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DESIGN OF FRACTIONAL OSCILLATOR CIRCUIT FOR SENSING DIFFERENT TYPES OF LOSSY CAPACITORS: A NEW PERSPECTIVE ON STABILITY

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Abstract. This article explores the novel concept of modeling lossy capacitive sensors as fractional capacitors and leveraging fractional oscillators a signal conditioning circuit to enhance sensor performance. The fractional oscillator offers several distinct advantages, notably, detecting a wide range of leakage resistance and capacitance values, while also enabling determination of sensor location within the circuit. To address low leakage resistance sensing, the oscillator is designed at 100 kHz, with comprehensive considerations for non-idealities such as limited gain and gain-bandwidth product. A simplified theory for analyzing the stability of the oscillator is discussed in which the stability is determined by comparing imaginary frequency to oscillating frequency.

Key words: fractional order capacitor, fractional order oscillator, signal conditioning circuit, lossy capacitive sensors, theory for analyzing the stability

Introduction

Oscillators are best known for two major applications viz. signal generator and signal conditioning circuit [1-3]. Resistive and capacitive sensors can easily be interfaced with an oscillator circuit for detection of various physical parameters like moisture, water level, vapors, different types of gases etc. The basic principle is that the change in physical parameter changes the oscillating frequency of the circuit. The oscillator will oscillate only when the roots of the characteristics equation lie on the jω-axis or on the right side of *s*-plane. Therefore, while designing oscillator as a signal conditioning circuit, its stability has to be taken care of. Most of the oscillators are second order circuits. When resistive and capacitive sensors are interfaced to the oscillator they preserve the order of the circuit. However, when lossy capacitive sensors are interfaced they reduce the order of the oscillator. It is because most of the lossy capacitors have a constant phase behaviour in a certain frequency range and therefore can be modelled as a fractional capacitor having an impedance:

$$Z_F = \frac{1}{Fs^{\alpha}} \ , \tag{1}$$

where F is called is its fractance and α is called its order. Therefore, when lossy capacitive sensors are interfaced to the oscillator, its order reduces and the circuit may not function properly. This is explained in the next paragraph.

Let a second order oscillator have a loop transfer function:

$$T_1(s) = \frac{1}{s^2+s+1} \ . \tag{2}$$

It is assumed that order $n = 2$ is obtained by using two ideal capacitors in fig. 1,*a*.

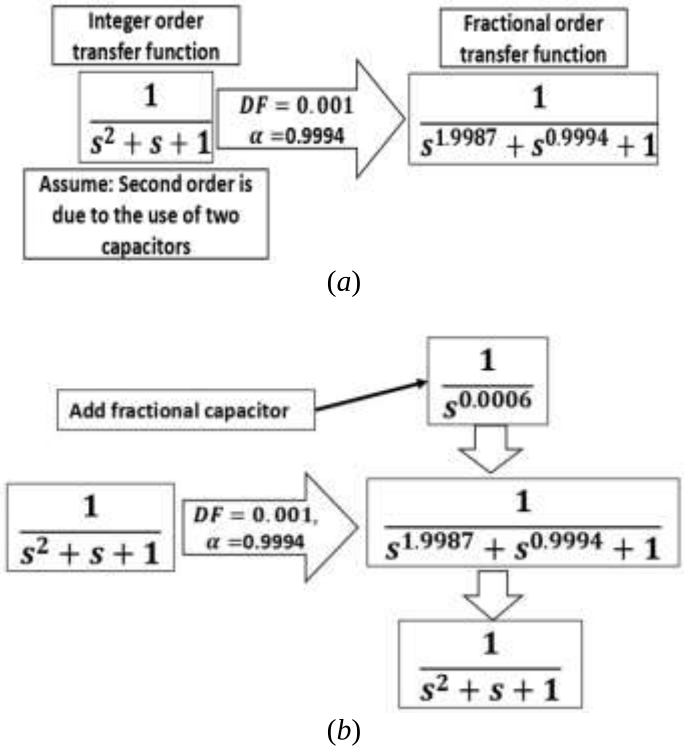


Fig.1. The effect of lossy capacitors on integer order transfer function:
formation of fractional order transfer function (*a*);
restoring the order of the system using fractional capacitor (*b*)

$T_1(s)$ is called integer order transfer function because its order is integer, i.e. $n = 2$. If the dissipation factor of these capacitors increases to 0.001, then the capacitors become lossy and their impedance be given as:

$$Z_C = \frac{1}{Fs^{0.943}}. \tag{3}$$

Hence, the transfer function of the circuit changes to:

$$T_2(s) = \frac{1}{s^{1.9987}+s^{0.9994}+1}. \tag{4}$$

$T_2(s)$ is called fractional order transfer function, as the order becomes 1.9987 which is not an integer. Use of such lossy capacitors can degrade the performance of oscillators. The performance can be restored by adding fractional capacitors to the circuit. Fig. 1,*a* shows the effect of lossy capacitors on integer order circuits, and fig. 1,*b* demonstrates an example where a fractional capacitor of order 0.0006 is added to restore the order of the circuit. It is necessary to restore the order of the oscillator because, as the order of the circuit reduces, the sensitivity of the oscillator as a signal conditioning circuit reduces. Therefore, when lossy capacitive sensors are to be used, a fractional oscillator is an apt choice for the signal conditioning circuit.

Section II describes the proposed fractional order oscillator.

1. Fractional oscillator

The proposed signal conditioning circuit is a new type of fractional oscillator [4-11], whose diagram is shown in fig.2.

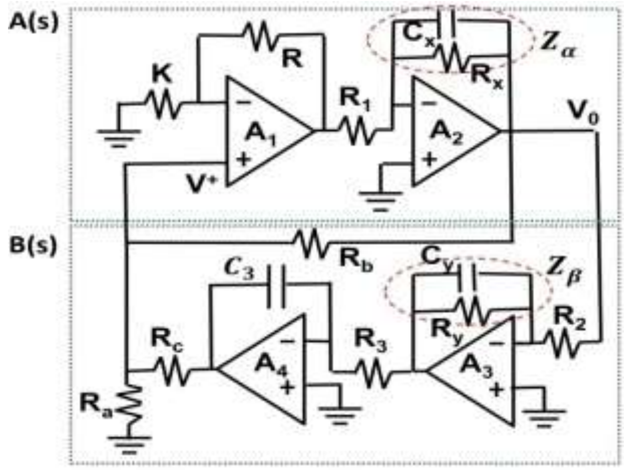


Fig.2. Proposed fractional oscillator circuit

In this section we discuss the operation of the proposed circuit as an oscillator and in the next section its working as a signal conditioning circuit will be explained. The circuit has two lossy capacitors Z_α and Z_β . In fig. 2 simple model of lossy capacitors are given. The actual lossy capacitors can have complex models.

The impedance $Z_\alpha = \frac{1}{R_x C_x s+1} = \frac{1}{F_1 s^\alpha}$. And the impedance $Z_\beta = \frac{1}{R_y C_y s+1} = \frac{1}{F_2 s^\beta}$. We will use the fractional order models to derive the Barkhausen criteria for the oscillation. The circuit has four op-amps of which A_1 and A_2 are the parts of gain network A(s). The other two op-amps A_3 and A_4 are the parts of the feedback network B(s).

The gain, $A(s)$, of the oscillator is given as $A(s) = -\left(1+\frac{r}{k}\right)\left(\frac{1}{R_1 F_1 s^\alpha}\right)$. The output of the oscillator, V0, is positively feedback to A1 through the network B(s). The transfer function of the feedback network is given as:

$$B(s) = \frac{V^+}{V_o} = \left(\frac{1}{G_1} + \frac{1}{G_2 R_2 F_2 R_3 C_3 s^{(1+\beta)}}\right), \tag{5}$$

where $G_1 = 1 + \frac{R_b}{R_a || R_c}$ and $G_2 = 1 + \frac{R_c}{R_a || R_b}$. Once the gain and feedback network of the oscillator are identified, the Barkhausen criteria, $A(s)B(s) = 1$, can be used to derive the oscillating frequency. To simplify the algebric expression, let us consider $G = \left(1+\frac{r}{k}\right)$, $G_{11} = \frac{G}{G_1}$ and $G_{12} = \frac{G}{G_2}$. Then the Barkhausen criteria is:

$$A(s)B(s) = 1 , \tag{6}$$

$$\frac{-G}{F_1 R_1 s^\alpha}\left(\frac{1}{G_1} + \frac{1}{G_2 R_2 F_2 R_3 C_3 s^{(1+\beta)}}\right) = 1 , \tag{7}$$

$$\frac{G_{11}}{F_1 R_1 s^\alpha} + \frac{G_{12}}{F_1 R_1 C_2 R_2 R_3 C_3 s^{(1+\beta)}} = -1 , \tag{8}$$

$$s^{(1+\alpha+\beta)} + \frac{G_{11}}{F_1 R_1} s^{(1+\beta)} + \frac{G_{12}}{F_1 R_1 F_2 R_2 R_3 C_3} = 0 . \tag{9}$$

The characteristic equation of the oscillator (9) can be expanded into its real and imaginary parts which can further be equated to zero. Let the imaginary part is equal to zero at a frequency ω_1, then we get:

$$\omega_1 = \left(\frac{G\cos\left(\frac{\pi\beta}{2}\right)}{G_1R_1F_1\cos\left(\pi\frac{(\alpha+\beta)}{2}\right)}\right)^{\frac{1}{\alpha}}, \tag{10}$$

$$\Rightarrow G = \frac{G_1R_1F_1{\omega_1}^{\alpha}\cos\left(\pi\frac{(\alpha+\beta)}{2}\right)}{\cos\left(\frac{\pi\beta}{2}\right)}. \tag{11}$$

Similarly, let the real part be zero at a frequency ω_2. Expanding and equating the real part of (9) to zero at ω_2, we get:

$$\omega_2 = \left(\frac{G\cos\left(\frac{\pi\beta}{2}\right)}{G_2R_1F_1R_2R_3F_2C_3\sin\left(\pi\frac{(\alpha+\beta)}{2}\right)}\right)^{\frac{1}{(1+\alpha+\beta)}}. \tag{12}$$

When both the real and imaginary parts of (9) are zero, $\omega_1 = \omega_2$, and the circuit oscillates.

2. Fractional oscillator as a signal conditioning circuit for wide range lossy capacitive sensor

In this section, with the help of ***Example 1***, we show the design of the oscillator as a signal conditioning circuit for a lossy capacitive sensor having a wide capacitance (C_y) range of 10 pF to 1000 pF. The value of leakage resistance is 1 kΩ.

Example 1: Design a fractional oscillator based signal conditioning circuit to detect the capacitance of a lossy capacitive sensor having Ry =1 kΩ. The capacitance (Cy) range is 10 pF to 1000 pF.

Solution: Initially an oscillator need be designed using the given values of sensor parameters. Next, we make some modifications in the designed oscillator to make it work as a signal conditioning circuit.

Initial oscillator design: Initially, we have to choose a suitable oscillating frequency as well as a suitable value of α and β. Let us choose Z_β as the sensor as shown in fig. 3.

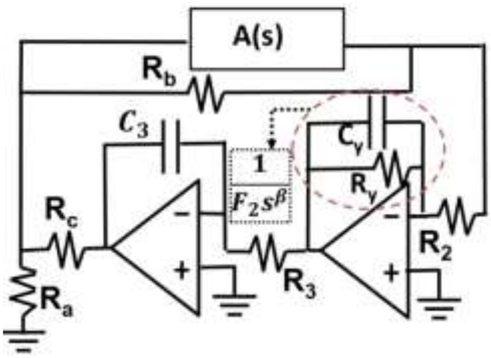


Fig. 3. Circuit diagram of the fractional oscillator using $Z\beta$ as sensor

Since, the capacitance (C_y) of the sensor, Z_β, varies, its corresponding order i.e β and fractance F_2 also vary. We need to find the minimum and maximum possible value of β of the sensor. We require the minimum value to calculate the required value of α for the impedance $Z\alpha$. The minimum value of C_y is 10 pF. Table 1 shows the minimum value of β at different frequencies which is near to zero. The value of α and β should be chosen in such a way that (α + β) > 1. The values of β at 1 kHz and 10 kHz are extremely small, using which the circuit cannot be designed practically. We choose the minimum value of β = 0.012. Therefore, the required value of α will be $\alpha \approx 1 - \beta \approx 1$.

Table 1. Minimum value of β corresponding to Cy values

f_0 (Hz)	1 k	10 k	100 k
C_x (pF)	10	10	10
R_x (k Ω)	1 k	1 k	1 k
β_{min}	4×10^{-5}	4×10^{-5}	4×10^{-5}

The impedance $Z\alpha$ having $\alpha = 1$ is a simple capacitor. It is to be noted that, if we had chosen $Z\alpha$ as the sensor, then we would have obtained $\beta = 1$ to fulfill the condition $(\alpha+\beta) > 1$. But choosing $\beta = 1$ is a bad idea. Observing eq. (11), we find that $\beta = 1$ will produces a very gain G because its denominator will be $\cos\left(\frac{\pi}{2}\right) = 0$. Practically getting such a high gain is not possible. As the circuit is designed at a high frequency, a high gain will affect the output. Once the oscillating frequency is chosen, the maximum value of β can be calculated using maximum value of C_y. It is calculated to be $\beta max = 0.375$. Therefore, the value of β varies between 0.012 to 0.375 whenever the sensor capacitance (C_y) varies between 10 pF to 1000 pF.

Stability: Initially we design the oscillator for α = 1, β = 0.357 (corresponding to C_y =1000 pF) and f_0 = 100 kHz. Following the design steps, different circuit components are chosen as R1 = 30 kΩ, R2 = 1 kΩ, K = 10 kΩ, Ra = 1 kΩ, Rb = 3067 Ω, Rc = 2 kΩ, and C3 = 10 nF. Using these values, the design variables R and R3 are calculated to be R = 653 kΩ and R3 = 109 Ω. The stability of the oscillator circuit in this example can be found out by analyzing the characteristic equation (9) in W plane (the stability of fractional order circuits are generally analyzed in W plane [12] instead s plane). In the s plane the characteristic equation (corresponding to C_y = 1000 pF) of the designed oscillator is given as:

$$D(s) = s^{1+1+0.375} + 3.94 \times 10^5 s^{1.375} + 5.47 \times 10^{13}\ . \tag{13}$$

The above expression can be written as:

$$D(s) = s^{\left(\frac{1000+1000+375}{1000}\right)} + 3.94 \times 10^5 s^{\left(\frac{1000+375}{1000}\right)} + 5.47 \times 10^{13}\ . \tag{14}$$

Let $= s^{\frac{1}{m}}$, m = 1000, then the above equation becomes:

$$D(W) = W^{(1000+1000+375)} + 3.94 \times 10^5 s^{1000+375} + 5.47 \times 10^{13}\ . \tag{15}$$

Equation (15) has 2357 roots in W plane. The system will be stable if all the roots of (15) have $\angle W > \left|\frac{\pi}{2m}\right|$ radian. The system will be oscillatory if one pair of the roots will have $\angle W = \left|\frac{\pi}{2m}\right|$. And the system will be unstable if any root have $\angle W < \left|\frac{\pi}{2m}\right|$. Solving (15) in Matlab we found that a pair of roots have $\angle W = \pm 0.09°$ (m = 1000, so $\frac{\pi}{2m}$ = 0.0016 radian which is 0.09°); while all other roots have $\angle W > |0.09|°$.

Therefore, the circuit, as expected, will oscillate for Cy = 1000 pF and the oscillating frequency ($fosc$) [12] is given as:

$$s = W^m, \tag{16}$$

$$f_o = \frac{Im\{s\}}{2\pi} = 100\ \text{kHz}. \tag{17}$$

Now, if *Cy* decreases to 10 pF, then $\beta = 0.004$ and $F_2 = 2.48\ n\mho s^{0.004}$.
The new characteristic equation becomes:

$$D(W) = W^{(1000+1000+4)} + 3.94 \times 10^{5} s^{1000+4} + 5.47 \times 10^{13}\ . \tag{18}$$

Solving (18) in Matlab it was found that a pair of roots have $\angle W = \pm 0.0911°$, which makes the circuit stable and non-oscillatory. In order to restart the oscillation for $Cy = 10$ pF, we need to make $\omega_1 = \omega_2$. This can be done by tuning *Rc*. The value of *Rc* which will restart the oscillations can be found out using the **Algorithm 1.**

Algorithm 1. How to calculate the value of Rc for which the oscillator will have sustained oscillations for the full range of CP
Start: number of iteration, ***N*** ; **ε** = 1, **r** = 5; iteration counter, ***I;*** **TempRc[1]** = Rc
While *N* **do** $G_1(i) = 1 + \frac{R_b}{R_a \| \mathbf{TempRc(i)}}$ $\omega_1(i) = \left(\frac{G \cos\left(\frac{\pi\beta}{2}\right)}{G_1 R_1 F_1 \cos\left(\pi \frac{(\alpha+\beta)}{2}\right)} \right)^{\frac{1}{\alpha}}$ $\omega_{osc}(i) = \left(\frac{G \cos\left(\frac{\pi\beta}{2}\right)}{G_2 R_1 F_1 R_2 R_3 F_2 C_3 \sin\left(\pi \frac{(\alpha+\beta)}{2}\right)} \right)^{\frac{1}{(1+\alpha+\beta)}}$ *D*(**i**)=*ωosc*(**i**) - ω_1(**i**)
If *D*(**i**) $\leq \epsilon$ *Rc* ← **TempRc and stop** **Else TempRc(i** + 1) = **TempRc(i)** – **r** **End**

Using **Algorithm 1**, the value of R_C which makes the system oscillatory is 12 **Ω**. Fig. 4 shows the plot of $\angle W$ for different values of *C y* when *Rc* = 12 **Ω**, *Rc* = 1 k**Ω** and *Rc* = 2 k**Ω**.

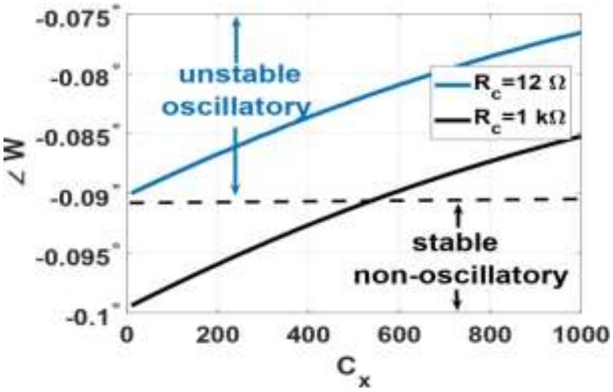


Fig. 4. *Rc* can be used for sustained oscillations for different ranges of *Cy*

It is apparent from fig. 4 that, the circuit will be in unstable state irrespective of the value of *Cy*, when *Rc* = 12 **Ω**. However, as the value of *Rc* increases, the circuit instability region decreases. For example, when *Rc* = 1 kΩ, the circuit is unstable for *C y* = 560 pF to 1000 pF. But for the range *Cy* = 10 pF to 560 pF, the circuit is stable and non-oscillatory because $\angle W > 0.09°$.

The result of the above example can be concluded as, "adjusting the value of *Rc* = 12 Ω leads to sustained oscillations for the given range of sensor capacitance".

3. A new theory for stability for the proposed oscillator

Determining the stability of the oscillator using the conventional method is a complex process as it involves numerical computation of large number of roots. In ***Example 1***, the number of roots are 2357 which takes some amount of time to compute using Matlab. Further we need search roots having $\angle W = |\frac{\pi}{2m}|$ radian. This again takes some time.

In this part a new theory has been proposed which simplifies the process of determining the stability of the oscillator. The proposed stability theory is not a general theory rather it is applicable only to the oscillators having a characteristics equation in the following format.

$$D(s) = s^{(1+\alpha+\beta)} + a_1 s^{1+\beta} + a_2 \,. \tag{19}$$

Theory: The proposed oscillator is:

1) stable and non-oscillatory if $\omega 1 > \omega 2$.
2) stable and oscillatory if $\omega 1 = \omega 2$.
3) unstable but oscillatory if $\omega_1 < \omega_2$
4) The oscillating frequency can be obtained by solving $\frac{dRe\{D(s)\}}{d\omega} = 0$.

In this part no mathematical proof has been given. This theory has been established by several verifications that has been performed using MATLAB simulations.

Example 2 demonstrates the simplicity with which the stability of the oscillator can be determined.

Example 2: Find the stability of the oscillator realized in ***Example 1*** using the proposed theory.

Solution: The values of ω_1 and ω_2 can be calculated using (11) and (12) respectively. Utilizing the component values given in ***Example 1***, we find $\omega_1 = \omega_2 = 2\pi \times 100$ Mrad/s. Therefore, the system is stable and the oscillating frequency is given by $\omega osc = 100$ Mrad/s. The results are identical to ***Example 1***. Table 2 compares the results of the two methods.

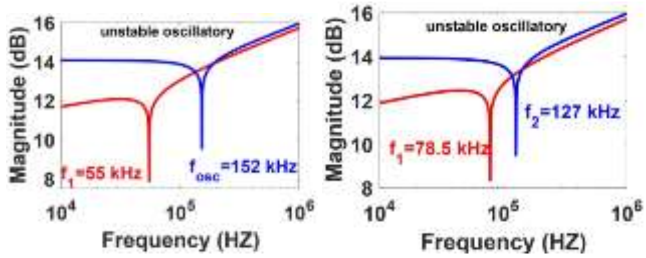
Table 2. Comparison of conventional and proposed method of stability $\left(f1 = \frac{\omega_1}{2\pi}, f2 = \frac{\omega_2}{2\pi})\right)$

	Conventional Method		Proposed Method		Is Stable/ Oscillates ?
$R_c(\Omega)$	∠W (◦)	f_{osc} (kHz)	f_1(kHz)	f_2(kHz)	
1000	0.085	124	78.5	121	No/Yes
1500	0.088	110	91.6	108	No/Yes
2000	0.090	100	100	100	Yes/Yes
2500	0.092	92	105	93	Yes/No
3000	0.093	85.6	110	87	Yes/No
1000	0.085	124	78.5	121	No/Yes

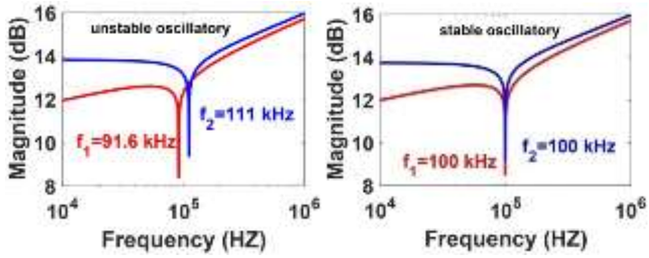
The stability of the circuit changes if *Rc* is varied. So, in Table 2 we set *Rc* to different values and check the stability using the two methods.

In the column 'conventional method', the value of $\angle W$ has been computed for different values of Rc. Also the oscillating frequency is calculated using (17). In the column 'proposed method', ω_1 and ω_2 has been calculated. It can be observed from the table that whenever, $\omega_1 < \omega_2$, $\angle W < \frac{\pi}{2m}$ which ensures instability. Also if $\omega 1 > \omega 2$, $\angle W > \frac{\pi}{2m}$which ensures stability. Therefore, Table II validates the proposed theory.

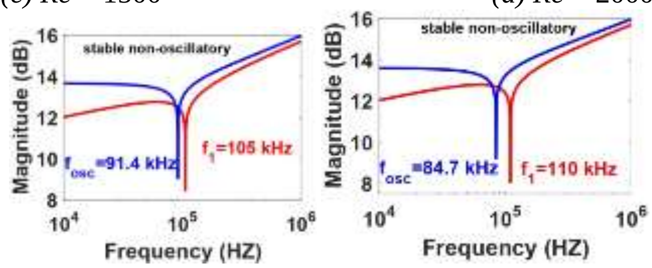
The position of ω_1 can be visualized by plotting Im$\{D(s)\}$ with respect to ω. Similarly the position of ω_{osc}can be visualised by plotting Re$\{D(s)\}$ with respect to ω. Fig. 5 shows the plot of Im$\{D(s)\}$ and Re$\{D(s)\}$ for the values of Rc given in Table 2.



(a) Rc = 500 *(b) Rc* = 1000



(c) Rc = 1500 *(d) Rc* = 2000



(e) Rc = 2500 *(f) Rc* = 3000

Fig. 5. Plot of Im$\{D(s)\}$ and Re$\{D(s)\}$ for different values of Rc

The original value of Rc = 2000 Ω. It can be observed from these figures that as the value of Rc decreases, the system becomes unstable but oscillatory. As the value of Rc increases, the system becomes stable but non-oscillatory.

4. Design of the oscillator at high frequency

The main advantage of using fractional oscillator as a signal conditioning circuit is that it can detect low leakage resistance (1 kΩ) lossy capacitor. But in order to detect low leakage resistance, the circuit is to be operated at high frequency. At high frequency the limited gain and gain-bandwidth product start to dominate the frequency response of the circuit. Let G_{A1}, G_{A2}, G_{A3} and G_{A4} be the gain of the op-amps A, A_2, A_3 and A_4 at high frequency ($f \geq$ 100 kHz) respectively. The expression of these gains can be given as:

$$G_{A1} = \frac{G\omega_t}{\omega_t + Gs}, \tag{20}$$

$$G_{A2} = \frac{G_x}{1+(1+G_x)\frac{s}{\omega_t}}, \tag{21}$$

$$G_{A3} = \frac{G_y}{1+(1+G_y)\frac{s}{\omega_t}}, \tag{22}$$

$$G_{A4} = \frac{Gs}{1+(1+Gs)\frac{s}{\omega_t}}. \tag{23}$$

Where ω_t, is the gain-bandwidth product of op-amps; $G_x = \frac{\frac{R_x}{R_1}}{R_x C_x s+1}$ and $G_y = \frac{\frac{R_y}{R_1}}{R_y C_y s+1}$. For LF411 op-amps $\omega_t = 6\pi$ Mrad/s; Using this expression, the loop transfer function of the oscillator is given as:

$$T(s) = A_x B_x + 1, \tag{24}$$

where, $A_x = G_{A1} G_{A2}$ and $B_x = \frac{1}{G_1} + \frac{G_{A2}}{G_{A4}}$.

Due to the extra pole introduction, the design equations of the oscillator as given in (11) and (12) may not provide desired results. Therefore, we need to choose the component values in such a way that generated sine waves are accurate as well as of high quality. In the following an ***Example 3*** is given to demonstrate the design problem.

Example 3: A sensor has a leakage resistance of 1 kΩ; its capacitance can vary from 1000 pF to 10 pF. Design an oscillator at 100 kHz to sense the change in capacitance. Discuss the effect of changing the resistor Rb on the frequency response of the oscillator.

Solution: The impedance of the senor with the nominal value of capacitance is given as $Z\beta$ = 1 kΩ||10 pF. At 100 kHz, β is calculated to be $\beta = \angle Z\beta$ -90° = 0.004. To make $\alpha + \beta \approx 1$, let us choose $\alpha = 1$ and $C1$ = 1 nF. The other components are chosen to be $R1$ = 300 Ω, $R2$ = 1 kΩ, K = 10 kΩ, Ra = 1 Ωk, Ω, Rc = 2 kΩ and $C3$ = 100 nF.

Fig. 6 shows the bode plot of (24) for different values of *Rb*.

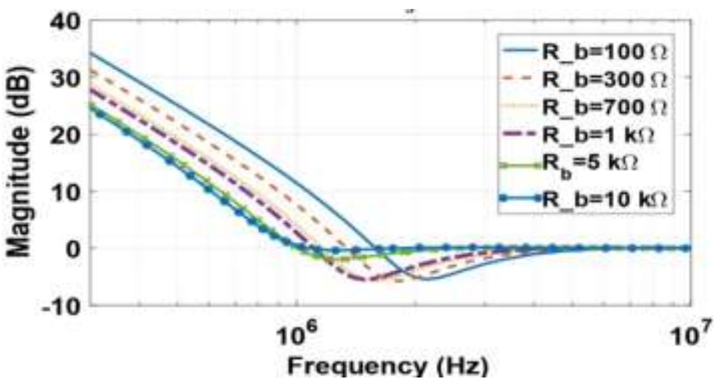


Fig. 6. The frequency response of the oscillator at high frequency for different values of *Rb*

Table 3 shows comparison of the ideal and non-ideal values of oscillating frequency. Here non-ideal means the oscillating frequency as derived from (24) for different values of *Rb*.

The following points can be observed from Fig. 6 and Table III:

1. For smaller values of Rb, there is a sharp trough in the magnitude response of eq. (24), which shows high quality factor. This shows that the sine wave generated for these values of Rb

will have low THD (Total harmonic distortion).

Table 3. Effect of the resistor *Rb* on oscillating frequency

Rb (kΩ)	Oscillating frequency		Error= *f*1 - *f*2 (kHz)
	Ideal (f*1*) (kHz)	non-ideal(f*2*) (kHz)	
0.1	540	311	229
0.3	328	265	63
0.7	258	230	28
1	240	217	23
5	201	167	34
10	200	143	57

2. However, for smaller value of *Rb*, as observed from Table II, the error is large. This shows that for smaller values of *Rb*, the accuracy of the circuit is less.

3. For larger values of *Rb*, the magnitude response flattens showing low quality factors.

4. However, for larger values of *Rb* (5 kΩ or 10 kΩ), the error is large.

From sensing point of view, what we can conclude that we need to select *Rb* values in the mid range such that it will maintain both accuracy as well as quality factor

Conclusion

In this work a new theory of stability for fractional oscillator has been proposed. It is easier to establish the stability of the oscillator using the proposed theory as compared to the conventional theory. But the main disadvantage of the proposed theory is that it is applicable to only a section of oscillators which has a format as discussed in this work. In addition to the stability, the frequency response of the oscillator is also discussed. The fractional oscillator is shown to be useful to detect low leakage resistance lossy capacitors. But to detect low leakage resistance, the circuit has to be operated at a high frequencies (100 kHz). At such high frequencies, the limited gain and gain -bandwidth product of the op-amps come into effect. It is shown that while designing the circuit, the components should be chosen wisely.

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РАЗРАБОТКА СХЕМЫ ДРОБНОГО ГЕНЕРАТОРА ДЛЯ РАЗЛИЧЕНИЯ ХАРАКТЕРИСТИК КОНДЕНСАТОРОВ С ПОТЕРЯМИ: НОВЫЙ ВЗГЛЯД НА СТАБИЛЬНОСТЬ

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Аннотация. В этой статье исследуется новая концепция моделирования емкостных датчиков с потерями в виде дробных конденсаторов и применения дробных генераторов в качестве схем формирования сигналов для повышения качества различения их характеристик. Дробный генератор обладает несколькими явными преимуществами, в частности, обнаружением широкого диапазона значений сопротивления утечки и емкости, а также возможностью определять местоположение датчика внутри цепи. Для решения проблемы обнаружения с низким сопротивлением утечки генератор спроектирован на частоту 100 кГц с учетом всех неидеальностей, таких как ограниченные усиление и произведение усиления на полосу пропускания. Обсуждается упрощенная теория анализа стабильности генератора, в рамках которой стабильность определяется путем сравнения частоты колебаний с ее мнимой составляющей.

Ключевые слова: конденсатор дробного порядка, генератор дробного порядка, схема формирования сигнала, емкостные датчики с потерями, теория для анализа устойчивости генераторов.

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