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Simulated-Inductance High-Stability Sine Oscillator

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Abstract – The theory of a new sine LC oscillator with simulated inductance using two operational amplifiers is developed. The resulting parallel resonant LC circuit may provide a high quality factor which assures very good frequency stability and very small harmonic distortions. The circuit oscillation condition is derived, the quality-factor equation and the voltage phase diagrams are established, then the performances are presented .

Key words: simulated inductance, sine oscillator, RC oscillator, high frequency stability.

1. INTRODUCTION

A double-simulation sine oscillator based on a resonant parallel circuit $L_{eq} \| C_{eq}$ is known, whose components are simulated by the help of OA's [1]. This oscillator has been named "the electronic quartz" because of their very high quality factor and frequency stability. Using a similar principle, we proposed a new $L_{eq}C$ oscillator whose only inductance is simulated by the help of two OA's [2], [3], [4].

2. OSCILLATOR PRINCIPLE

The circuit in Fig.1, without the D_1 and D_2 diodes, fed by v_i voltage from a generator with medium-value output resistance (less than 1 MΩ) is a band-pass Antoniou-type filter [2].

The circuit attached to C_1 capacitor, including the A_1 and A_2 operational amplifiers and the C_2, R_1, R_2, R_3, R_4 passive components represents a simulated small-loss inductance [2]:

$$L_{eq} = C_2 \frac{R_1 R_3 R_4}{R_2}$$

Thus, the C_1 capacitor and the L_{eq} inductance achieve a resonant parallel circuit with a high quality factor which is deteriorated by the generator output resistance. When the generator is eliminated and low resistances are used, the circuit in Fig.1 becomes a sine oscillator having the output-voltage amplitude limited by the amplifier supply sources.

To obtain small output-voltage amplitude it is necessary to use a limiting device such as a simple diode, two counter-parallel diodes, a serial group involving a Zener diode and a simple diode or two back to back Zener diodes.

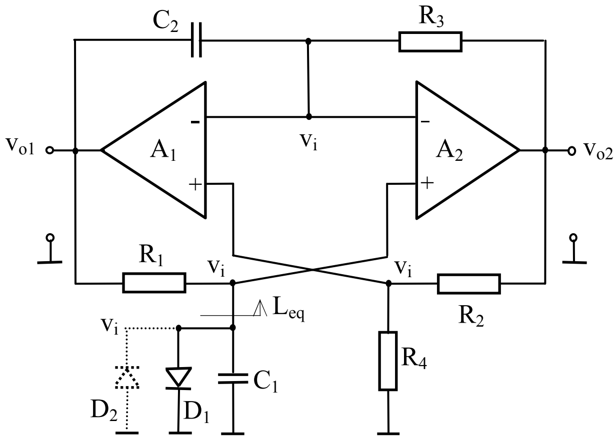

Fig.1. Oscillator scheme

The limiting device does not actually deteriorate the quality factor of the oscillating parallel C_1-L_{eq} circuit because of the very slight diode opening, whose dynamic equivalent resistance is moreover amplified by the quality factor [1].

This new-type oscillator [3, 4] is of the same category as the presented in the work [1] one, which may be obtained by a similar procedure from another Antoniou-type band-pass filter [2].

We have established both the circuits pass from the filter function to oscillator function when the quality factor exceeds a certain minimum value. When eliminates the generator and its output resistance the oscillating parallel C_1-L_{eq} circuit may attain a very high quality factor.

In order to derive the circuit oscillation condition one uses the open-loop technique. Thus, removing the limiting diodes and supposing ideal OA's and capacitors, the circuit open loop becomes as in Fig.2.

For the A_1 amplifier output one may write the voltage equation:

$$v_{o1} = v_i \frac{R_4}{R_2 + R_4}\left(1 + \frac{Z_2}{R_3}\right) - v_{o2}\frac{Z_2}{R_3} \qquad (1)$$

Likewise, for the A_2 amplifier output one may write:

$$v_{o2} = v_{o1} \frac{Z_1}{R_1 + Z_1}\left(1 + \frac{R_3}{Z_2}\right) - v_{o1}\frac{R_3}{Z_2} \qquad (2)$$

Deriving v_{o1} from equation (2) and replacing him in the equation (1) one obtains:

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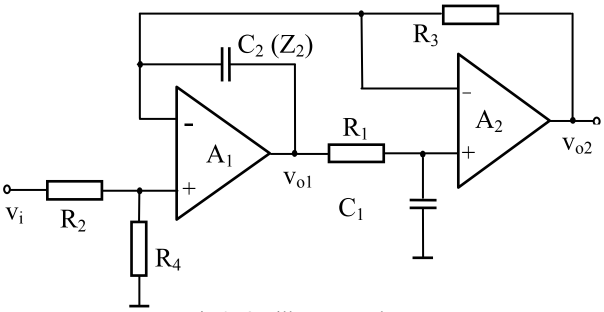


Fig.2. Oscillator open loop

$$v_i \frac{R_4}{R_2+R_4}\left(1+\frac{Z_2}{R_3}\right)=v_{o2}\left[\frac{1}{\frac{Z_1}{R_1+Z_1}\left(1+\frac{R_3}{Z_2}\right)-\frac{R_3}{Z_2}}+\frac{Z_2}{R_3}\right] \quad (3)$$

Here, to carry out the oscillation condition, must be taken the equality $v_i = v_{o2}$. So, after some simple calculus one finds the characteristic equation:

$$Z_1Z_2+\frac{R_1R_3R_4}{R_2}=0 \quad (4)$$

Replacing here $Z_1=\frac{1}{j\omega C_1}$ and $Z_2=\frac{1}{j\omega C_2}$

the characteristic equation becomes:

$$(j\omega)^2C_1C_2+\frac{R_2}{R_1R_3R_4}=0 \quad \text{or}$$

$$\omega^2C_1C_2-\frac{R_2}{R_1R_3R_4}=0 \quad (5)$$

Heaving always in the left part of this equation a real expression, this mean the amplitude oscillation condition is invariably fulfil. Thus, the circuit in Fig.1 is an oscillator. From equation (5) the oscillation frequency may be written:

$$\omega=\sqrt{\frac{R_2}{C_1C_2R_1R_3R_4}} \quad \text{or}$$

$$f=\frac{1}{2\pi}\sqrt{\frac{R_2}{C_1C_2R_1R_3R_4}} \quad (6)$$

In the case of equalities C_1=C_2=C, R_1=R_3=R the frequency will be:

$$f_o=\frac{1}{2\pi RC}\sqrt{\frac{R_2}{R_4}} \quad (7)$$

Thus, one may observe the frequency-adjusting possibility by the help of a potentiometer replacing both the resistors R_2 and R_4 (Fig.6). For yet R_2=R_4 the frequency has the simplest expression:

$$f_o=\frac{1}{2\pi RC} \quad (8)$$

The circuit simulation established this oscillates also with both diode amplitude limiter and small-loss capacitors.

3. VOLTAGE PHASE DIAGRAMS

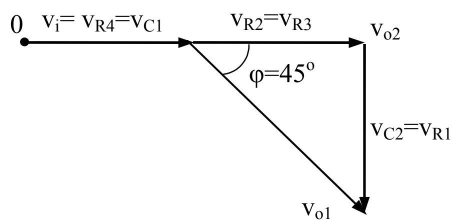
The output and input-voltage phase diagrams are provided in Fig.3 and Fig.4 for different situations. If the diodes are missing, from the R_1-C_1 divider in Fig.1 one may find the phase difference between voltages v_i and v_{o1}, for C_1=C_2 as:

$$tg\varphi=\sqrt{\frac{R_1R_2}{R_3R_4}} \quad (9)$$

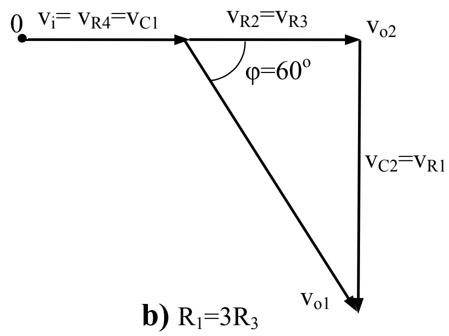
This may be modified through simultaneous adjustment of R_1 and R_2 resistors whose ratio must be kept invariable so that the frequency does not change. Unfortunately, as may see below, in this case the output-voltage amplitudes modify. It is yet possibly, if limiting diodes exist, to use v_i as oscillator constant output voltage (by the help of an AO repeater, Fig.5) instead of v_{o2}. Thus, the oscillator may be used as two voltage generator with adjustable phase displacement.

With relation (9), the output voltages v_{o1} and v_{o2} have the following amplitudes relative to v_i amplitude (v_{im}):

$$v_{o1m}=v_{im}\sqrt{1+\frac{R_1R_2}{R_3R_4}}\ ,\quad v_{o2m}=v_{im}\left(1+\frac{R_2}{R_4}\right) \quad (10)$$



a) R_1=R_3



b) R_1=3R_3

Fig.3. Voltage phase diagrams with C_1=C_2 and R_2=R_4.

For the case of equalities: R_1=R_3 and R_2=R_4 the diagram in Fig.3a is valid, φ=45° and the output-voltage amplitudes are: $v_{o1m}=\sqrt{2}v_{im}$ and $v_{o2m}=2v_{im}$. For R_1=3R_3 and R_2=R_4 the diagram in Fig.3b is valid, φ=60° and the output-voltage amplitudes are: $v_{o1m}=v_{o2m}=2v_{im}$. This last situation may be exploited to generate, with the help of another two OA's, a three-phase sine voltage [5]. If R_2≠R_4 (for example the case of frequency adjusting) the phase diagrams have the form of Fig.4.

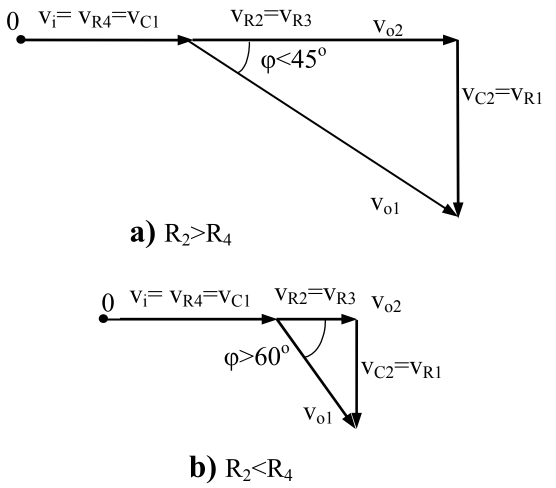


Fig.4. Voltage phase diagrams with $C_1=C_2$ and $R_2 \neq R_4$.

4. QUALITY FACTOR AND AMPLITUDE LIMITING

The calculus of the resonant circuit $L_{eq} \| C_1$ quality factor, including the regulating diode, OA input resistance and capacitor losses effects, for $C_1=C_2$ and $R_1=R_2=R_3=R_4=R$, gives the formula:

$$Q \cong \frac{r_{deq}}{R(2R + r_{deq})}(R_i \| 0.5R_{pC}) \qquad (11)$$

here: - r_{deq} is the diode equivalent dynamic resistance (established below),

- R_{pC} is the parallel loss resistance of each capacitor,
- R_i is the OA input resistance.

Usually heaving r_{deq}>>R the above formula may be simplified as:

$$Q \cong \frac{R_i \| 0.5R_{pC}}{R} \qquad (12)$$

Using low-value resistors R, low-loss capacitors and high-input resistance OA's a quality factor of 1000…2000 may be achieved at low frequency.

In fact, the simplest amplitude limitation may be obtained by means of one or two diodes (with counter-parallel connection) as shown in Fig.1. The symmetrical amplitude limitation using two devices assures better spectral purity. In accordance with [1] the diode (diodes) gives, in parallel with the resonant circuit L_{eq}-C_1, a dynamic equivalent resistance:

$$r_{deq} \approx kQr_{dp} \qquad (11)$$

where: - k is a coefficient depending upon the limiting diode type and number; for a single diode k=2.2 and for two counter-parallel diodes k=0.5 ; for a limiting branch with a Zener diode and an ordinary diode in series, back to back, k=1 and for two this last type counter-parallel branches k=0.25;

- Q is the quality factor of the resonant $C_1 \| L_{eq}$ circuit and it has a great value;

- r_{dp} is the dynamic "peak" resistance of a diode, defined as the v-i characteristic slope in the working point at v_i sine voltage amplitude [1].

One imposes a value of 1kΩ for the r_{dp} resistance if a single diode is being used, 2kΩ for two diodes and 3kΩ in the case of a Zener diode. This value assures a good compromise between the output voltage limitation efficiency and spectral purity respectively. Due to the Q quality-factor great value (as we seen it above) r_{deq} is great too, and the limiting diode slightly influences the output-voltage THD factor. A 0.01…0.02% THD value may be obtained [1]. Consequently, the output voltage form is extremely close to a sinusoidal one.

If we use a limiting branch with Zener and a simple diode in series, the v_{im} voltage amplitude is close to V_z voltage. So, we may obtain the wanted output voltage amplitude. It is also possible to use as a limiting device one or two (not lighting) LED's, when the v_i voltage amplitude is $v_{im} \approx 1.3$V. LED gives also the advantage of a better voltage thermal stability.

The most successful limiting solution is the use of one or two thermo-stabilized-transistor collector junctions from μA726 (Fairchild) integrated circuit. In this case the temperature influence on the output-voltage amplitude and frequency is minimized [1].

Fig.5 shows an oscillator with frequency adjusting by the help of the P potentiometer. This changes the R_2/R_4 ratio and, unfortunately, also changes the output voltage amplitudes apart from v_{im}, if limiting diodes exist. To use v_i as approximately-constant output voltage relative to the frequency the scheme needs an AO repeater.

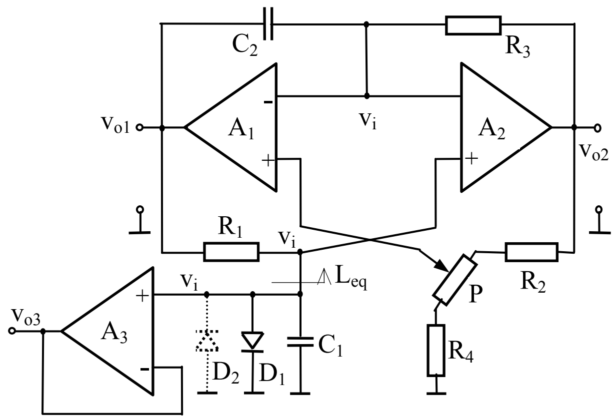


Fig.5. Adjusted-frequency oscillator

5. EXPERIMENT RESULTS

In Fig.6 a practical example of this type oscillator with simulated inductance is given, providing a sine signal of 2.34 KHz. The quality factor of the resonant circuit is Q=1580, obtained by using JFET-input OA's, low R resistances and low-loss capacitors. The oscillator has a frequency temporal instability of 2.10^{-6} and a THD of 0.02%.

To avoid the temperature effect it is necessary to use R-C reciprocally-thermal-compensated pairs and

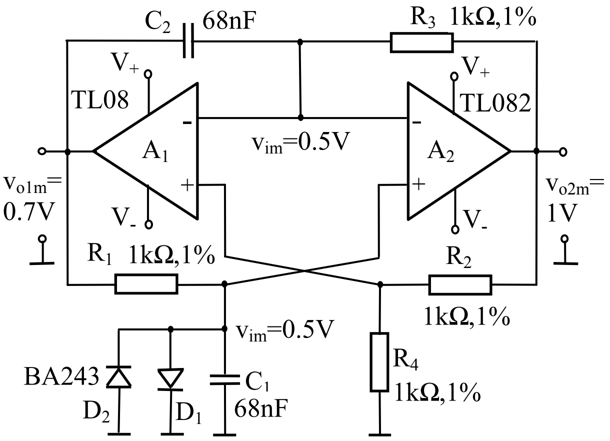


Fig.6. Experimented oscillator scheme.

collector junctions from μA726 IC with thermo-stabilized regime as limiting diodes [1]. Thus, it may obtain the relative frequency instability of $2.10^{-6}/^{o}C$ and relative voltage-amplitude instability of $2.10^{-4}/^{o}C$.

6. SIMULATION RESULTS

The simulations where developed with usual amplitude-limiting diodes (missing the μA726 IC model) and confirmed the oscillator theory and quality performances.

The time diagram of the input and output voltages is shown in Fig.7.

7. CONCLUSIONS

The theory of a new sine LC oscillator, with simulated inductance, using two operational amplifiers is developed. Using R-C components for inductance simulation, the oscillator becomes a RC one. The resulting parallel resonant L_{eq}-C circuit may provide a high quality factor (>1000), which assures very good frequency stability and very small harmonic distortions (THD of 0.02%).

In order to derive the circuit oscillation condition one used the open-loop technique. So, after calculus, one finds the characteristic equation and the frequency relation. One may observe the frequency-adjusting possibility by the help of a single potentiometer.

The phase-diagram of output voltages shows a phase displacement of 45^{o} or 60^{o}. This last situation may be exploited to generate, with the help of another two OA's, a three-phase sine voltage. The oscillator may be used as two-voltage generator with adjustable phase displacement.

Using R-C reciprocally-thermal-compensated pairs and collector-junctions from μA726 IC (with thermo-stabilized regime) as limiting diodes one may achieve a relative frequency instability of $2.10^{-6}/^{o}C$ and a relative voltage-amplitude instability of $2.10^{-4}/^{o}C$.

The simulations confirmed the oscillator theory and quality performances. This new circuit enriches the high-stability simulated-inductance oscillator family.

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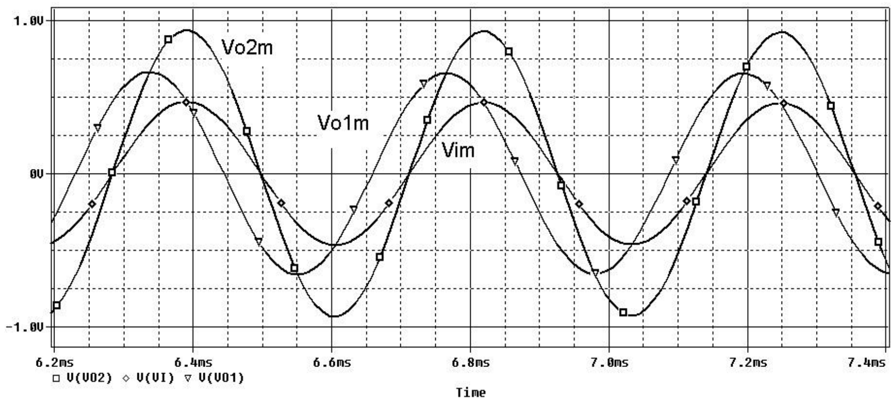

Fig.7. Time diagram of the input and output voltages