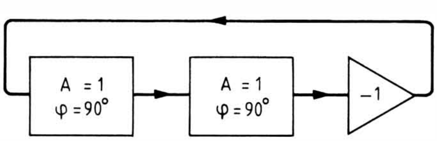
Phase-shifting oscillator

Low distortion design improves on Wien bridge

by Roger Rosens, Ing.

The use of a thermistor to stabilize an oscillator can lead to third harmonic distortion, especially at low frequencies. The circuit described here includes a simple network which virtually eliminates the third harmonic component. The result is an oscillator with a very flat frequency characteristic and very low distortion (typically 0.0005%)

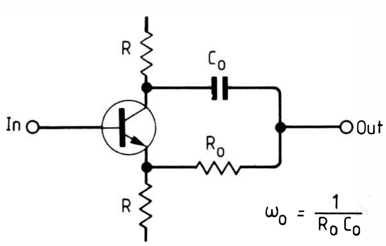
When a simple variable-frequency generator is required to give a low distortion sine wave, the commonly used circuit is the Wien-bridge oscillator. In its elementary form, this circuit requires only one op-amp as the active device. Using the kind of audio op-amp now available it is, however, possible to build other attractive circuits with only a little more complexity. Compared with the Wien, the phase-shifting oscillator presented here shows a flatter frequency characteristic and a significant reduction of the third-harmonic distortion caused by the stabilizer thermistor at low frequencies. The circuit is based on two 90° phase-shifting networks, followed by an inverter stage, giving a total loop phase shift of 360°.



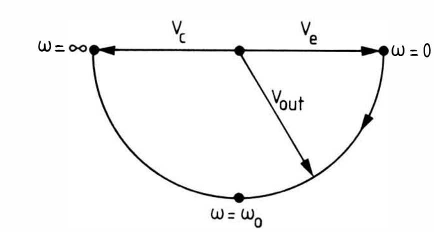
Operation of the phase-shifting network

The phase-shifting network is in fact a first order all-pass filter, the transfer function of which is defined by $F(p)=p-\omega_o/p+\omega_o$, where ω_o is the corner frequency. This function has a constant magnitude equal to 1 at all frequencies, while the phase shift varies from 0° to 180°. The phase shift attains 90° at the corner frequency ω_o; this will thus be the oscillation frequency.

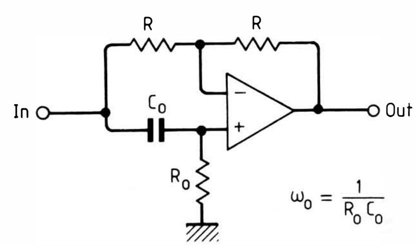
The first-order all-pass function can be realized with the following circuit:



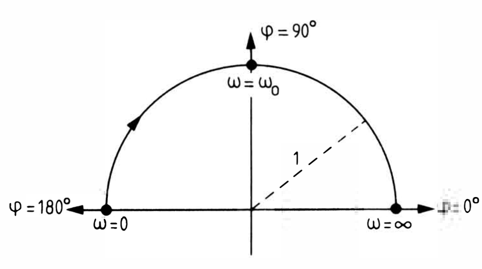
Assuming $R \ll R_o$, the output voltage phase will vary between the phase at the emitter (for $\omega=0$) and the phase at the collector (for $\omega=\infty$), which gives a phase variation of 180°.



An improved version of the all-pass circuit replaces the transistor with an op. amp.



The transfer function of this circuit is $F(p)=p-\omega_o/p+\omega_o$. The magnitude of thus always 1 and the phase angle is given by $\phi=180°-2\arctan\omega/\omega_o$. The polar plot is:



The oscillation frequency can be adjusted by varying R_o or C_o. Since there are two all-pass networks used in the oscillator circuit, a two-ganged element will be required to adjust the frequency.

The use of all-pass networks in an oscillator circuit has two important advantages:
– Stable amplification factor (equal to 1),

regardless of the equality between the ω_o of the all-pass circuits.
– Consequently, there is no need for close matching of the ganged element. The oscillator will have a very flat frequency characteristic while it is possible to use a low cost ganged potentiometer for the frequency adjustment.

Basic circuit diagram

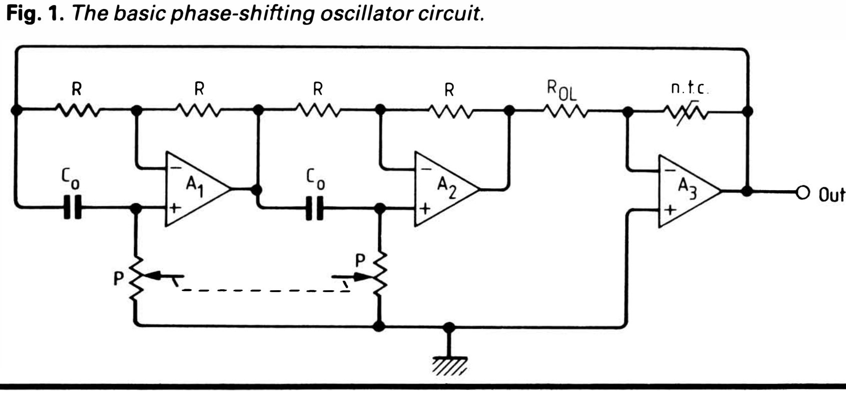
The complete oscillator circuit is quite simple (Fig. 1) The oscillation frequency is adjusted with P. The output level is stabilized with a thermistor (n.t.c.). Theoretically, the operating point is fixed at $R_{ntc}=R_{ol}$. If A_1 and A_2 are in the same package, their input bias currents will be about equal so that the offset voltages, caused by the voltage drops over P, will cancel each other at the output of A_2. Hence, the dc voltage on the thermistor will be negligible. This is important because this dc voltage causes second harmonic distortion, especially at low frequencies. For the same reason, the maximum resistance value of P must be limited to ≃100kΩ.

The circuit has two further interesting features:
–it can deliver three different sine waves of equal amplitude with relative phases of 0°, 90° and 180°.
– the frequency-adjustment potentiometers are both connected to ground. Compared with the Wien-bridge oscillator, this makes it easy to convert the circuit into a programmable oscillator. This is done by replacing the potentiometers by fixed resistors which may be switched by f.e.ts. The f.e.ts would all have their sources connected to circuit ground, which would make their gate drive very simple.

Distortion considerations

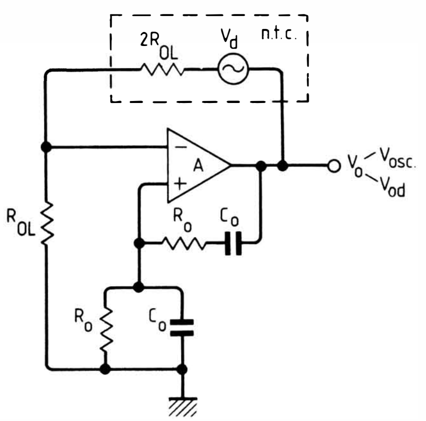
Two kinds of distortion are produced in the circuit:
– distortion generated by the active components.
– distortion generated by the amplitude stabilizing mechanism concerning the distortion in the op amps, a figure of

Fig. 1. *The basic phase-shifting oscillator circuit.*

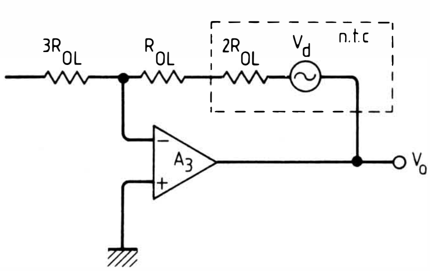


<0.01% can be obtained easily by choosing a quality audio op. amp.

The distortion introduced by the thermister is more difficult to reduce because a compromise has to be made between low distortion, fast settling time and good temperature stability. The n.t.c. distortion varies inversely with the settling time and the frequency while it is almost proportional to the temperature rise of the n.t.c. (see appendix 1). As is known, the relative temperature coefficient of the oscillator voltage is equal to $-1/2\Delta T$. Since a certain amount of thermistor distortion must be tolerated, it is important to reduce its effect on the output voltage as much as possible. This can be done by using an oscillator circuit with good frequency selectivity. One can calculate (see appendix 1) that the distortion generated in the n.t.c. consists mostly of third harmonic. We can now compare the output distortions between the Wien-bridge and the phase-shift oscillators. Let v_o be the oscillator output voltage, composed of: the fundamental, v_{osc}, and the distortion, v_{od}; and let v_d be the (3rd harmonic) distortion voltage generated by the n.t.c. v_d can also be defined as $d_3 v_{ntc}$ in which d_3 = distortion figure of the n.t.c. and v_{ntc} = oscillator voltage on the n.t.c. With the Wien bridge the circuit is:



For the phase-shifting oscillator, we can re-arrange the circuit so that v_{ntc} and v_{osc} are the same as on the Wien bridge circuit and this output stage results:



The output distortion can be determined in two ways: – by direct calculation of the transfer function v_{od}/v_d. Putting $=1/R_oC_o$, this results in:

$$\frac{v_{od}}{v_d}=\frac{-p^2+3p\omega_o+\omega_o^2}{p^2+\omega_o^2}$$

for the Wien bridge circuit, and

$$\frac{v_{od}}{v_d}=\frac{p^2+2p\omega_o+\omega_o^2}{2(p^2+\omega_o^2)}$$

for the phase-shift circuit. We can use the relation derived by Thomas Philips (*Electronic Engineering*, April 1981). If $F(p)$ is the transfer function of the frequency selective network, the distortion transfer function of the nth harmonic is given by:

$$\frac{v_{od(n)}}{v_{d(n)}}=\frac{F(j\omega_o)}{F(nj\omega_o)-F(j\omega_o)}$$

For the Wien bridge, $F(p)=p\omega_o/(p^2+3p\omega_o+\omega_o^2)$ and $F(j\omega_o)=1/3$,

$$\text{Thus } \frac{v_{od}}{v_d}=\frac{1/3}{F(nj\omega_o)-1/3}$$

For the phase-shift network, $F(p)=(p-\omega_o)(p+\omega_o)$ and $F(j\omega_o)=-1$.

$$\text{Thus } \frac{v_{od}}{v_d}=\frac{-1}{F(nj\omega_o)+1}$$

Of course the two methods give the same results. For the 3rd harmonics we find:

$$\frac{v_{od}}{v_d}=\frac{\sqrt{145}}{8}\approx 1.5$$

for the Wien-bridge circuit and, since

$$v_d=d_3v_{ntc}=d_3\times 2/3 v_{osc},$$

$$\frac{v_{od}}{v_{osc}}\approx 1.5\times 2/3 d_3\approx d_3$$

$$\frac{v_{od}}{v_d}=\frac{\sqrt{100}}{16}\approx 0.6$$

for the phase-shift network and thus

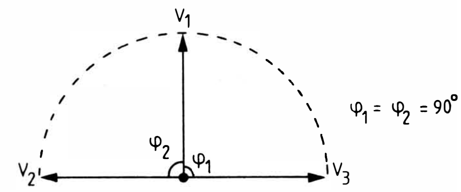
$$\frac{v_{od}}{v_{osc}}\approx 0.6\times 2/3\approx 0.4d_s$$

Conclusion: For similar operating conditions, the output distortion of the phase-shifting circuit is two and a half times less than that of the Wien-bridge. Since the phase-shifting circuit has no amplitude selectivity, this result is at first sight surprising. In fact, good harmonic suppression is a consequence of the circuit's "phase selectivity".

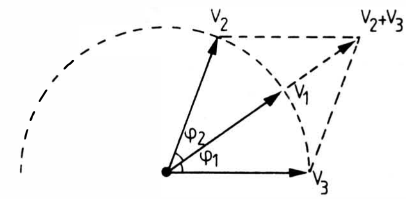
Additional circuit, to further reduce distortion

Choosing a practical compromise of the different circuit characteristics, the output distortion for the described circuit is 0.1% at 20Hz, decreasing to <0.01% above 100Hz. Further attempts to reduce these figures resulted in an additional circuit that virtually eliminates the third harmonic distortion generated by the ntc Let v_1,v_2 and v_3 be the voltages at the outputs of A_1 and A_2 and A_3.. The relationship of these voltage is given by the following diagrams:

for the fundamental:



– for the 3rd harmonic



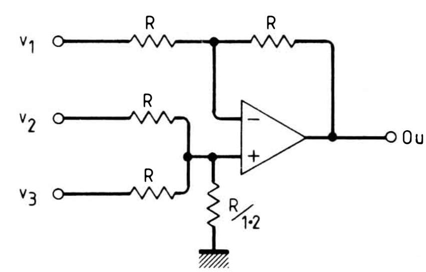
We can easily find that:

$$\phi_1=\phi_2=180°-2\arctan 3\approx 37°$$

$$v_2+v_3=1.6v_1, \text{ or}$$

$$v_1-\frac{v_2+v_3}{1.6}=0$$

This means that the third harmonic distortion can be eleiminated with a simple adder circuit. A suitable design is:



With regard to the fundamental, this circuit has no influence: v_2 and v_3 cancel each other, so that $v_{out}=(-)v_1$.

In practice, due to component tolerances, the distortion cannot be completely eliminated. The main source of error comes from the difference of ϕ_1 and ϕ_2, derived from the matching difference between the all-pass networks. When using 1% components and a ganging tolerance of 1dB for the dual potentiometer, the reduction of the 3rd harmonic is about 20 times. Since the distortion decreases with the frequency, the 1dB ganging tolerance is only required around the maximum resistance setting of the potentiometers.

Practical circuit and measured characteristics

The basic circuit has been optimized for the audio range 20Hz-20Hz. The selected op-amp is the NE5532, a dual circuit with low noise, low distortion and a still fair voltage gain of 2200 at 10kHz. (Some tests were also made with the TL072 but the results were not as good). With the addition of the distortion cancelling circuit, the distortion figure which was 0.1% at 20Hz falls to <0.005% over the whole frequency range.

The lower distortion limit is about 0.0002% (at 1000Hz). the final circuit diagram is shown in Fig. 2.The power supply for the circuit is ±12V to ±15V. The resistors are 1% metal film from the E96 series. Approximate values of the E24 series will also do the job. The range selecting capacitors should be preferably 1% polystyrene types. (For the 820 nF, selected polycarbonate capacitors were used with good result). The choice of the n.t.c. type was determined by the available op-amp current, the allowed distortion and the reqired output level. A 68kΩ, 20mW from Philips (code number 2322 634 32683) was selected. The operating point of the thermistor lies at about 3.4V and 910Ω which gives a dissipation of about 12mW and a minimum output voltage of 5V (typically 5.4V). The 100pF capacitor in the output stage compensates for a small lift in the frequency characteristic at the high frequency end of the range.

surements were carried out with fixed 1% resistors. www.keith-snook.info

– The large bandwidth of the NE5532 requires some precaution: the wiring must be very short and capacitive loads should be avoided. During the tests, the connection of the oscilloscope through a coax cable caused h.f. oscillations. The remedy is to load the circuit only via a series resistor ≥100Ω. Preferably, a 600Ω (R_{out}) will be chosen in order to obtain a standard generator impedance.

Appendix 1: distortion generated in the n.t.c.

The resistance of an n.t.c. resistor is given by the exponential law: $R = Ae^{B/T}$. When subjected to an ac voltage, the n.t.c. temperature will vary cyclically and hence its resistance will be modulated. This means that the instantaneous voltage/current relationship will be non-linear; in other words, some distortion has been generated. The amount of distortion can be calculated starting from the following basic

When we apply to the n.t.c. a sine wave voltage with an r.m.s. value, v_o: $v_{ntc} = \sqrt{2}v_o\cos\omega t$. We define the corresponding operating point by P_o, R_o and T_o which are related by:

$$P_o = \frac{v_o^2}{R_o} = \delta\Delta T = \delta(T_o - T_{amb}) \quad (4)$$

By using (4), (3) can also be written as:

$$Pdt = HdT = P_o dt$$

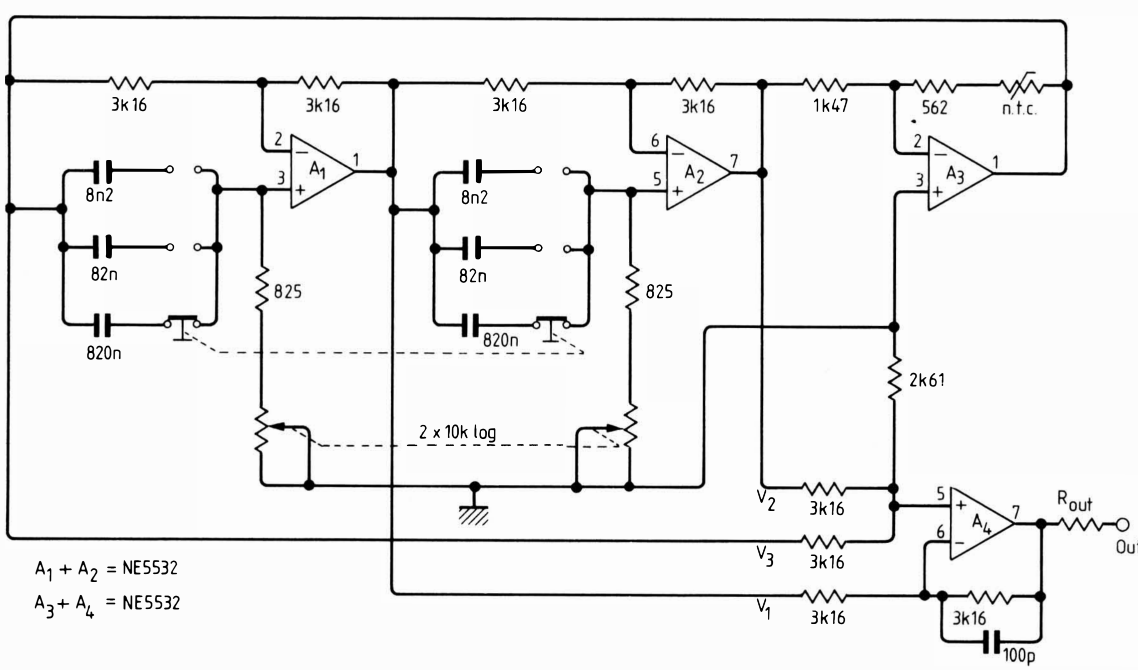
$$\text{or } \frac{(\sqrt{2}v_o\cos\omega t)^2}{R}dt = HdT + P_o dt \quad (5)$$

(1) can be transformed into $lnR = lnA + B/T$ and after differentiation:

$$\frac{dR}{R} = \frac{B}{T^2}dT \quad (6)$$

For small variations of the n.t.c. temperature, R and T may be approximated in the equations (5) and (6) by R_o and T_o; this gives:

Fig. 2. *The complete circuit for an audio oscillator.*



The circuit characteristics, as measured on the breadboard model, are:

– level flatness (20Hz-20KHz): 0.04dB

– temperature dependence: −0.03dB/K

– harmonic distortion ($R_{load} \geq 1k\Omega$) : <0.004% (typically 0.0005%)

The signal characteristics at the outputs of op-amps A_1, A_2 and A_3 are:

– level flatness : 0.03dB at the output of A_3

– harmonic distortion : 0.06dB at the output of $A_1$and A_2

: 01.% at 20Hz decreasing to 0.01% above 1000Hz

Remarks

– During the development of the circuit, consumer grade potentiometers were used. At some resistance setting, these potentiometers introduced a lot of noise and signal distortion due to the poor contact resistance. Therefore, the distortion mea-

expressions:

$$R = Ae^{B/T} \quad (1)$$

$$P = v^2 \quad (2)$$

$$Pdt = HdT + \delta\Delta dt \quad (3)$$

where R = resistance of the n.t.c.

A,B = (nearly) constants depending on the n.t.c. type

T = absolute n.t.c. temperature (in K)

P = power dissipated by the n.t.c.

v = voltage across the n.t.c.

H = heat capacity of the n.t.c. ceramic material (in J/K)

δ = dissipation factor of the n.t.c. (in W/K)

ΔT = temperature increase of the n.t.c. caused by the power dissipated in it.

$$HdT = \frac{2v_o^2}{R_o}\cos^2\omega t\,dt - P_o dt$$

$$= P_o(2\cos^2\omega t - 1)dt$$

$$HdT = P_o\cos^2\omega t dt \quad (7)$$

$$\text{and } \frac{dR}{R_o} = -\frac{B_2}{T_o}dT \quad (8)$$

Eliminating dT between (7) and (8) results in:

$$\frac{dR}{R_o} = -\frac{BP_o}{HT_o}\cos 2\omega t\,dt$$

and, after integration:

$$\frac{R - R_o}{R_o} = -\frac{BP_o}{2\omega HT_o^2}\sin 2\omega t$$

$$\text{or } R=R_o 1-\frac{BP_o}{2\omega HT_o^2}\sin 2\omega t$$

The current is given by:

$$i=\frac{v_{ntc}}{R}$$

$$=\frac{\sqrt{2}v_o\cos\omega t}{R_o\left(1-\frac{BP_o}{2\omega HT_o^2}\sin 2\omega t\right)}$$

which is nearly equal to

$$\frac{\sqrt{2}v_o}{R_o}\cos\omega t\left(1+\frac{BP_o}{2\omega HT_o^2}\sin 2\omega t\right)$$

$$=\frac{\sqrt{2}v_o}{R_o}\left(\cos\omega t+\frac{BP_o\sin\omega t}{2\omega HT_o^2}\ \frac{\sin 3\omega t}{2}\right)$$

The current is thus composed of the fundamental and of a third harmonic. This would be the same if a voltage, composed of a fundamental and a 3rd harmonic, were applied to a fixed resistor R_o. For the fundamental component, the term is negligible with regard to the term $\cos\omega t$; so, the third harmonic distortion can be approximated by

$$d_3=\frac{BP_o}{4\omega HT_o^2}$$

$$\text{or } d_3=\frac{B\delta\Delta T}{4\omega H(T_{amb}+\Delta T)^2} \qquad (9)$$

Table 1. *Distortion measurement results.*

Frequency (Hz)		110	263	520	1092	2636	5224	9564
Harmonic components (dB)	H2	−104	−112	−117	−122	−119	−113	−108
	H3	−117	−124	−121	−117	−116	−115	−114
	H4	−121	−124	−124	−123	−125	−123	−123
	H5	−119	−120	−121	−120	−118	−118	−119
	H7	−125	−128	−130	−126	−128	−126	—

Measurements were made using an HP3580A spectrum analyser preceded by a passive notch filter, giving a measuring limit of −130dB.

This function is zero for $\Delta T=0$ and $\Delta T=\infty$. Its maximum is reached for $\Delta T=T_{amb}$ (in K). For small values of ΔT, the distortion is almost proportion to ΔT. The expression $B\delta/H$ can be seen as a measure for the distortion proper to a certain type. For the used n.t.c., $B=3900$k, $\delta=0.11$mW/K and $H=0.5$mJ/K.

Using (1), expression (9) can be transformed to:

$$d_3=\frac{1}{4\omega\tau}\left(-\frac{T_{amb}}{B}\ln\frac{R_{amb}}{R_o}\right)\ln\frac{R_{amb}}{R_o} \qquad (10)$$

Where $\tau=H/\delta$ thermal time constant of the n.t.c.

R_{amb}=n.t.c. resistance at the ambient temperature

R_o=n.t.c. resistance at the operating point.

In the particular case when R_o is only slightly less than R_{amb} we have

$$\ln\frac{R_{amb}}{R_o}=\ln\left(1+\frac{R_{amb}-R_o}{R_o}\right)$$

$$\approx\frac{R_{amb}-R_o}{R_o}$$

and (10) becomes $d_3\approx\frac{1}{4\omega\tau}\ \frac{R_{amb}-R_o}{R_o}$,

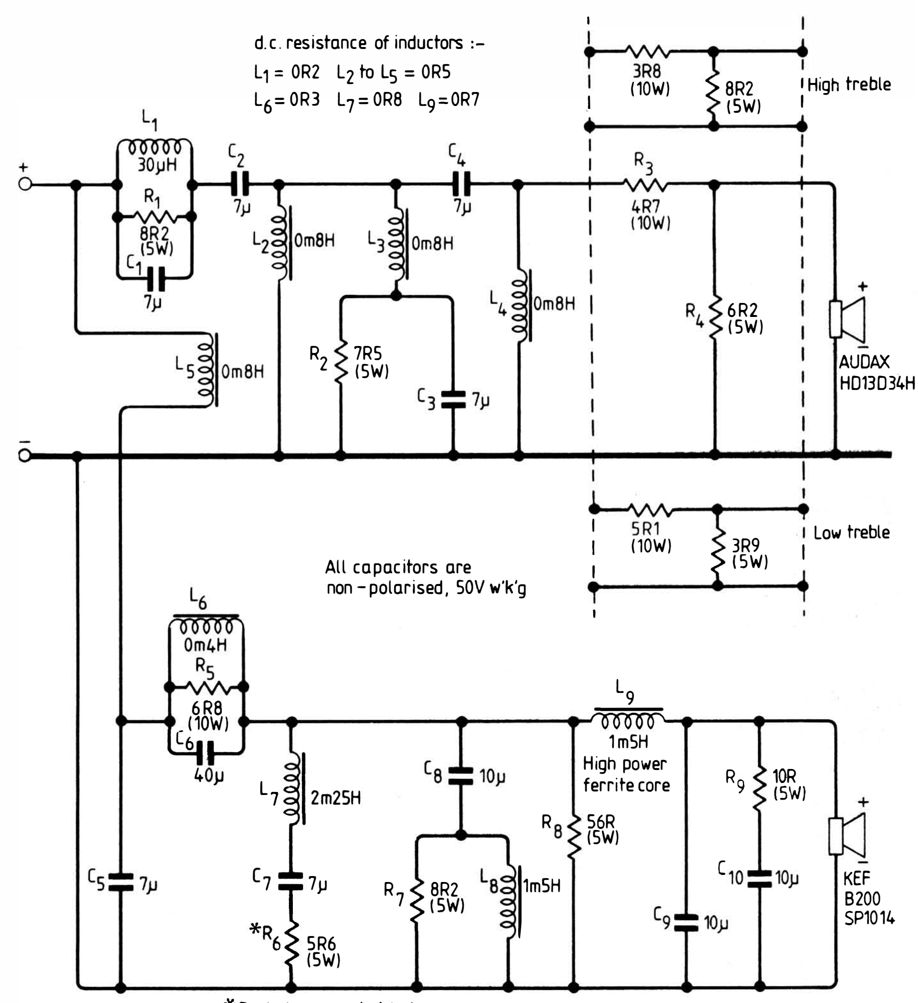
which conforms to the analysis of Dr F. N. H. Robinson (*Int. Journal of Electronics*, No. 2, 1980). In our circuit, the calculated n.t.c. distortion is about 0.13% at 20Hz which would give a distortion figure of 0.05% at the output of A_3. The measured distortion is 0.1%. The reason for this difference has not been determined exactly, though it looks as if H decreases at increasing frequency. This could be explained by the spherical shape of the n.t.c. material which causes a non-uniform current density and hence, especially at higher frequencies, a non-uniform temperature variation inside the n.t.c.

Book-shelf loudspeaker improvements

An article by J. Wilkinson describing the design and construction of a high-quality book-shelf loudspeaker was originally published in the October 1977 issue and improvements to the design followed in the June 1979 issue. Subsequent testing has prompted further small improvements.

Three small component changes in the crossover circuit have been made. One of these, namely changes in value of R_3 and R_4, has resulted from critical listening and comparison tests and gives a few dB attenuation in all three switch settings to compensate for room reflections of the tweeter's output. Changes in the values of R_5 and R_6 give a little extra dip in the crossover's output response curve at around 1kHz to compensate for a peak in the woofer's response curve at this frequency. Connecting the input of the low-pass filter before, instead of after L_1 gives a virtually inaudible improvement in performance but is nevertheless the best option from a theoretical viewpoint.

Extensive listening tests have also revealed a slight deterioration in sound quality caused by the 'anti-reflection' fillet attached to the bass-unit sub-baffle. The best solution is to replace the wood with 1/2in bituminous felt or similar material. A modified printed-circuit board, all the necessary components and the speakers can be obtained from Falcon Acoustics Ltd, Tabor House, Norwich Road, Mulbarton, Nr Norwich, Norfolk NR14 8TT.



*R_6 is incorporated in L_7