feedback to the input transistor. The voltage gain of the amplifier is lost, but that is easy to make up with an earlier class A stage.

The logic of the subtraction method is now easy to follow. In terms of volts F should follow A about like a slave; any difference is the distortion. So crossover distortion now appears as change in Tr_1 V_{BE}. That can be measured by using a difference amplifier (AC variety) attached at A and F (attach its positive input to the left of F). Result is a ten-fold fall in crossover distortion.

On trace C the crossover distortion appears as two spikes. These derive from capacitor C_3 in Fig. 1, there to reduce HF gain, preventing the HF oscillation that would otherwise occur. At high frequencies the transistor delays translate into large phase lags, turning negative into positive feedback.

With C_3 in position Tr_2 base acts like a virtual earth at HF, so Tr_2 voltage gain falls at 6dB per octave.

But C_3 also prevents points DE from rising rapidly in voltage. Rapid rise at DE pumps current down through C_3 into Tr_2 base, inhibiting rapid rise at DE. So Tr_2 collector is slew-rate limited by C_3. That will delay crossover, causing distortion as follows.

Trace D. Reconnecting the 6dB capacitor: Suppose a sinusoidal voltage is applied at A, and it has risen to 0V. Now DE should jump upwards instantly by 0.7V, but because of C_3 the points DE take time to effect that jump. While the jump is taking place F stays at 0V, but the signal at A continues to slew upwards, causing a growing error between the volts at A and those at F. When the jump at DE is finally completed, the crippling current flowing down through C_3 suddenly stops. The circuit reverts to type, with F slavishly jumping to the new voltage at A.

To summarise: a ramping voltage difference opened up between A and F, and then was suddenly chopped. That difference is the crossover distortion and explains each spike: a ramp which is suddenly chopped.

On trace C the chopping is slower than the ramp.

Once the cause has been traced, the spike can be tackled. Disconnect the upper end of C_3 from D, and connect it instead to F. Normally F follows D about, so C_3 upper plate is effectively connected as before. But during the crossover jump, F is stationary. The upper plate of C_3 no longer follows the rapid voltage change at Tr_2 collector and no disturbing current is now pumped down through C_3 which has been disconnected from the action.

But feedback is also disconnected during the DE jump, so C_3 is not needed to cut HF gain.

Reconnecting C_3 in this way yields a further thirty-fold reduction in spike amplitude.

Trace E. Revised amplifier with the changes so far proposed yields the amplifier in **Fig. 3**. Trace D shows the behaviour of Tr_1 V_{BE} during the cycle. The sinusoid visible is merely the V_{BE} needed at Tr_1 to drive the amplifier through its signal cycle (see below).

So the crossover distortion for the modified amplifier can easily be separated out, trace E. At this low level a new type of distortion appears; a square wave exactly out of phase with the signal cycle. Remembering that the influence of a spike is proportional to its length, then the spikes can now be ignored. The square wave is the residual crossover distortion.

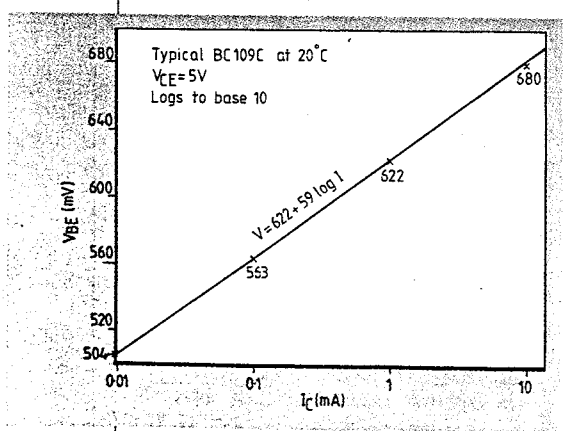
To tackle the square wave, its cause must first be identified. It comes from transistor V_{BE}, as shown in **Fig. 4.** From the formula in Fig. 4 one may readily deduce in sequence three results. Firstly, to multiply collector current by a factor F, the $\triangle V$ needed on the base is 60 $\log_{10}$ F (60 is usually written for 59, $\triangle V$ is in mV).

For small increases of collector current (F near 1) it then follows that $\triangle V$ may be calculated instead by assuming constant V_{BE} and a resistor R=25/I in series with the emitter. I is emitter current in mA.

Finally deduce that 1mV extra on the base increases I_C by 4%, a rule that may be used up to about 5mV.

The variations listed in Fig. 4 do not alter the slope of the line, and therefore have no effect on these formulae, which are quite accurate, of the 2% variety.

Fig. 4. Base volts required for collector current, with a typical BC109C. The line keeps the same slope, but may rise or lower by up to 10mV with a different BC109C, a different type of silicon transistor, or a 5°C change. Germanium lowers the line by about 450mV.



To study crossover refer to Fig. 3. Under quiescent conditions Tr_3 is on (to supply Tr_1) so E is at 3.4V. For crossover E must drop 0.7V to 2.7V, so current in R_6 increases from 5.6mA to 6.3mA which is a 12.5% increase requiring 3.1mV extra on Tr_2 base. Tr_1 must provide an extra 3.1μA to drive up by 3.1mV the PD across R_3, and of course Tr_2 base will take an extra 2.3μA (0.7mA/300). Tr_1 must provide an extra 5.4μA in all, 0.8% of its present current, requiring 0.2mV step on its base.

That step of the input signal brings about crossover, and has no effect on the output. So the step is lost, duly appearing as distortion in trace E.

It is not much harder to show that a total swing of 2mV is needed at Tr_1 base to drive the amplifier through the signal cycle, traces C, D and F. But note that the battery fell to 7V under the load. When +1V (the upper peak) is applied to the speaker, E has risen to 4.4V, so 2.6mA flows in R_6. 1mA of this is needed by Tr_3 base so Tr_2 passes just 1.6mA.

Next work out Tr_2 I_C max; then use the F formula . . .

Trace F. Current source: Point E in Fig. 3 needs to drop 0.7V for crossover, and 0.7mA extra from Tr_2 will produce that drop in R_6.

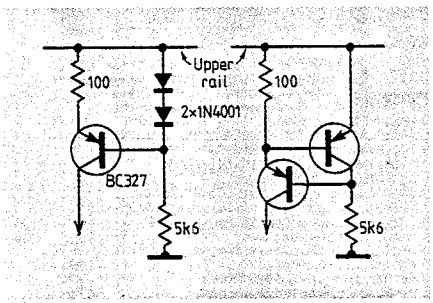


Fig. 5. Current source to replace R_6 in Fig. 3. The left circuit was used, but right circuit is better when there is significant dissipation.

But suppose R_6 is replaced by the 5mA current source shown in **Fig. 5.** Then when Tr_2 I_C rises quite slowly from just below 5mA to just above 5mA, point E must instantly drop through 0.7V. The difference between I_C and 5mA is base current for the transistors, and it must now change from one base to the other, requiring that 0.7V instant jump at E. Tr_2 enforces this rapid jump by extracting charge from point E.

Previously 0.7mA change in Tr_2 current was required for crossover. Now hardly any change in Tr_2 current is required, so hardly any voltage will be required at Tr_1 base either, and the square wave of trace E will disappear.

Trace F is the crossover distortion when the current source of Fig. 5 is inserted (C_3 may need to go to 330pF). In the figure no jump is apparent but on the oscilloscope a jump of about 0.01mV can just be seen — a twenty-fold reduction on trace D. Two small short spikes are left; the first of these shows there is a short time when the circuit stops lifting the output voltage.

A well known type of current source is the bootstrap, joining BB of Fig. 3 by a capacitor to the mid point of R_6. But here that is worse than useless because during crossover BB voltage is not moving. Tying the centre tap of R_6 to BB would actually impede the voltage change taking place at that centre tap. In this type of circuit any current source should be active.

Aural evaluation

Crossover distortion can most easily be heard if the signal is a low frequency sinusoid, say 200Hz, especially if the distortion can be removed at will by switching in an amplified diode. But the real issue is whether it can be heard on programme material of speech and music.

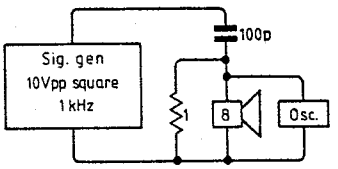
Listening quite carefully to 1V peak speech/music with the circuit of Fig. 1, reveals a quiet irregular hiss, which stops when the signal falls silent.

The hiss is more audible when a solitary male is singing — a low frequency signal can produce more harmonics within the audio band — but is less evident when he is talking. The jumps are at no fixed frequency. With Fig. 3 no crossover distortion at all could be heard.

When Fig. 3 is supplied with programme material, the 0.2mV steps of trace E are still visible via the difference amplifier, bobbing about in an irregular fashion. But can they be heard?

Listening to them in isolation, at a constant repetition rate, at a frequency to which the ear is sensitive (such as 1kHz, with the speaker connected via 100k to a signal generator delivering 2V p-p square wave at this frequency, in a quiet room, then the answer is yes — if one's ear is within one foot of the speaker.

But this test is ridiculously severe. The frequency has been held constant, the genuine signal which always accompanies crossover distortion has been removed, and the ear is unnaturally close to the speaker.



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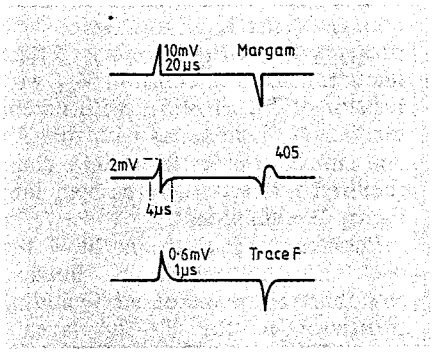

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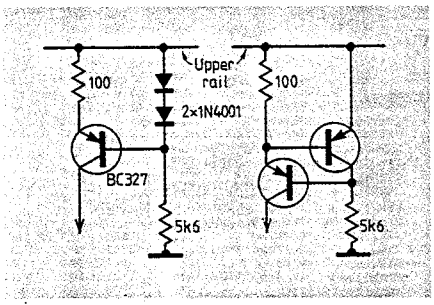

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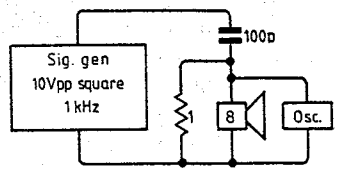

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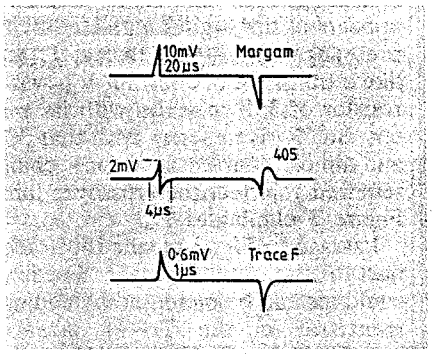

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duration into account the Quad 405 spikes do 28 times the damage of trace F, and Margam's spikes are 167 times worse. Squaring the amplitudes to compare power would give much more spectacular figures.

R_4 is a menace

Imagine a diode dropped into Fig. 1 between D and E. During crossover F is stationary, and 0.2mV change at A is required to produce the crossover jump at DE. The calculation to that effect appears at first sight unaffected by the presence of R_5-R_4-C_1. In fact Tr_1 acts like a transistor of constant V_{BE} with a resistor of 38Ω in series with its emitter. But R_4 is in series with that 38Ω, and almost doubles the 0.2mV change required to effect the crossover jump. Figure 3 eliminates R_4.

Passage to Fig. 3 meant 100% feedback of the output voltage. Feedback could instead be increased by adding a transistor in the Tr_1-Tr_2 area to increase loop gain. That is difficult, and adds components instead of subtracting them. A third disadvantage is that R_4 would be left in position.

It is now possible to say that during crossover the input impedance found at A in Fig. 3 is low, perhaps 11k (300×38Ω). If further loss of signal at crossover (above 0.2mV) is to be avoided, the output impedance of the preceding class A amplifier should be under 1k.

Summary

The crossover distortion found in Fig. 1 was improved by dropping in a diode, using 100% voltage feedback, reconnecting the 6dB capacitor, and feeding the gain stage from an active current source. The middle two suggestions might seem original. But recent IC power amplifiers do seem to reconnect the 6dB capacitor. They offer to the user just one compensation terminal, with instructions to connect it via a suitable capacitor to the output terminal. That is just what Fig. 3 would require, whereas Fig. 1 requires two points to be brought out for compensation.

In any event, it might appear that the amplified diode has had its day. Without its aid the tolerably quiet distortion audible as trace A has been reduced about 53dB to the level of trace F by a series of changes that requires just one more component. Similar improvements could be expected in expanded versions of Fig. 1. ■

References

1. Vanderkooy, J., and Lipshitz, S.P., *Wireless World*, July 1978, pp. 83-85: see Figures 4c, 5a, 6a.
2. Margam, E. *Electronics and Wireless World*, July 1987, pp. 739-742.

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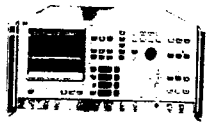

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RACAL 9008 automatic modulation meter £550

WANTED. Top quality 'high-end' test equipment for stock or will sell on commission. Please call, post or Fax list, any quantity. Signal generators, spectrum analysers etc urgently required for waiting customers.

ALL OUR EQUIPMENT IS SOLD IN EXCELLENT, FULLY FUNCTIONAL CONDITION AND GUARANTEED FOR 90 DAYS. MAIL ORDERS AND EXPORT ENQUIRIES WELCOMED. PLEASE TELEPHONE FOR CARRIAGE QUOTE. ALL INSTRUMENTS ARE AVAILABLE EX-STOCK AS AT COPY DATE. GOOD QUALITY TEST EQUIPMENT ALWAYS WANTED FOR STOCK. PRICES QUOTED ARE SUBJECT TO ADDITIONAL VAT.

2018A synthesized signal generator to 520MHz £2250
2091C/2092C white noise receiver/transmitter, pair £1750
2356 2357 level oscillator/level meter £1000
2370 spectrum analyser 110MHz £2750
2380/82 400MHz spectrum analyser £11,000
2431A 200MHz frequency counter £110
2438 (303J) 520MHz universal counter timer £450
2501 RF power meter 0.3W DC-1GHz £150
2828A/2829 digital simulator/analyser £1500
2833 digital in-line monitor £250
2952 mobile radio test set £1500
2870 data communications tester £1000
6460 microwave power meter with head 6421 £300
6460/1 microwave power meter with head 6423 £350
6056B 2-4GHz signal source £850
OA2805A PCM regenerator test set £750
TF1245A/1246 Q-Meter and oscillator £400
TF2002B/2170B 88MHz signal generator £300
TF2011 FM signal generator 130-180MHz £150
TF2013 FM signal generator 800-960MHz £350
TF2120 variable phase waveform generator £250
TF2162 audio attenuator £100
TF2163S UHF attenuator DC-1GHz 0-142db £325
TF2300 modulation meter £200
TF2300A modulation meter £300
TF2300B modulation meter £400
TF2304 modulation meter, automatic £400
TF2331 distortion meter £150
TF2500 audio frequency power meter £100
TF2600B video voltmeter 1mV-300V fsd £150
TF2807A PCM multiplex tester £400
TF2905/8 sine squared pulse & bar generator £275
TF2908 blanking & sync mixer £150
TF2910/4 video non-linear distortion analyser £750
TF893A audio power meter £50
TM4520 inductor set £250

ADDITIONAL EX-STOCK ITEMS

ROHDE & SCHWARZ SWOFIII videoskop £2000
ROHDE & SCHWARZ PUC instrument computer £850
ROHDE & SCHWARZ UPSF video noise meter £1250
SHIBASOKU 217A/33 SECAM colour bar generator £325
SOUND TECHNOLOGY 1700B low distortion test set £850
SOUND TECHNOLOGY 1000A FM stereo sig gen Band II £500
TAKEDA RIKEN TR9305 audio spectrum analyser FFT 0.0025Hz-100kHz. GPIB option £2950
TEKTRONIX 576 transistor curve tracer £2950
TEKTRONIX SG503, TG501 in TM503 main frame £1200
TEKTRONIX SG502 oscillator, FG501 in TM503 £395
TEKTRONIX AM503 current probe amplifier £500
TEKTRONIX 7633/7A26/7B53A/ storage oscilloscope £1250
TEKTRONIX P6019 & 134 current probe & amplifier £195
TIME ELECTRONICS 404S milli-volt source £100
TOA PM-30R RF volt-meter 1mV-10V fsd £250
WILTRON 610C sweep generator 4-18.5GHz £1500

CIRCLE NO. 132 ON REPLY CARD