OPTIMILLER: AN INTERACTIVE ENVIRONMENT THAT HELPS STUDENTS IN THE UNDERSTANDING, DESIGN AND OPTIMIZATION OF MILLER ELECTRONIC OSCILLATOR CIRCUITS FOR QCM SENSORS

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Abstract: The quartz crystal oscillator used as mass sensor in damping media suffers significant losses implying the need to adapt the oscillator design to compensate them. In this paper, a CAD tool to help students in the understanding, design and optimization of Miller oscillators for the realization of high sensitivity quartz crystal microbalance (QCM) sensors for liquid media is presented. This tool is oriented not only to the practical teaching of advanced Thickness Shear Mode (TSM) acoustic wave sensors for mass changes detection, but also to aid designers in the development of QCM sensors.

Key words: CAD tool; Miller oscillator; QCM

1. INTRODUCTION

The quartz crystal microbalance is a thin plate of piezoelectric crystal with one rigidly attached metal film electrode on each side. The crystal is made to vibrate at its resonant frequency by inserting it in the feedback path of an oscillator circuit. In gravimetric applications, the crystal is in direct contact with its environment and the changes in the crystal resonant frequency, caused by environmental changes, are used as analytical signal.

In particular, the changes of mass deposited on the crystal surface, are directly reflected in frequency changes in such a way that an increase in mass, will cause the circuit oscillate more slowly.

Despite the long history of quartz crystal electronic oscillators circuits, the success of their use as mass sensors in damping media, still depends strongly on the designer's ability and experience. The design must be adapted so that the oscillation remains in spite of the large reduction that the quality factor of the quartz experiences in those media. Although it is not difficult assemble an oscillator that works, the procedure required to build an oscillator that meets some predetermined requirements is not so simple. In the case of oscillators to be used as mass sensors in damping media, this kind of procedure has not been sufficiently developed.

With the objective of providing a tool that allows students to understand the operation of the quartz crystal oscillators, the software system OptiMiller has been developed. OptiMiller is a CAD tool that aims at helping not only students but also users in the design and optimization of Miller electronic oscillator circuits for QCM sensors [8].

Different oscillator circuit topologies are used in QCM. This tool is based on Miller oscillator topology. The basic structure of a Miller oscillator is represented in Fig. 1 [1,2,3].

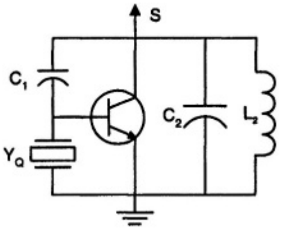


Figure 1. Basic structure of Miller oscillator circuit

This tool allows the tasks indicated in the Fig. 2 to be automated. These tasks are described in the next point.

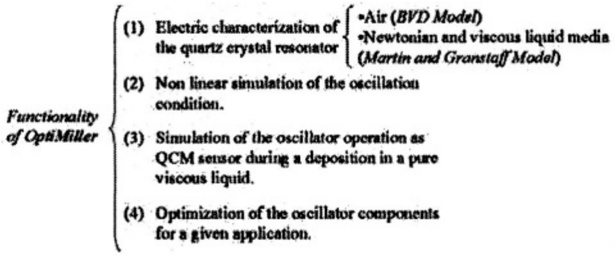


Figure 2. Tasks carried out by OptiMiller

2. OPTIMILLER FACILITIES

The interaction with the user is carried out through the main window of the program, which consists of a menu and a button bar that enable the use of different tools. This window is represented in Fig. 3.

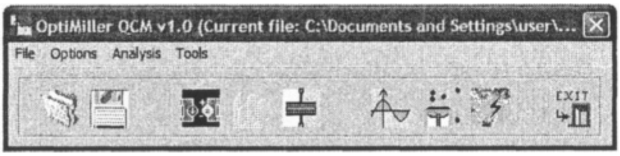


Figure 3. Main window of OptiMiller

2.1 BVD equivalent circuit

The quartz impedance Window allows students the quartz crystals performance to be understood in different environments (e.g. air or damping media).

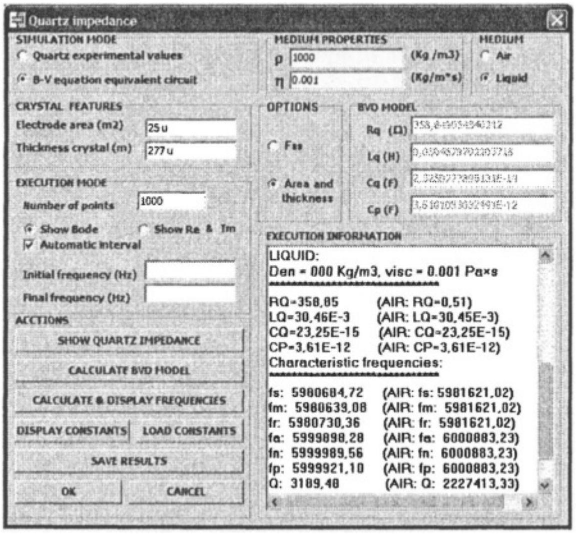
OptiMiller enables users the electric characterization of the quartz crystal resonator to be executed. The user has to introduce the experimental values for the Butterworth Van Dyke (BVD) equivalent circuit, measured by means of an impedance analyzer, or the crystal physical characteristics and the working environment characteristics, defining the quartz. In Fig. 4, the quartz impedance window has been represented. Through this window, the user can do the following tasks:

- Obtain the BVD equivalent circuit of the quartz resonator.
- Obtain the characteristic frequencies of the resonator.

- Obtain the graphical visualization of the impedance according to the frequency.
- Store the results in a text file.

OptiMiller enables the student to obtain the BVD equivalent circuit of an AT quartz resonator starting from its dimensions and physical parameters, as much as in air as in a newtonian and purely viscous liquid medium. In the last case, the density and viscosity of the liquid characterize the influence of the medium in the behavior of the resonator. The tool calculates the BVD equivalent circuit modified by Martin and Granstaff for a quartz crystal loaded by a liquid [4]. The application also facilitates that the experimental values obtained by means of impedance analyzer can be introduced, for its later use in the simulations of the behavior of the oscillator.

Once the electric circuit of the quartz has been defined, the program allows calculating series and parallel frequencies, minimum and maximum phase frequencies, and minimum module frequencies, as well as the resonator quality factor, in order to define the operation point of the sensor [5].



○ Quartz experimental values
● B-V equation equivalent circuit

ρ 1000 (Kg /m3)
η 0.001 (Kg/m*s)

○ Air
● Liquid

Electrode area (m2) 25 u
Thickness crystal (m) 277 u

○ Fas
● Area and thickness

Number of points 1000
● Show Bode ○ Show Re & Im
☑ Automatic interval
Initial frequency (Hz)
Final frequency (Hz)

```
LIQUID:
Den = 000 Kg/m3, visc = 0.001 Pa×s
**********************************

RQ=358,85       (AIR: RQ=0,51)
LQ=30,46E-3     (AIR: LQ=30,45E-3)
CQ=23,25E-15    (AIR: CQ=23,25E-15)
CP=3,61E-12     (AIR: CP=3,61E-12)
Characteristic frequencies:
**********************************

fs:  5980684,72   (AIR: fs: 5981621,02)
fm:  5980639,08   (AIR: fm:  5981621,02)
fr:  5980730,36   (AIR: fr:  5981621,02)
fa:  5999898,28   (AIR: fa:  6000883,23)
fn:  5999989,56   (AIR: fn:  6000883,23)
fp:  5999921,10   (AIR: fp:  6000883,23)
Q:  3189,48       (AIR: Q:  2227413,33)
```

Figure 4. Quartz Impedance Window of OptiMiller

In Fig. 4, an example of obtaining the BVD equivalent circuit and the characteristic frequencies of a quartz resonator is shown. In this case, the calculation was made for a quartz resonator of thickness **277μm** and area of electrode **25 mm^2,** in air and submerged in distilled water at 25°C (density **1000 Kg/m^3,** viscosity 0.001 Pa·s). The obtained values are summarized in

Table 1. In this way, the student can easily compare the values obtained in both media, and to observe the influence of the liquid in the behavior of the resonator.

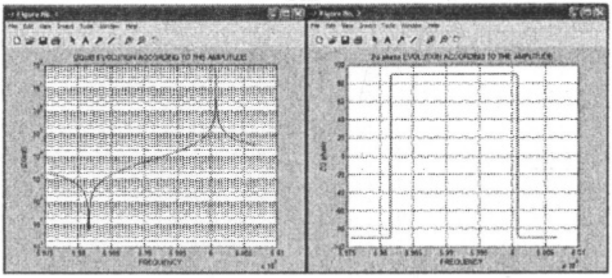
Table 1. **OptiMiller results for BVD equivalent circuit and characteristic frequencies in the case of quartz thickness 277μm and area of electrode 25 mm^2, in air and submerged in distilled water at 25°C (density 1000 Kg/m3, viscosity 0.001 Pa·s)**

	Air	Distilled water
R_Q (Ω)	0.51	358.8
C_Q (fF)	23.25	23.25
L_Q (mH)	30.45	30.46
C_P (pF)	3.61	3.61
f_s (MHz)	5.981621	5.980685
f_m (MHz)	5.981621	5.980639
f_r (MHz)	5.981621	5.980730
f_a (MHz)	6.000883	5.999898
f_n (MHz)	6.000883	5.999990
f_p (MHz)	6.000883	5.999921
Q	2227413	3189.5

Another utility contributed by OptiMiller for the understanding of the quartz resonators operation is the possibility to have a graphical visualization of its impedance according to the frequency, so that student can appreciate visually the damping of the resonator when it works in a liquid medium. This graphic representation of the impedance can be shown through the Bode diagram (module and phase), or by means of the observation of the real and imaginary part. The graphic resolution and the interval of frequencies to be represented can be selected. To obtain the graphic representations, the program connects with the mathematical simulation tool Matlab (MathWorks Inc.), sending it the data to be represented which undertakes the graphic realization as it is shown in Fig. 5.

Moreover, OptiMiller enables the storage of calculations done in a text file in code ASCII: the values of the elements of the resonator BVD equivalent circuit, the characteristic frequencies and the impedance values. In this way, the student can use them in other simulation environments.

Air



Distilled water

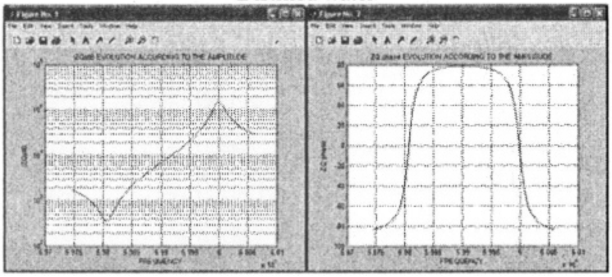
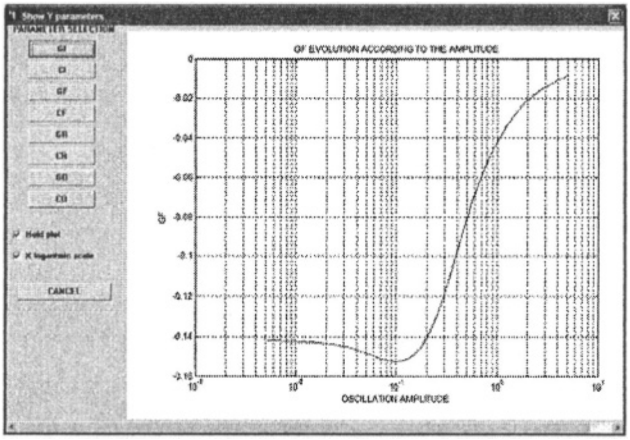


Figure 5. Graphic representation of the impedance resonator bode diagram for the example of Fig. 4 and Table 1

2.2 Active device model

The active device model Window allows students the amplifier non-linear performance to be shown by means of different graphics.To carry out the non-linear simulation of the oscillation condition of a Miller oscillator circuit it is necessary to characterize the amplifier. In order to do this, the non-linear behaviour of the active device is described by using non-linear admittance parameters (*y* parameters) whose values are a function of the input signal level. For this reason, the user has to introduce these parameters in relation to the oscillation amplitude. The introduction of the data is made by means of a text file that contains a table with the values in ASCII. These parameters are obtained by using an electrical simulator like SPICE or from an impedance analyzer. These values will be used later by OptiMiller in the simulation of the oscillation condition to obtain the frequency and amplitude of the output signal of the circuit [6].In addition, once the amplifier data have been introduced, OptiMiller allows student the graphical visualization of the amplifier *Y* parameters according to the amplitude, in logarithmic or linear scale, connecting with Matlab. In Fig. 6 an example of the variation of the transconductance of an OTA660 amplifier for 6MHz is represented.



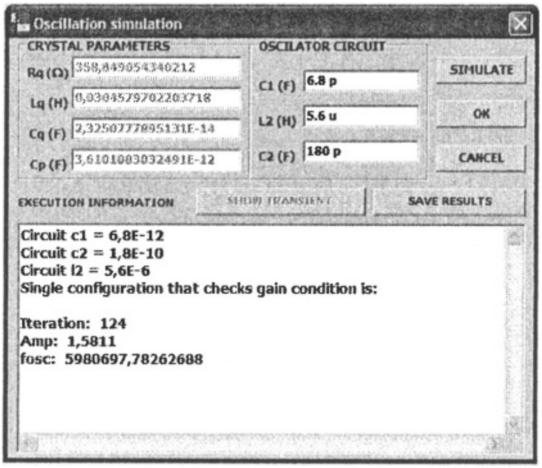
☑ Hold plot

☑ X logarithmic scale

Figure 6. Admittance parameters visualization Window. Variation of the transconductance of an OTA660 amplifier working at 6MHz

2.3 Oscillation condition: non-linear simulation

Once the values both the BVD equivalent circuit and the amplifier admittance parameters according to the amplitude have been introduced, OptiMiller enables the students to carry out the non linear simulation of the oscillation condition of a Miller oscillator circuit [6]. In order to do this, the tool provides the oscillator condition simulation Window, represented in Fig. 7. This window enables to specify the value of the passive components of the Miller oscillator circuit (feedback capacitor, C_1, and filter L_2C_2). Once these values are specified, the user can simulate the operation of the defined circuit in order to check the oscillation condition and to find both the frequency and amplitude that verify the oscillation condition. Moreover, OptiMiller enables the students to graphically study the transient state of the oscillator (values of frequency according to the amplitude), as well as to store the results of the simulation in an ASCII text file.



Rq (Ω) 358,849054340212
Lq (H) 0,0304579702203718
Cq (F) 2,3250777895131E-14
Cp (F) 3,6101083032491E-12
C1 (F) 6.8 p
L2 (H) 5.6 u
C2 (F) 180 p

```
Circuit c1 = 6,8E-12
Circuit c2 = 1,8E-10
Circuit l2 = 5,6E-6
Single configuration that checks gain condition is:

Iteration:  124
Amp:  1,5811
fosc:  5980697,78262688
```

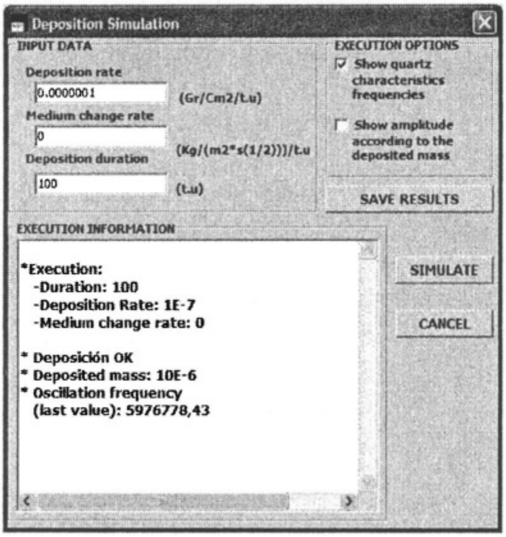
Figure 7. Simulation of oscillator condition Window

2.4 QCM sensor simulation

The OptiMiller deposition simulation Window allows students the behavior of the Miller oscillator as sensor QCM during a deposition of mass [7] to be understood, that is, it is possible simulating a mass deposition and showing the crystal oscillation frequency evolution during that deposition (see Fig. 8).

The user should specify the following parameters:

- *Deposition velocity:* quantity of mass that will be deposited in the electrode (in grams for unit of time and for square centimeter).
- *Velocity of change of the medium:* index that indicates the variation of the liquid medium in which the electrode is submerged for unit of time (product density for viscosity of the medium) [1].
- *Duration of the deposition:* expressed in units of time.



Deposition rate
0.0000001 (Gr/Cm2/t.u)
Medium change rate
0 (Kg/(m2*s(1/2)))/t.u
Deposition duration
100 (t.u)

☑ Show quartz characteristics frequencies
☐ Show amplitude according to the deposited mass

*Execution:
-Duration: 100
-Deposition Rate: 1E-7
-Medium change rate: 0

* Deposición OK
* Deposited mass: 10E-6
* Oscillation frequency
(last value): 5976778,43

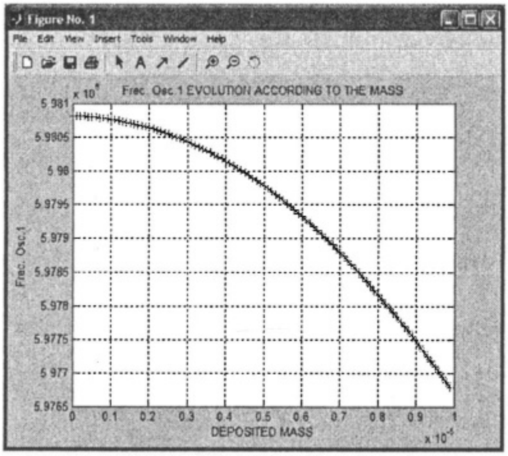


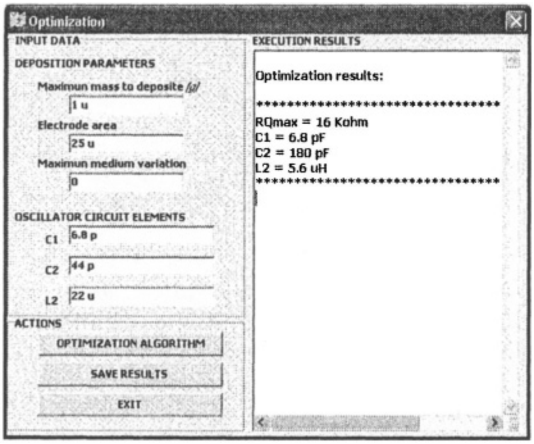
Figure 8. Window of simulation of the oscillator behavior during a mass deposition

OptiMiller modifies the quantity of deposited mass and the characteristics of the medium with respect to the time, and it carries out a non linear simulation of the oscillation condition at each instant to calculate both the oscillation amplitude and frequency that fulfill the gain condition. The tool indicates as a result whether the oscillation is stable or not along the whole deposition, and it enables to graphically observe the evolution of the oscillation frequency according to the deposited mass. In addition, OptiMiller enable the calculation of the new characteristic frequencies of the quartz to the end of the deposition, as well as observing the evolution of the oscillation amplitude according to the deposited mass.

2.5 Optimization of Miller oscillators for liquid media

OptiMiller provides a tool that helps the user in the design and optimization of Miller oscillators for its use as QCM sensor in liquid media [9].

The access to the optimization tool of is carried out through the window represented in the Fig. 9. This window enables the good values of the components of a Miller oscillator electronic circuit to be obtained for a given application. The optimization is carried out starting from the data of the quartz equivalent circuit, the characteristics of the active device and the initial values of the feedback capacitor C_1 and of the filter components C_2L_2. To characterize the sensor application and therefore the working operation conditions of the oscillator, it is necessary to indicate both the quantity of maximum mass that will be deposited in the sensor electrode, and the area of the same one (to calculate the superficial density of mass). Besides the characteristics of the liquid medium in which the deposition will be carried out must be indicated (by means of the density-viscosity product). The program redesigns the circuit by means of the execution of an optimization algorithm [9], and it calculates, should they exist, the values for the components (C_1, C_2 and L_2) such that the circuit is able to oscillate for the conditions of the suitable application.



Maximun mass to deposite (g): 1 u

Electrode area: 25 u

Maximun medium variation: 0

C1: 6.8 p

C2: 44 p

L2: 22 u

```
Optimization results:

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RQmax = 16 Kohm
C1 = 6.8 pF
C2 = 180 pF
L2 = 5.6 uH
********************************
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Figure 9. Optimization Window

3. SUMMARY

A computer program for QCM based on Miller oscillator circuit is presented. This tool allows students to understand and to analyze the performance quartz crystal microbalance based on Miller oscillator circuit. In addition, OptiMiller helps users in the design and the optimization of the Miller oscillator circuit. It gives to the designer the variation of the important parameters to work within the specifications under all conditions.

Which this tool can be obtained the BVD equivalent circuit of the AT quartz from its dimensions and physical parameters, both in air and in pure viscous and newtonian liquid media. In this last case, the density and viscosity of the liquid characterize the influence of the media. The program also enables the user to introduce experimental quartz values to be used in the simulations of the oscillator behavior. With the purpose of carrying out simulations taking into account the non linear behavior of the active device, the values of the admittance parameters of the active device as a function of the amplitude can be introduced. Once the values of the oscillator components were specified, the non linear simulation of the oscillation condition, the simulation of the oscillator operation as QCM sensor during a deposition in liquid, and the optimization of the circuit components for a given application can be carried out. This last process consists of calculating new values for the components, so that the new circuit is able to oscillate under conditions of maximum mass to deposit and viscosity of the media.

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