Phase-shifting oscillator

Low distortion design improves on Wien bridge

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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 $F(p) = -\frac{P - \omega_0}{P + \omega_0}$, where $\omega_0$ 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 $\omega_0$. This will thus be the oscillation frequency.

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

Assuming $R \ll R_0$, 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 $F(p) = \frac{P - \omega_0}{P + \omega_0}$. The magnitude of thus always 1 and the phase angle is given by $\phi = 180° - 2 \arctan \omega/\omega_0$. The polar plot is:

The oscillation frequency can be adjusted by varying $R_0$ or $C_0$. 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),
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Fig. 1. The basic phase-shifting oscillator circuit.

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 $R_{osf} = R_{ob}$. 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 $\approx 100\Omega$.

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.t.s. The f.e.t.s 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
<0.01% can be obtained easily by choosing a quality audio op. amp. The distortion introduced by the thermistor 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 $\frac{1}{2}\Delta T$. 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. The n.t.c. distortion, fast settling time and good temperature coefficient of the oscillator 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. The n.t.c. distortion, fast settling time and good temperature coefficient of the oscillator can be the voltages at the outputs $V_{o1}$ and $V_{o2}$, and the distortion, $V_{d}$; and let $V_{d}$ be the (3rd harmonic) distortion voltage generated by the n.t.c. $V_{d}$ can also be defined as $d_{3}V_{n1}$ in which $d_{3}$ = distortion figure of the n.t.c. and $V_{n1}$ = oscillator voltage on the n.t.c. With the Wien bridge the circuit is:

$$\frac{v_{t}}{d_{t}} = \frac{\frac{1}{2} + \frac{2}{2} + \frac{3}{3} + \frac{4}{4}}{2}$$

for the phase-shifting oscillator, we can re-arrange the circuit so that $V_{o1}$ and $V_{o2}$ are the same as on the Wien bridge circuit and this output stage results:

$$V_{d} = \frac{\sqrt{145}}{8} = 1.5$$

for the Wien-bridge circuit and, since

$$V_{d} = d_{3}V_{n1} = d_{3} \times 2d_{3}V_{o1},$$

$$V_{d} = 1.5 \times 2d_{3}V_{o1},$$

$$V_{d} = \frac{\sqrt{100}}{16} = 0.6$$

for the phase-shift network and thus

$$V_{d} = 0.6 \times 2d_{3} = 0.4d_{3}$$

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 $A_{1}$, $A_{2}$ and $A_{3}$. The relationship of these voltages is given by the following diagrams:

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:

$$F(nj\omega) = F(j\omega)$$

For the Wien bridge, $F(p) = p\omega_{0}(p^{2} + 3\omega_{0}^{2} + \omega_{0}^{2})$ and $F(j\omega) = 1_{3}$,

Thus $v_{d} = \frac{1}{d_{3}}F(nj\omega) = \frac{1}{d_{3}}$

For the phase-shift network, $F(p) = (p-\omega_{0})(p+\omega_{0})$ and $F(j\omega) = -1$.

Thus $v_{d} = \frac{-1}{d_{3}} F(nj\omega) + 1$

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

$$v_{d} = \frac{\sqrt{145}}{8} = 1.5$$

We can easily find that:

$$\phi_{1} = \phi_{2} = 180^\circ - 2 \arctan 3 = 37^\circ$$

$$v_{2} + v_{3} = 1.6v_{1},$$

or

$$v_{1} = \frac{v_{2} + v_{3}}{1.6} \approx 0$$

This means that the third harmonic distortion can be eliminated 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 $\phi_{1}$ and $\phi_{2}$, 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 noise figure 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 required 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 9100 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.

The circuit characteristics, as measured on the breadboard model, are:
- level flatness (20Hz-20KHz): 0.04dB
- temperature dependence: -0.03dB/K
- harmonic distortion (Rload=1kΩ) : <0.004% (typically 0.005%)

The signal characteristics at the outputs of op-amps A1, A2 and A3 are:
- level flatness : 0.03dB at the output of A1
- harmonic distortion : 0.06dB at the output of A1 and A2
: 0.1% at 20Hz decreasing to 0.01% above 1000Hz

Appendix 1: distortion generated in the n.t.c.
The resistance of an n.t.c. resistor is given by the exponential law: 
\[ R = A e^{B/T} \] (1)

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)

The signal characteristics at the outputs of op-amps A1, A2 and A3 are:
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: 0.1% 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 measurements 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 (Rout) will be chosen in order to obtain a standard generator impedance.

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

By using (4), (3) can also be written as:
\[ Pdt=HdT=P_0dt \]

(1) can be transformed into \( lnR=lnA+B/T \) and after differentiation:
\[ \frac{dR}{R}=-\frac{B}{T^2}dT \]

For small variations of the n.t.c. temperature, \( R \) and \( T \) may be approximated in the equations (5) and (6) by \( R_0 \) and \( T_0 \); this gives:

\[ H=T_0=2\pi \cos^2\omega t \] (7)

and \( \Delta T=T_0-T \) (8)

Eliminating \( dT \) between (7) and (8) results in:
\[ \frac{dR}{R_0}=-\frac{B_0}{H T_0} \]

and, after integration:
\[ \frac{R-R_0}{R_0} = -\frac{B_0}{2oHT_0} \sin 2\omega t \]
or \( R = R_0 \frac{1 - B P_0 \sin 2 \omega t}{2 \omega H T_0} \)

The current is given by:

\[
i = \frac{\sqrt{2} V_0 \cos \omega t}{R}(1 - \frac{B P_0 \sin 2 \omega t}{2 \omega H T_0})
\]

which is nearly equal to

\[
i = \frac{\sqrt{2} V_0 \cos \omega t}{R_0}(1 - \frac{B P_0 \sin 2 \omega t}{2 \omega H T_0})
\]

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 \( R_0 \). 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

\[
d_j = \frac{B \phi \Delta T}{4 \omega L (T_{amb} + \Delta T)^2}
\]

or

\[
d_j = \frac{B \phi \Delta T}{4 \omega L (T_{amb} + \Delta T)^2}
\]

This function is zero for \( \Delta T = 0 \) and \( \Delta T = \infty \). Its maximum is reached for \( \Delta T = T_{\text{amb}} \) (in K). For small values of \( \Delta T \), the distortion is almost proportional to \( \Delta T \).

The expression \( B \phi H \) can be seen as a measure for the distortion proper to a certain type. For the used n.t.c., \( B = 3900 \text{K} \), \( \delta = 0.11 \text{mW/K} \) and \( H = 0.5 \text{mJ/K} \).

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

\[
d_j = \frac{1}{4 \omega L} \left( - \frac{T_{\text{amb}} \ln R_{\text{amb}}}{B} \right) \ln \frac{R_{\text{amb}} - R_0}{R_0}
\]

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

\[
R_{\text{amb}} = \text{n.t.c. resistance at the ambient temperature}
\]

\[
R_0 = \text{n.t.c. resistance at the operating point}
\]

In the particular case when \( R_0 \) is only slightly less than \( R_{\text{amb}} \), we have

\[
\ln R_{\text{amb}} = \ln \left( 1 + \frac{R_{\text{amb}} - R_0}{R_0} \right)
\]

and (10) becomes

\[
d_j = \frac{1}{4 \omega L} \left( - \frac{T_{\text{amb}} \ln R_{\text{amb}}}{B} \right) \ln \frac{R_{\text{amb}} - R_0}{R_0}
\]

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.

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**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 \( R_8 \) 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.

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**Table 1. Distortion measurement results.**

<table>
<thead>
<tr>
<th>Harmonic components (dB)</th>
<th>Frequency (Hz)</th>
<th>110</th>
<th>263</th>
<th>520</th>
<th>1092</th>
<th>2636</th>
<th>5224</th>
<th>9564</th>
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<tbody>
<tr>
<td>H2</td>
<td>-104</td>
<td>-112</td>
<td>-117</td>
<td>-122</td>
<td>-119</td>
<td>-113</td>
<td>-108</td>
<td></td>
</tr>
<tr>
<td>H3</td>
<td>-117</td>
<td>-124</td>
<td>-121</td>
<td>-117</td>
<td>-116</td>
<td>-115</td>
<td>-114</td>
<td></td>
</tr>
<tr>
<td>H4</td>
<td>-121</td>
<td>-124</td>
<td>-123</td>
<td>-123</td>
<td>-123</td>
<td>-123</td>
<td>-123</td>
<td></td>
</tr>
<tr>
<td>H5</td>
<td>-122</td>
<td>-121</td>
<td>-122</td>
<td>-120</td>
<td>-118</td>
<td>-118</td>
<td>-119</td>
<td></td>
</tr>
<tr>
<td>H7</td>
<td>-125</td>
<td>-128</td>
<td>-130</td>
<td>-128</td>
<td>-128</td>
<td>-126</td>
<td>-126</td>
<td></td>
</tr>
</tbody>
</table>

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