RC OSCILLATOR WITH EXTREMELY LOW HARMONIC DISTORTION

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Received October 5, 1979

Presented by Prof. Dr. S. CSIBI

1. Introduction

Improvement of the studio and transmission systems and sound-tracking methods has imposed stricter requirements on the measuring equipment. This is valid especially in the case of the measuring devices used for the determination of nonlinear distortion in studio equipment. If one intends to measure low distortion, it is essential to produce a much lower level of harmonics in the measuring gear itself, and this can mean serious difficulties in the design of the generator and the measuring device.

This paper intends to introduce the principle of the ultra low distortion sinewave generator constructed under an engagement for research and development work between the BEAG and the Institute of Communication Electronics; and we should like to point out some of the practical problems of realization as well. The principle of the system has been patented [7].

2. Principles of operation

A sinewave with a very small harmonic content can be generated according to several principles. The so-called "exact sinewave oscillator" [1] has considerable distortion when realized and this distortion can be reduced only at the cost of decreasing stability of the amplitude and increasing transient times. This is equally true for the VAN der POL oscillator [2], moreover distortion can't be even theoretically zero in this case. Oscillators with quasi linear amplitude stabilization [3, 4] have two main sources of distortion: the quasi linear components are not perfectly linear in practice; and the control signal (proportional to the amplitude) necessarily contains a certain amount of ac especially at low frequencies.

Small distortion, great stability of the amplitude and fast transients are contradictory requirements, demanding new concepts for signal generation. Such concepts are described in the thesis by D. MEYER—EBRECHT [5], in the paper by E. VANNERSON and K. C. SMITH [6] and in the technical description of some products.

The block-diagram of the system introduced in the following sections is shown in Fig. 1. The frequency of the oscillation is determined by the linear system consisting of two integrators and an inverting amplifier. This system is characterized by the following differential equation:

$$\ddot{x}+\varepsilon\dot{x}+x=0 \tag{1}$$

Damping is determined by the $-1/\varepsilon$ resistor (the resistor can be of either positive or negative sign).

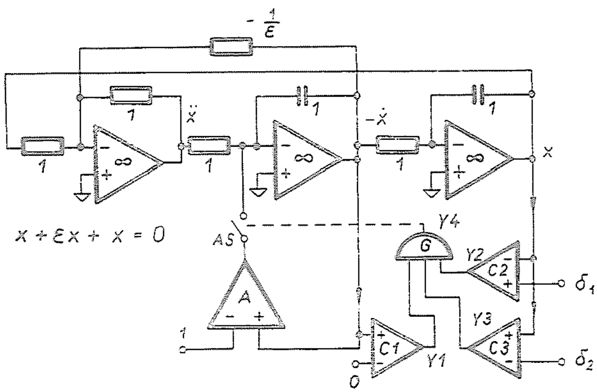

Fig. 1. State variable oscillator with fast amplitude control

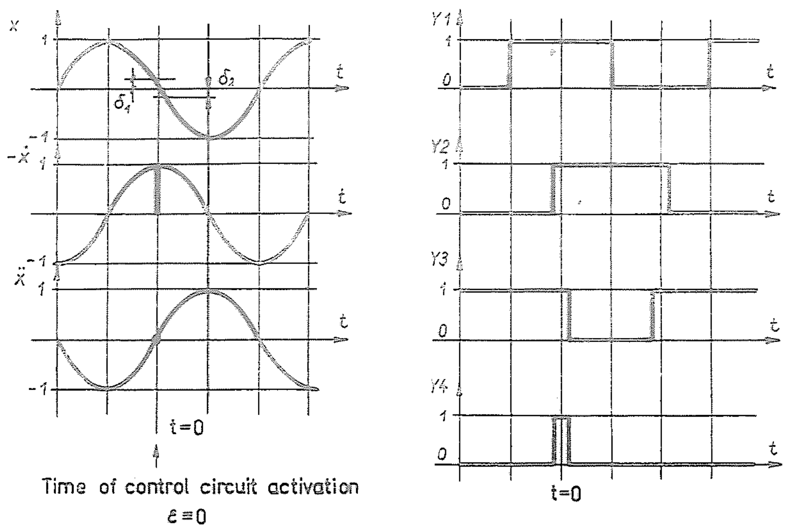

Fig. 2. Generation of the fast control signal

Operation of the so-called fast amplitude control circuit can be analyzed studying the waveforms in Fig. 2. (These are the waveforms in the case of $\varepsilon=0$.) The control circuit interferes with the oscillator circuit for a short time when $-\dot{x}$ reaches its positive maximum: closing the analog switch AS it restores the initial condition of $-\dot{x}$ when $x=0$. Thus the oscillator starts every period with the same initial conditions and the distortion is determined by the properties of the free running linear system. The time interval of the control is set by the comparators $C1$, $C2$, $C3$ and the gate G: a narrow pulse ($Y4$) is generated when $-\dot{x}$ is positive and $\delta_1 < x < \delta_2$. The relative width of the pulse is constant at all frequencies. If the gain of the differencial amplifier A is high, restoration of the initial condition can be accomplished within a very short time. In the following discussion it is assumed that this process takes place in an infinitely short time at $t=0\pm 2k\pi$ ($k=1, 2, \ldots$) and the solution of the differential equation is

$$-\dot{x}=\exp\left(-\frac{\varepsilon}{2}t'\right)\cos\left(\sqrt{1-\frac{\varepsilon^2}{4}}\,t'\right)=\exp(-at)\cos(t);$$
$$a=\frac{\varepsilon}{2\sqrt{1-\frac{\varepsilon^2}{4}}};\qquad t=\sqrt{1-\frac{\varepsilon^2}{4}}\,t';\qquad \omega\equiv 1 \tag{2}$$

Harmonics can be calculated in this case in the following way:

$$X_n=\frac{1}{\pi}\int_0^{2\pi}\exp(-at)\cos(t)\cos(nt)\,dt=$$
$$=\frac{1}{2\pi}[1-\exp(-2a\pi)]\left[\frac{a}{a^2+(n-1)^2}+\frac{a}{a^2+(n+1)^2}\right], \tag{3}$$

$$Y_n=\frac{1}{\pi}\int_0^{2\pi}\exp(-at)\cos(t)\sin(nt)\,dt=$$
$$=\frac{1}{2\pi}[1-\exp(-2a\pi)]\left[\frac{n-1}{a^2+(n-1)^2}+\frac{n+1}{a^2+(n+1)^2}\right]. \tag{4}$$

These yield for the amplitude of the harmonics:

$$Z_n=\sqrt{X_n^2+Y_n^2}=\frac{1}{\pi}[1-\exp(-2a\pi)]\frac{\sqrt{a^2+n^2}}{\sqrt{[a^2+(n-1)^2][a^2+(n+1)^2]}} \tag{5}$$

Distortion can be small only if $a \ll 1$ and in this case the following approximations are valid:

$$Z_1 \cong \frac{1}{\pi} 2a\pi \frac{\sqrt{a^2+1}}{a\sqrt{a^2+4}} \cong 1 \tag{6}$$

$$Z_n \cong 2a \frac{n}{(n-1)(n+1)} \cong \frac{2a}{n}, \qquad n>1 \tag{7}$$

As

$$|Z_n| \cong \left|2a \frac{n}{(n-1)(n+1)}\right| < \left|2a \frac{1}{n-1}\right|, \tag{8}$$

the distortion factor is

$$k \cong \sqrt{\sum_{n=2}^{\infty} Z_n^2} < 2|a| \sqrt{\sum_{n=1}^{\infty} \frac{1}{n^2}} = |a| \frac{2\pi}{\sqrt{6}}. \tag{9}$$

From these results it is clear that a distortion factor of 10^{-5} can be realized if the figure of merit $|Q| \geqq 1.28 \cdot 10^5$ (Q can be of either sign).

With the system in Fig. 1, such high values of Q can't be realized and this necessitates the implementation of a slow amplitude control or Q-control circuit.

3. Control of Q

The task of the Q-control circuit is the compensation of the losses present in the linear system, that is, maximation of Q.

The fast amplitude control circuit restores the initial condition of $-\dot{x}$ during each cycle at a time when the voltage across the other energy-storing element is always definitely the same. This can be done by charging or discharging the capacitor in the feedback branch of the second op amp (Fig. 1), that is, by making up for the changes in its charge.

The lost charge can be calculated as follows:

$$\Delta x = 1 - \exp\left(-\frac{\varepsilon}{2} \frac{2\pi}{\sqrt{1-\frac{\varepsilon^2}{4}}}\right) \tag{10}$$

if the capacitor's value is unity.

At the moment of fast control activation a step

$$\Delta z = \frac{1}{b} b\, \Delta x = \Delta x \tag{11}$$

appears at the output of the integrating amplifier (Fig. 3) and changes the value of ε through the function $\varepsilon(z)$.

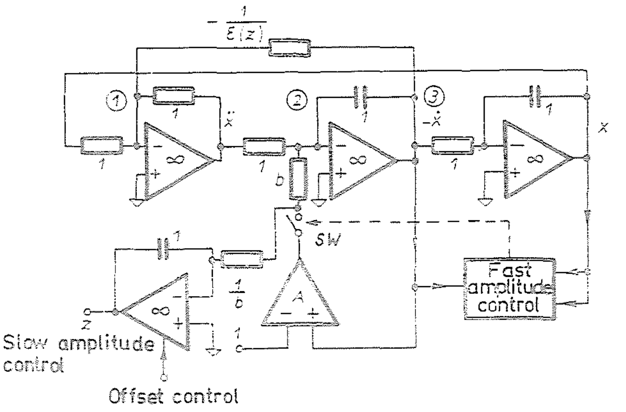

Fig. 3. State variable oscillator with fast and slow amplitude control

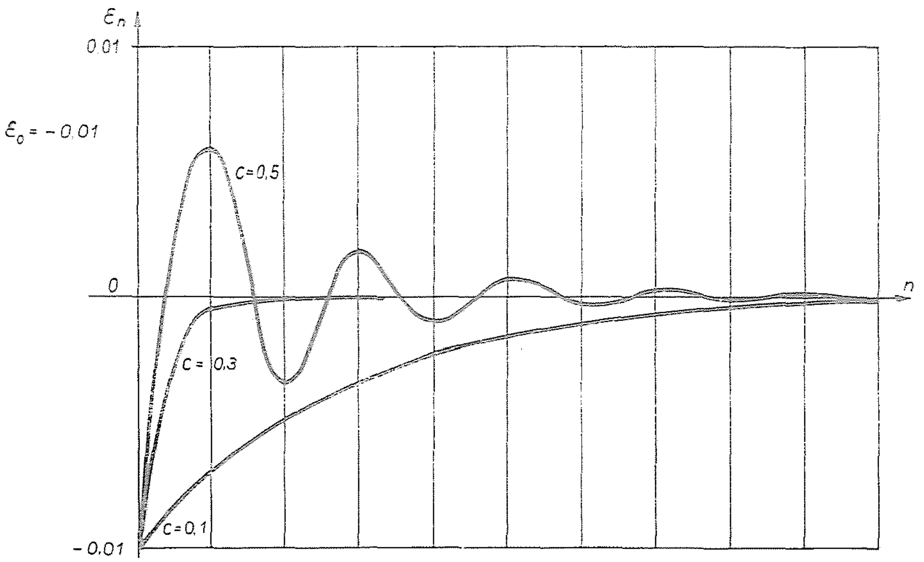

Fig. 4. Transients of the Q value

Q is changed according to the information gained at the end of the cycle; in the next cycle there'll be a new Q. z doesn't change between fast controls.

Operation of the system can be described by

$$x'_{n+1} = \exp\left(-\frac{\varepsilon_n}{2}\frac{2\pi}{\sqrt{1-\frac{\varepsilon_n^2}{4}}}\right) \tag{12}$$

and

$$\varepsilon_{n+1} = \varepsilon_n - C\Delta z_{n+1} = \varepsilon_n + C\,(x'_{n+1} - 1);$$
$$C > 0; \quad n = 0, 1, \ldots \tag{13}$$

where x'_n is the amplitude at the end of the cycle and C is the gain of the slow control circuit. $\varepsilon(z)$ was assumed to be linear in the interval where (13) is valid. ε_0 is given.

Fig. 4 shows the typical waveforms. It is obvious from the figure that $C \cong 0.3$ is the optimum if we want Q to be settled as fast as possible.

4. Experiences gained during the realization

The system in Fig. 3 has been actually realized. Fig. 5 shows one possible solution of the fast and slow amplitude control problem.

In Fig. 5a the fast control circuit is shown. Loop gain is set by the differential amplifier T_1, T_2. This differential amplifier also serves the purpose of comparing the reference to the attenuated and shifted value of $-\dot{x}$. It gives a signal at its symmetrical output (on resistor R_3) proportional to the difference. This signal charges or discharges the integrator. Diodes D_1 and D_2 help to shorten transient times. At the moment of fast control operation switching transistor T_3 is switched on.

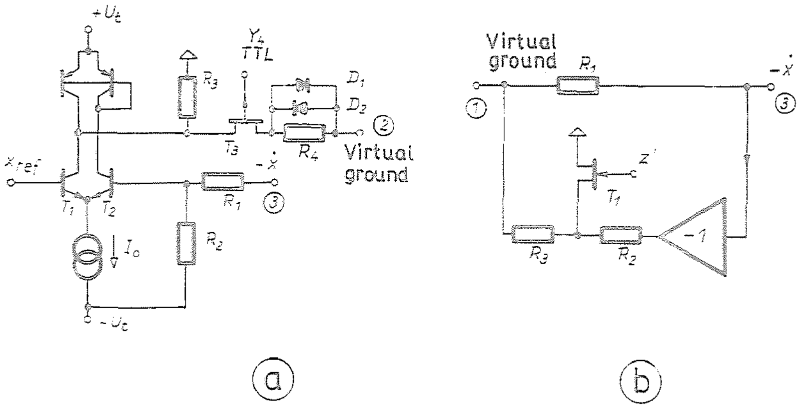

Fig. 5. Simplified schematic of the amplitude control circuitry

Fig. 5b shows the slow control circuit. By means of R_1, ε is set to a negative value to help the oscillation build up. In the end ε is adjusted to zero with the aid of the inverting amplifier, the attenuator formed by R_2, R_3 and T_1, functioning as a controlled resistor.

Fine adjustment of the distortion can be done with the offset potentiometer shown in Fig. 3. The following list of measured values illustrate the range of realizable distortions.

Frequency of oscillation	2. harm. μV	3. harm. μV	4. harm. μV	Dist. factor
29.7 Hz	<10	<10	6	$<1.17 \cdot 10^{-5}$
100 Hz	10	7	7	$1.07 \cdot 10^{-5}$
270 Hz	12	7	7	$1.18 \cdot 10^{-5}$
937 Hz	16	7	6	$1.4 \cdot 10^{-5}$
2.8 kHz	24	6	–	$1.88 \cdot 10^{-5}$
9.7 kHz	17	10	10	$1.68 \cdot 10^{-5}$
17.8 kHz	24	16	10	$2.33 \cdot 10^{-5}$

$$U_{out} = 1.31\ V_{rms}$$

The realized system is operating in the whole audio range and can be programmed in frequency.

References

A novel concept is presented for the generation of a sinewave with ultra low distortion in the 1 Hz – 100 kHz band. A short summary of the presently known methods is followed by some calculations using a simple model of the system that yield the theoretical limitations inherent in the concept. The realized circuit and the results of measurements are presented as well.

Summary

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