CHAPTER I

INTRODUCTION

The present dissertation work is based on some studies on OTA-C oscillators. In the present chapter after describing the general type of signal generating circuits (both harmonic as well as relaxation oscillators) a detailed review of harmonic oscillators realised with different types of active building blocks has been presented.

1.1 STATE OF ART IN OSCILLATORS

Oscillators are circuits that produce specific, periodic waveforms such as square, triangular, sawtooth, and sinusoidal. They generally use some form of active device, lamp, or crystal, surrounded by passive devices such as resistors, capacitors, and inductors, to generate the output.

There are two main classes of oscillator: relaxation and sinusoidal. Relaxation oscillators generate the triangular, sawtooth and other nonsinuoidal waveforms . Sinusoidal oscillators consist of amplifiers with external components used to generate oscillation, or crystals that internally generate the oscillation. The focus here is on sine wave oscillators, created using operational amplifiers op amps.

Sine wave oscillators are used as references or test waveforms by many circuits. A pure sine wave has only a single or fundamental frequency—ideally no harmonics are present. Thus, a sine wave may be the input to a device or circuit, with the output harmonics measured to determine the amount of distortion. The waveforms in relaxation oscillators are generated from sine waves that are summed to provide a specified shape.

Op-amp oscillators are circuits that are unstable—not the type that are sometimes unintentionally designed or created in the lab—but ones that are intentionally designed to remain in an unstable or oscillatory state. Oscillators are useful for generating uniform signals that are used as a reference in such applications as audio, function generators, digital systems, and communication systems.

Two general classes of oscillators exist: sinusoidal and relaxation. Sinusoidal oscillators consist of amplifiers with RC or LC circuits that have adjustable oscillation frequencies, or crystals that have a fixed oscillation frequency. Relaxation oscillators generate triangular, sawtooth, square, pulse, or exponential waveforms, and they are not discussed here.

Op-amp sine-wave oscillators operate without an externally-applied input signal. Instead, some combination of positive and negative feedback is used to drive the op amp into an unstable state, causing the output to cycle back and forth between the supply rails at a continuous rate. The frequency and amplitude of oscillation are set by the arrangement of passive and active components around a central op amp.

Op-amp oscillators are restricted to the lower end of the frequency spectrum because op amps do not have the required bandwidth to achieve low phase shift at high frequencies. Voltage-feedback op amps are limited to a low kHz range because their dominant, open-loop pole may be as low as 10 Hz. The new current-feedback op amps have a much wider bandwidth, but they are very hard to use in oscillator circuits because they are sensitive to feedback capacitance. Crystal oscillators are used in high-frequency applications up to the hundreds of MHz range.

1.1.1 Requirements for Oscillation

The canonical, or simplest, form of a negative feedback system is used to demonstrate the requirements for oscillation to occur. Figure 1 shows the block diagram for this system in which V_{IN} is the input voltage, V_{OUT} is the output voltage from the amplifier gain block (A), and β is the signal, called the feedback factor, that is fed back to the summing junction. E represents the error term that is equal to the summation of the feedback factor and the input voltage.

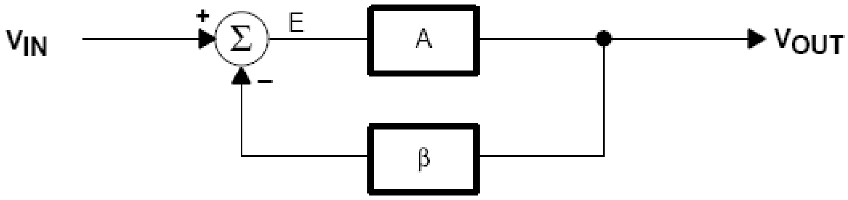

Figure 1.1 Canonical Form of a Feedback System With Positive or Negative Feedback

The corresponding classic expression for a feedback system is derived as follows. Equation 1.2.1 is the defining equation for the output voltage; equation 1.2.2 is the corresponding error:

$$V_{OUT} = E \times A \tag{1.2.1}$$

$$E = V_{IN} + \beta V_{OUT} \tag{1.2.2}$$

Eliminating the error term, E, from these equations gives

$$\frac{V_{OUT}}{A} = V_{IN} - \beta V_{OUT} \tag{1.2.3}$$

and collecting the terms in V_{OUT} yields

$$V_{IN} = V_{OUT}\left(\frac{1}{A} + \beta\right) \tag{1.2.4}$$

Rearrangement of the terms produces equation 5, the classical form of feedback expression:

$$\frac{V_{OUT}}{V_{IN}} = \frac{A}{1+A\beta} \tag{1.2.5}$$

Oscillators do not require an externally-applied input signal; instead, they use some fraction of the output signal created by the feedback network as the input signal.

Oscillation results when the feedback system is not able to find a stable steady-state because its transfer function can not be satisfied. The system goes unstable when the denominator in equation 1.2.5 becomes zero, i.e., when $1 + A\beta = 0$, or $A\beta = -1$. The key to designing an oscillator is ensuring that $A\beta = -1$. This is called the *Barkhausen criterion*. Satisfying this criterion requires that the magnitude of the loop gain is unity with a corresponding phase shift of 180° as indicated by the minus sign. An equivalent expression using the symbology of complex algebra is $A\,\beta = 1\angle{-180°}$ for a negative feedback system. For a positive feedback system, the expression is $A\beta = 1\angle 0°$ and the sign of the $A\beta$ term is negative in equation 1.2.5.

As the phase shift approaches 180° and $|A\beta| \to 1$, the output voltage of the now-unstable system tends to infinity but, of course, is limited to finite values by an energy-limited power supply. When the output voltage approaches either power rail, the active devices in the amplifiers change gain. This causes the value of A to change and forces $A\beta$ away from the singularity; thus the trajectory towards an infinite voltage slows and eventually halts. At this stage, one of three things can occur: (i) Nonlinearity in saturation or cutoff causes the system to become stable and lock up at the current power rail. (ii) The initial change causes the system to saturate (or cutoff) and stay that way for a long time before it becomes linear and heads for the opposite power rail. (iii) The system stays linear and reverses direction, heading for the opposite power rail. The second alternative produces highly distorted oscillations (usually quasi-square waves), the resulting oscillators being called relaxation oscillators. The third produces a sine-wave oscillator.

1.1.2 Phase Shift in the Oscillator

The 180° phase shift in the equation $A\beta = 1\angle{-180°}$ is introduced by active and passive components. Like any well-designed feedback circuit, oscillators are made dependent on passive-component phase shift because it is accurate and almost drift-free. The phase shift contributed by active components is minimized because it varies with temperature, has a wide initial tolerance, and is device dependent. Amplifiers are selected so that they contribute little or no phase shift at the oscillation frequency. These constraints limit the op-amp oscillator to relatively low frequencies.

A single-pole RL or RC circuit contributes up to 90° phase shift per pole, and because 180_ of phase shift is required for oscillation, at least two poles must be used in the oscillator design. An LC circuit has two poles, thus it contributes up to 180° phase shift per pole pair. But LC and LR oscillators are not considered here because low frequency inductors are expensive, heavy, bulky, and highly nonideal. LC oscillators are designed in high frequency applications, beyond the frequency range of voltage feedback op amps, where the inductor size, weight, and cost are less significant. Multiple RC sections are used in low frequency oscillator design in lieu of inductors.

1.1.3 Gain in the Oscillator

The oscillator gain must be unity ($A\beta = 1\angle{-180°}$) at the oscillation frequency. Under normal conditions, the circuit becomes stable when the gain exceeds unity, and oscillations cease. However, when the gain exceeds unity with a phase shift of –180°, the nonlinearity of the active device reduces the gain to unity and the circuit oscillates. The nonlinearity becomes significant when the amplifier swings close to either power rail because cutoff or saturation reduces the active device (transistor) gain. The paradox is that worst-case design practice requires nominal gains exceeding unity for manufacturability, but excess gain causes increased distortion of the output sine wave.

When the gain is too low, oscillations cease under worst case conditions, and when the gain is too high, the output wave form looks more like a square wave than a sine wave. Distortion is a direct result of excessive gain overdriving the amplifier; thus, gain must be carefully controlled in low-distortion oscillators. Phase-shift oscillators have distortion, but they achieve low-distortion output voltages because cascaded RC sections act as distortion filters. Also, buffered phase-shift oscillators have low distortion because the gain is controlled and distributed among the buffers.

Most circuit configurations require an auxiliary circuit for gain adjustment when low-distortion outputs are desired. Auxiliary circuits range from inserting a nonlinear component in the feedback loop, to automatic gain control (AGC) loops, to limiting by external components such as resistors and diodes. Consideration must also be given to the change in gain resulting from temperature variations and component tolerances, and the level of circuit complexity is determined based on the required stability of the gain. The more stable the gain, the better the purity of the sine wave output.

1.2 OSCILLATORS

There are two types of oscillators.

- Relaxation oscillators
- Harmonic oscillators (Sine Wave Oscillator Circuits)

1.2.1 Relaxation oscillators

Relaxation oscillators are those which generates other types of wave form such as square or saw-tooth. We shall study another type of waveform generators which, generate non-sinusoidal waveform. One such class of electronic circuit is known as multivibrator. A multivibrator is essentially a switching circuit.

1.2.1.1 Types of multivibrators

The multivibrators are of three types, namely.

(i) Bistable multivibrators

(ii) Monostable multivibrators

(ii) Astable multivibrators

(i) Bistable multivibrators

As the name indicates, the bistable multivibrators have two stable state. This circuit can remain in either stable state indefinitely and moves to the other stable state only when appropriately Triggered. It has two stable state, it may remain permanently in either of two states. Bistable multivibrator is known by following names also Eccles Jorden circuit, flip-flop and binary.

It has following applications:

(a) It is used for performance of digital operation such as storing of binary bits of information.

(b) For counting purpose.

(c) Generation of pulse waveform of square waveform.

(d) Processing of pulse waveform.

(e) For frequency division.

Bistable multivibrators may be of two types depending on the biasing applied for transistors. If the transistors are biased in fixed bias configuration then it is called fixed-bias bistable multivibrators while if, transistors are biased in self-bias configuration multivibrator circuit is called self-bias bistable multivibrators.

(ii) Monostable multivibrators

The monostable multivibrators has one stable state and one quasi-stable (temporary) state. When its output is in quasi-stable state it changes its state automatically, while when it is in stable state, it can be changed only by triggering externally. Since, this multivibrator has only one stable state it is called monostable multivibrators.

A triggering signal is required to have a transistor from stable state to quasi-stable state where it can remain for a time period determine by the circuit components. After that time it automatically comes back to initial stable state. Let T be the time required for circuit to retun back to stable state from quasi-stable state.

Monostable multivibrator is known by the following names also single shot multivibrator, delay circuit and gating circuit.

Applications:

(a) As a delay circuit: As there is a transition from quasi-stable state to stable state after predetermined time T.

(b) This multivibrator is also employed for generating clean and sharp pulses from the distorted, old pulses, worn-out during use in communication system.

(iii) Astable Multivibrator

The astable Multivibrator has no stable state. It is also called as free running multivibrator. It has two quasi-stable or temporarily stable states. Multivibrator switches back and forth from one state to the another after a predetermined length of time and no triggering pulse is needed for change over. This length of time is determine by the circuit constant.

1.2.2 Harmonic oscillators (Sine Wave Oscillator Circuits)

There are many types of sine wave oscillator circuits and variants—in an application, the choice depends on the frequency and the desired monotonicity of the output waveform. The focus of this section is on the more prominent oscillator circuits: Wien bridge, phase shift, and quadrature. The transfer function is derived for each case using the techniques described in section 6 of this note and in references 4, 5, and 6.

1.2.2.1 Wein Bridge Oscillator

The Wien bridge is one of the simplest and best known oscillators and is used extensively in circuits for audio applications. Figure 7 shows the basic Wien bridge circuit configuration. On the positive side, this circuit has only a few components and good frequency stability. The major drawback of the circuit is that the output amplitude is at the rails, which saturates the op-amp output transistors and causes high output distortion. Taming this distortion is more challenging than getting the circuit to oscillate. There are a couple of ways to minimize this effect. These will be covered later; first the circuit is analyzed to obtain the transfer function.

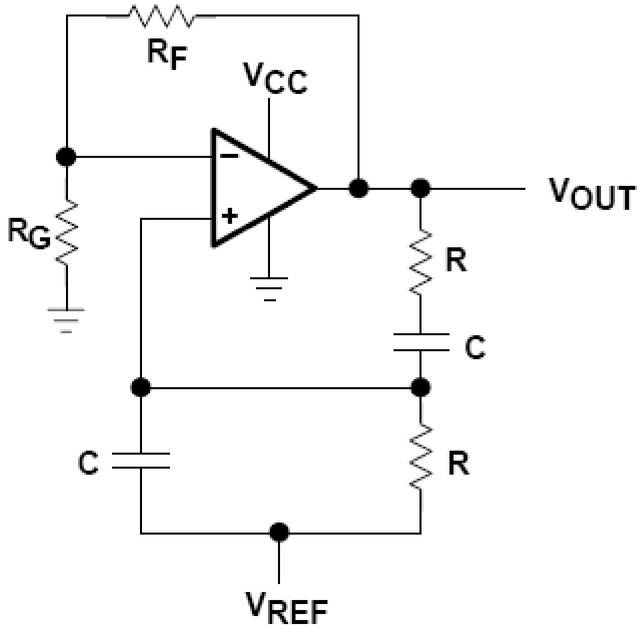

Figure 1.2 Wein-Bridge Circuit Schematic

The Wien bridge circuit has the form already detailed in section 6, and the transfer function for the circuit is derived using the technique described there. It is readily apparent that $Z_1 = R_G$, $Z_2 = R_F$, $Z_3 = (R_1 + 1/sC_1)$ and $Z_4 = (R_2 \parallel 1/sC_2)$. The loop is broken between the output and Z_1, V_{TEST} is applied to Z_2, and V_{OUT} is calculated. The positive feedback voltage, V_+, is calculated first in equations 10 through 12. Equation 10 shows the simple voltage divider at the noninverting input. Each term is then multiplied by $(R_2C_2s + 1)$ and divided by R_2 to get equation 11.

$$V_+ = V_{TEST}\left(\frac{Z_2}{Z_3+Z_4}\right) = V_{TEST}\left[\frac{\left(\frac{R_2}{R_2C_2s+1}\right)}{\left(\frac{R_2}{R_2C_2s+1}\right)+\left(R_1+\frac{1}{C_1s}\right)}\right] \tag{10}$$

$$\frac{V_+}{V_{TEST}} = \frac{1}{1+R_1C_2s+\frac{R_1}{R_2}+\frac{1}{R_2C_1s}+\frac{C_2}{C_1}} \tag{11}$$

Substituting $s = j\omega_o$, where ω_o is the oscillation frequency, $\omega_1 = 1/R_1C_2$, and $\omega_2 = 1/R_2C_1$, gives equation 12.

$$\frac{V_+}{V_{TEST}} = \frac{1}{1+\frac{R_1}{R_2}+\frac{C_2}{C_1}+j\left(\frac{\omega_o}{\omega_1}-\frac{\omega_2}{\omega_o}\right)} \tag{12}$$

Some interesting relationships now become apparent. The capacitor at the zero, represented by ω_1, and the capacitor at the pole, represented by ω_2, must each contribute 90° of phase shift toward the 180° required for oscillation at ω0. This requires that C_1 = C_2 and R_1 = R_2. Setting ω_1 and ω_2 equal to ω0 cancels the frequency terms, ideally removing any change in amplitude with frequency because the pole and zero negate one another. This results in an overall feedback factor of β = 1/3 (equation 14).

$$\frac{V_+}{V_{TEST}} = \frac{1}{1+\frac{R}{R}+\frac{C}{C}+j\left(\frac{\omega_o}{\omega}-\frac{\omega}{\omega_o}\right)} = \frac{1}{3+j\left(\frac{\omega_o}{\omega_o}-\frac{\omega_o}{\omega_o}\right)} \tag{13}$$

$$\frac{V_+}{V_{TEST}} = \frac{1}{3} \tag{14}$$

The gain, A, of the negative feedback portion of the circuit must then be set such that |Aβ| = 1, requiring A = 3. R_F must be set to twice the value of R_G to satisfy this condition. The op amp in Figure 7 is single supply, so a dc reference voltage, V_{REF}, must be applied to bias the output for full-scale swing and minimal distortion. Applying V_{REF} to the positive input through R_2 restricts dc current flow to the negative feedback leg of the circuit. V_{REF} was set at 0.833V to bias the output at the midrail of the single supply, rail-to-rail input and output amplifier, or 2.5 V. (see reference [7]. V_{REF} is shorted to ground for split supply applications.

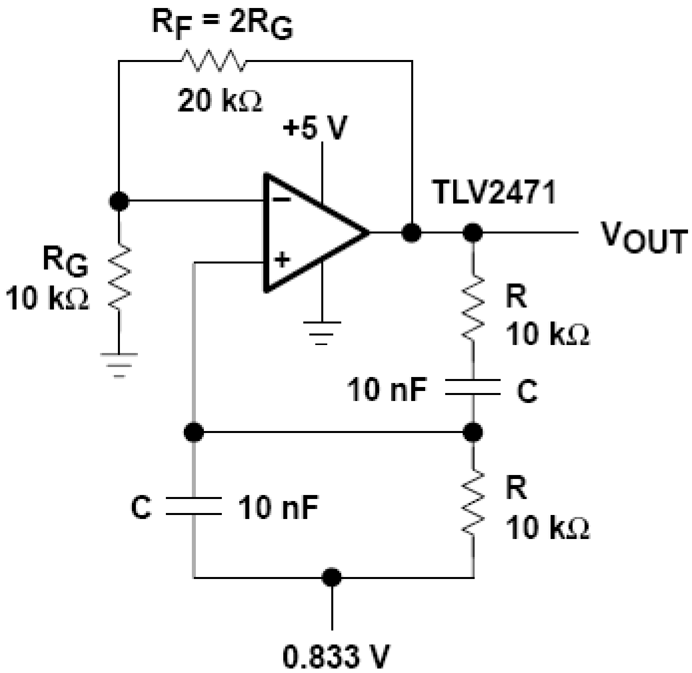

Figure 1.3 Final Wein-Bridge Oscillator Circuit

The final circuit is shown in Figure 8, with component values selected to provide an oscillation frequency of $\omega_o = 2\pi f_o$, where f_o = 1/(2πRC) = 1.59 kHz. The circuit oscillated at 1.57 kHz, caused by varying component values with 2.8% distortion. This high value results from the extensive clipping of the output signal at both supply rails, producing several large odd and even harmonics. The feedback resistor was then adjusted ±1%. Figure 9 shows the output voltage waveforms. The distortion grew as the saturation increased with increasing R_F, and oscillations ceased when R_F was decreased by a mere 0.8%.

1.2.2.2 Phase-Shift Oscillator, Single Amplifier

Phase-shift oscillators have less distortion than the Wien bridge oscillator, coupled with good frequency stability. A phase-shift oscillator can be built with one op amp as shown in Figure 14. Three RC sections are cascaded to get the steep slope, dφ/dω, required for a stable oscillation frequency, as described in section 3. Fewer RC sections results in high oscillation frequency and interference with the op-amp BW limitations.

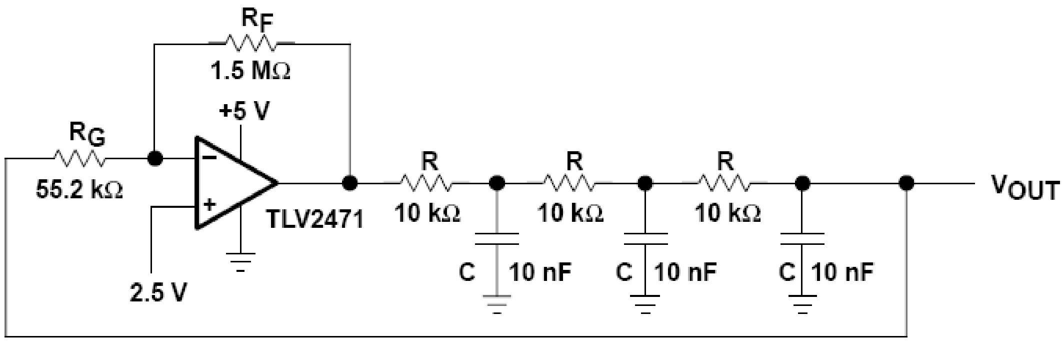

Figure 1.4 Phase-Shift Oscillator (Single Op Amp)

The usual assumption is that the phase shift sections are independent of each other, allowing equation 14 to be written. The loop phase shift is –180° when the phase shift of each section is –60°. This occurs when $\omega = 2\pi f = 1.732/RC$ (tan 60° = 1.732…). The magnitude of β at this point is $(1/2)^3$, so the gain, A, must be 8 for the system gain of unity.

$$A\beta = A\left(\frac{1}{RCs+1}\right)^3 \tag{15}$$

The oscillation frequency with the component values shown in Figure 14 is 3.76 kHz rather than the calculated oscillation frequency of 2.76 kHz. Also, the gain required to start oscillation is 27 rather than the calculated gain of 8. These discrepancies are partially due to component variations, however, the biggest factor is the incorrect assumption that the RC sections do not load each other. This circuit configuration was very popular when active components were large and expensive. But now op amps are inexpensive, small, and come four-to-a-package, so the single-op-amp phase-shift oscillator is losing popularity. The output distortion is a low 0.46%, considerably less than the Wien bridge circuit without amplitude stabilization.

1.2.2.3 Quadrature Oscillator

The quadrature oscillator shown in Figure 20 is another type of phase-shift oscillator, but the three RC sections are configured so each section contributes 90° of phase shift. This provides both sine and cosine waveform outputs (the outputs are *quadrature*, or 90° apart), which is a distinct advantage over other phase-shift oscillators. The idea of the quadrature oscillator is to use the fact that the double integral of a sine wave is a negative sine wave of the same frequency and phase, in other words, the original sine wave 180° phase shifted. The phase of the second integrator is then inverted and applied as positive feedback to induce oscillation.

The loop gain is calculated from equation 18. When $R_1C_1 = R_2C_2 = R_3C_3$, equation 18 reduces to equation 19. When ω = 1/RC, equation 18 reduces to 1∠–180, so oscillation occurs at ω = 2πf = 1/RC. The test circuit oscillated at 1.65 kHz rather than the calculated 1.59 kHz, as shown in Figure 21. This discrepancy is attributed to component variations. Both outputs have relatively high distortion that can be reduced with a gain-stabilizing circuit. The sine output had 0.846% distortion and the cosine output had 0.46% distortion. Adjusting the gain can increase the amplitudes. The penalty is reduced bandwidth.

$$A\beta = A\left(\frac{1}{R_1C_1s}\right)\left\{\frac{R_3C_3s+1}{R_3C_3s(R_2C_2s+1)}\right\} \tag{16}$$

$$A\beta = A\left(\frac{1}{RCs}\right)^2 \tag{17}$$

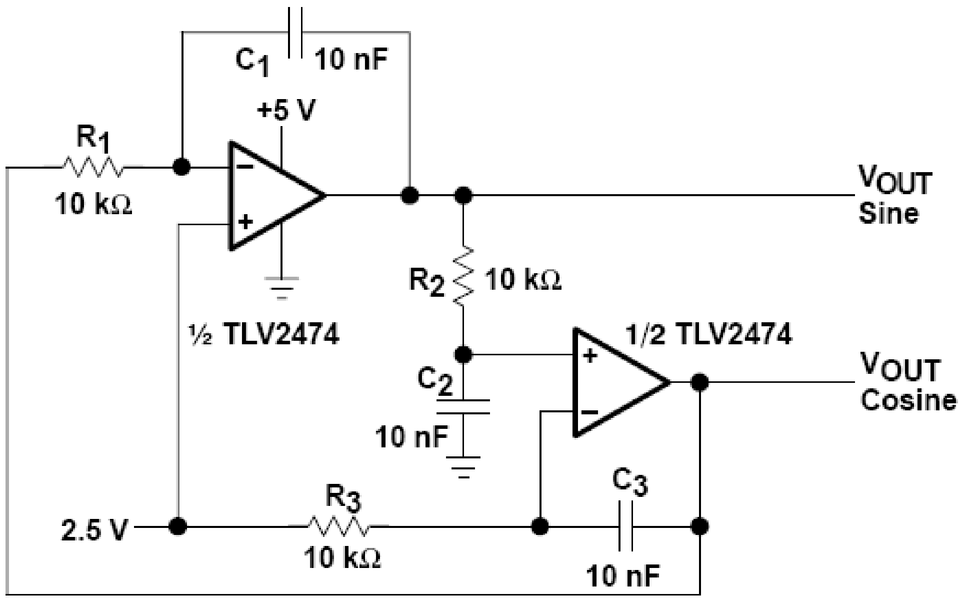

Figure 1.5 Quadrature Oscillator

1.3 LITERATURE SURVEY OF DIFFERENT TYPES OF HARMONIC OSCILLATORS

Sinusoidal oscillators are important building blocks of many instrumentation, communication, measurement and control systems. The realisation of sinusoidal oscillators has attracted the attention of researchers in the area of analog signal processing since long. Their use has been very well documented in many standard texts in these areas. IC Op-Amps were the main building blocks for the realisation of sinusoidal oscillators during the decades of seventies and eighties. A variety of aspects related to the analysis, synthesis and design of Op-Amp-based sinusoidal oscillators has been investigated in numerous publications spread over this period. The classical wein bridge, RC- phase shift and twin-T oscillators had a difficulty of tuning the condition and frequency of oscillation through a single variable element. Shiva Prasad [1] and Dutta Roy [2] presented novel modifications of the classical wein bridge oscillator resulting in single resistance control of frequency of oscillation. Hrisbek and Newcomb [3] proposed a two Operational Amplifier-based sinusoidal oscillator whose oscillation frequency could be controlled by a single resistance. With a FET replacing the frequency controlling resistance (in variable voltage controlled-resistance mode), many voltage controlled oscillators (VCO) were reported. The real work on the realisation of single element controlled sinusoidal oscillators can be said to have taken off after the publication of Hrisbek and Newcomb's VCO [3]. In 1978, Soliman and Awad [4] proposed a single Op-Amp-based single capacitor controlled sinusoidal oscillator. In 1979 Senani, for the first time, proposed a canonic, Single Resistance Controlled Oscillator (SRCO) [5] in which the frequency of oscillation was controlled by a single grounded resistance. A network synthetic approach for designing single element controlled oscillator was first proposed by Dutta Roy [6]. Many single element controlled oscillators using one or more Op-Amps were discovered since then, for instance see [7]-[13] and the references cited therein. Use of active compensation techniques or composite amplifiers to improve the performance of sinusoidal oscillators have been investigated by a number of researchers [14]-[17]. Active-R oscillators (in which the Op-Amp pole has been used as a design parameter) have been proposed in [18]-[27]. Active-C oscillators, which can be implemented in CMOS, employing the Op-Amp pole and capacitor ratios, have been proposed in [28]-[30]. Multiphase sinusoidal oscillators have been reported in [31] - [32]. Design of VCO using Op-Amp has been reported in [33].

Several schemes for the amplitude control of Op-Amp oscillators have also been reported (for instance, see [34]-[37] and the references cited therein).

Current Conveyor (CCI), an innovative active building block (ABB), was proposed by Smith and Sedra [38] in 1968. Sedra and Smith shortly afterwards, proposed the ‘so called’ second version of the Current Conveyor more popularly known as CCII [39]. These building blocks have been employed by many researchers to design sinusoidal oscillators with different properties [40] - [70]. An excellent summary of all the work done on realisation of sinusoidal oscillators using Current Conveyors has been given in [71]. This survey contains the details of the work done till 1990.

With different modifications in the basic conveyor structure, elements like Differential Voltage Complementary Current Conveyor (DVCCC) [72], Differential Difference Current Conveyor (DDCC) [73], Inverting Current Conveyor (ICC) [74], fully differential second generation Current Conveyor (FDCCII) [75] have been used by several researchers for realisation of sinusoidal oscillators.

Transconductance-Capacitor networks have been used for designing fully-integrated filters in both CMOS and bipolar technologies. The use of Operational Transconductance Amplifiers (OTA) and capacitors (without resistors) became popular during late eighties and mid-nineties for the design of the so-called OTA-C oscillators. The research in this area was motivated by the fact that the frequency of oscillation could be tuned electronically by changing the bias current of one or more OTA and the circuits were suitable for IC implementation in both bipolar and CMOS technology due to using only transistors and capacitors and almost complete elimination of resistors. A comprehensive catalogue of all possible OTA-C sinusoidal oscillators was reported by Senani, Tripathi, Bhaskar and Banarjee in [76], [77]-[79], which also cites most of the other important works done in this area.

Since Current Conveyors were not available as an off-the –shelf components, many of the Current Conveyor based oscillators proposed in [40] - [70] could not be implemented practically. PA630_from Photonics Canada was the first IC, which contained a Current Conveyor. PA630 along with AD844 from Analog Devices, have generally been used to practically implement Current Conveyor-based oscillators.

The operational transimpedance amplifier AD844, more popularly known as Current Feedback Operational Amplifier (CFOA), was developed by Analog Devices as a high speed Op-Amp which did not suffer from slew rate limitations and gain bandwidth (GB) conflict for medium and low frequency applications. The CFOA consists of a CCII+ in cascade with a buffer. Though the CFOA was intended to be a substitute for the traditional VOA, it is actually a four-terminal device whereas the traditional VOA is a three-terminal device. Senani [80] emphasized this point categorically and proposed a number of circuits in which CFOA has been used as a four-terminal active building block for the realisation of various functions. CFOA has been employed for realisation of sinusoidal oscillators by many researchers. Celma, Martinez and Carlosena [81] proposed the CFOA version of the Wein bridge oscillator (WBO). It was shown that the CFOA-based WBO was superior in terms of harmonic distortion, dynamic range, frequency accuracy etc. Motivated by these advantages, the investigations on single element controlled oscillators using CFOA soon gained momentum. In the same year Liu, Shih and Wu [82] presented two canonic realisations (three resistors and two capacitors (3R-2C)) in which one of the capacitors was floating and one non-canonic realisation (4R-3C) in which all the capacitors were grounded. Senani and V. K. Singh [83] presented an approach for the synthesis of canonic SRCOs using a single CFOA. [84] - [87] give a good account of the work done on single CFOA-based single element controlled oscillators.

Several other active building blocks viz. Current/Voltage Followers [88]-[92], Current Differencing Buffered Amplifiers (CDBA) [93] and Operational Transresistance Amplifiers (OTRA) [94] have also been used for the design of SRCOs.

Owing to its flexibility and versatility compared to Operational Amplifiers, Current Conveyors and CFOAs, FTFN has also been used for the realisation of sinusoidal oscillators. Liu and Liao [95] reported a current-mode quadrature sinusoidal oscillator using a single FTFN in 1996. The structure employed a single FTFN (sometimes referred as NFTFN), two capacitors (both grounded) and five resistors. The condition of oscillation (CO) and frequency of oscillation (FO) could be controlled by varying separate resistors.

In the same year Hou, Yean and Chang [96] published a catalog of six single FTFN-based oscillators which employed 3/4 capacitors and 3/4 resistors. Four of these circuits enjoyed independent control of condition of oscillation through a resistor and for the other two circuits the frequency of oscillation could be varied by varying a separate resistor.

Liu used two FTFNs (one PFTFN and one NFTFN) [97] to propose a SRCO/VFO which employed three capacitors (all grounded) and two resistors. The circuit has very good frequency stability properties and the frequency of oscillation and condition of oscillation can be set independently.

Abuelma'atti and Al-Zaher [98] used the transformation proposed by Senani in his classical work on equivalent form of single Op-Amp-based sinusoidal oscillators [12] on two Op-Amp-based sinusoidal oscillators, to propose 14 two FTFN-based sinusoidal oscillators. All the oscillators had the same characteristic equations, employed two capacitors, and six resistors.

Abuelma'atti and Al-Zaher [99] reported a generalised structure of single FTFN-based curren-mode oscillator. From this generalised structure they derived fully decoupled VFOs and single frequency oscillators (SFOs) employing 6-8 passive elements which include 2-3 capacitors. It is interesting to note that in all these oscillators one terminal of the FTFN has not been used for any connection thus making the FTFNs equivalent to Op-Amps with an additional current output. Thus, the oscillators proposed therein are truly speaking not new, but a mere repetition of the structures already proposed in [7], [12].

Bhaskar [100] proposed a single FTFN-based VFO realized with an AD844, which employed two grounded capacitors, three resistors and the on-chip buffer available in AD844. This circuit has non-interacting control of CO and FO and had very good frequency stability properties.

Cam, Toker, Cicecoglu and Kuntman [101] proposed a generalised single FTFN-based structure which employed seven admittances. From the generalised CE of the proposed structure they derived eight (2C-5R)-based SRCOs and eight (2C-4R) based single frequency oscillators. The general structure reported by them like the general structure reported in [99] did not use the FTFNs fourth terminal in the circuit and thus, is equivalent to a single Op-Amp based generalised structure proposed in [7], [12].

A minimal realisation of FTFN+ (same as PFTFN)-based SRCO was proposed by Lee and Wang [102], which uses one grounded capacitor, one floating capacitor and three resistors. The CO and FO of the circuit can be varied independently.

A grounded capacitor SRCO using only one PFTFN has been proposed by Bhaskar [103], which uses two grounded capacitors and four resistors. The circuit does not offer independent control of CO although FO is controllable through a single resistance.

Bhaskar and Senani [104] have proposed a two FTFN-based SRCO in which both the capacitors employed are grounded. This oscillator has the provision of explicit current output.

1.4 ORGANIZATION OF THE DISSERTATION

In the second chapter, operational transconductance amplifier (OTA) as a signal processing element has been reviewed in detail. Various signal processing circuits viz, amplifiers, impedance converters, active filters have also been reviewed.

In the third chapter a detailed review of some of the important works carried out on OTA-C oscillators has been presented. Some experimental results have also been given.

In the fourth chapter after reviewing the method proposed by R. Senani, D. R. Bhaskar and M. P. Tripathi, the approach has been extended to derive a catalogue of 4-OTA-C based sinusoidal oscillators. Some experimental results have also been presented.

In the fifth chapter, the summary of all the four chapters and scope for further work has been suggested.

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