How to Model a Phase-Locked Loop (PLL) in Excel – part #2

-This is the continuation of part #1 of the PLL tutorial. The first part described the block diagram and derived the numerical equation used in modeling the low pass filter.

- Before implementing the PLL it is good to model the low pass filter (LPF) as a stand alone component.

- We do this since the LPF is the most complex part of the system and it is a very good practice in practical electronics and in engineering in general, to test all the blocks and subsystems individually before putting them together into a large system.

- The last part begins the implementation of the full model in the worksheet.

In

X

K_pd

R

Out_LF

C

K_vco

VCO

Out

Noise
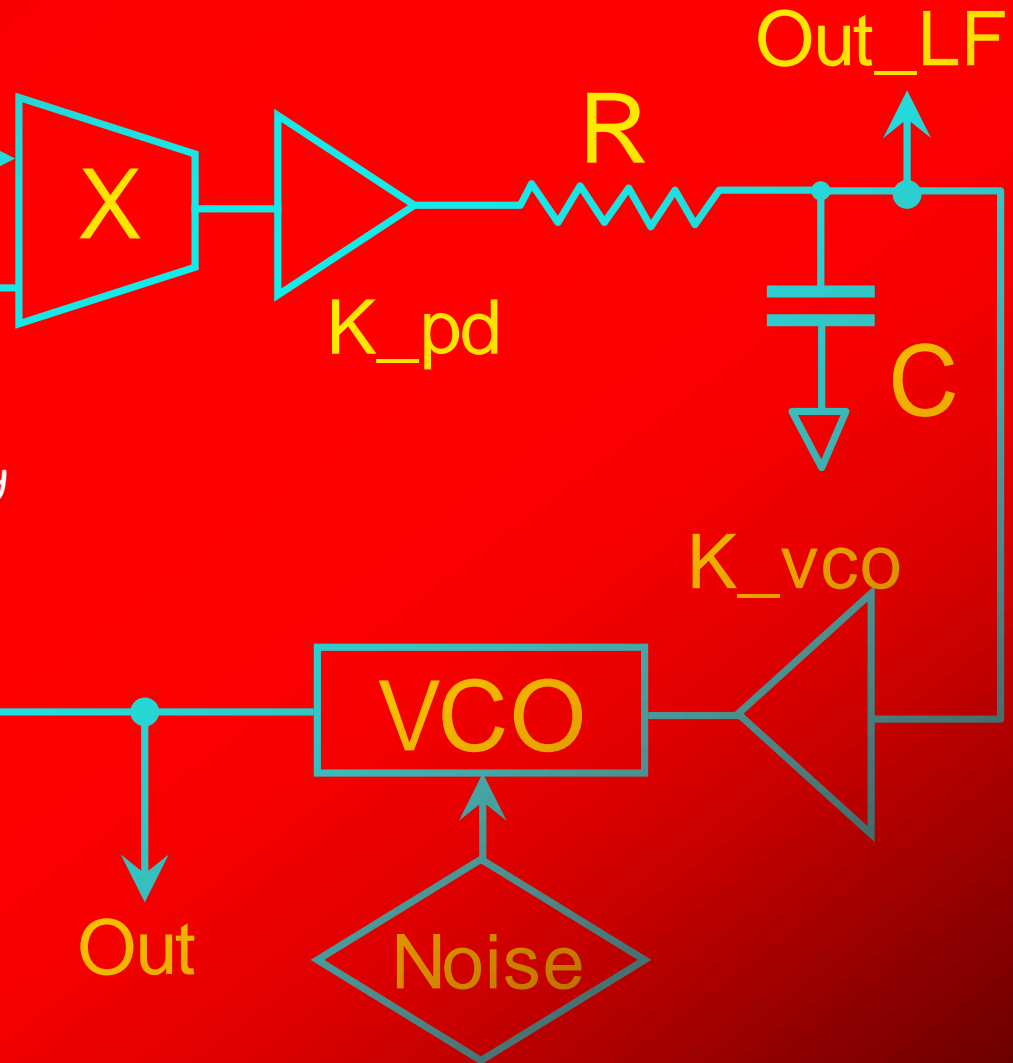
Verifying the functionality of the low pass filter:

- Open a new workbook and call it "PLL_Tutorial".
- Select the tab of worksheet "Sheet1" and rename it LPF
- Create the labels as indicated in the snapshot to the right in cells B3, B5, B5 and range B11:E11
- Pad the range B13:E13 with zeros and give the input parameters the values from the picture
- Create the time series T14: "=B13+C$5" and copy down to cell B300
- Create the rectangular input wave oscillating between   -1 and 1 with a frequency from cell C7 (1Hz)

      C14: "=SIGN(SIN(2*PI()*C$7*B14))"

-Using the two formulas based on the backward and forward derivative approximations from in the previous section of the tutorial, create the output series in columns D and E:

$$\begin{cases} \text{D14: "=(C\$5*C14+C\$3*D13)/(C\$3+C\$5)"} & \longleftarrow \quad u_{out}(n) = \dfrac{h \cdot u_{in}(n) + R \cdot C \cdot u_{out}(n-1)}{R \cdot C + h} \\[2em] \text{E14: "=E13+C\$5/C\$3*(C13-E13)"} & \longleftarrow \quad u_{out}(n) = u_{out}(n-1) + \dfrac{h}{R \cdot C} \cdot \left[u_{in}(n-1) - u_{out}(n-1) \right] \end{cases}$$

- Copy B14:E14 down to B300:E300
- Plot the following three curves on the same chart against the time series: u_in, u_out_B and u_out_F
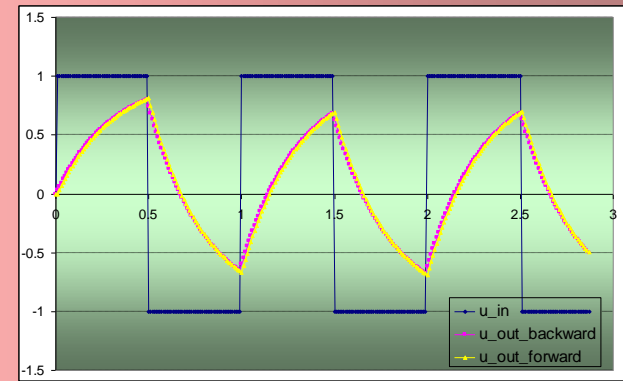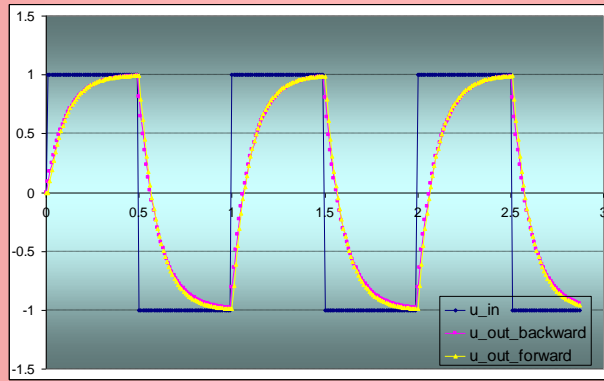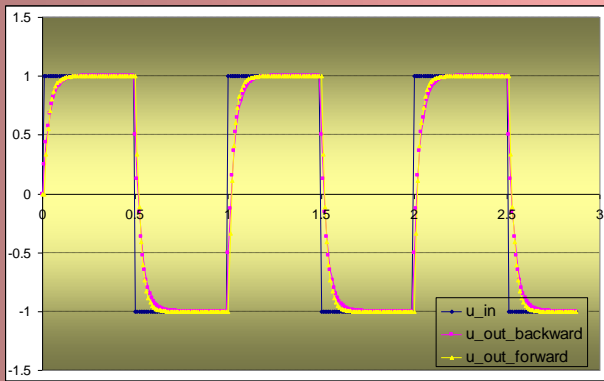
- The above curves correspond to RC values of 0.03 sec., 0.1 sec. and 0.3 sec.
- The responses look just right for a low pass filter and the difference between the backward and forward approximations are small (you can verify that the difference drops with the time step size).

<u>Let's redraw the PLL block diagram:</u>

-We added a gain stage (V_{VCO}) for the control voltage in the voltage control oscillator (VCO). This is an important parameter since it controls the range of output frequency of the VCO
- The output $u_{out}(t)$ and input $u_{in}(t)$ voltages are the inputs to the phase detector block
- The phase detector block outputs a voltage called $u_{PD}(t)$ into the filter and the filter outputs a voltage called $u_{PD}(t)$ into the VCO
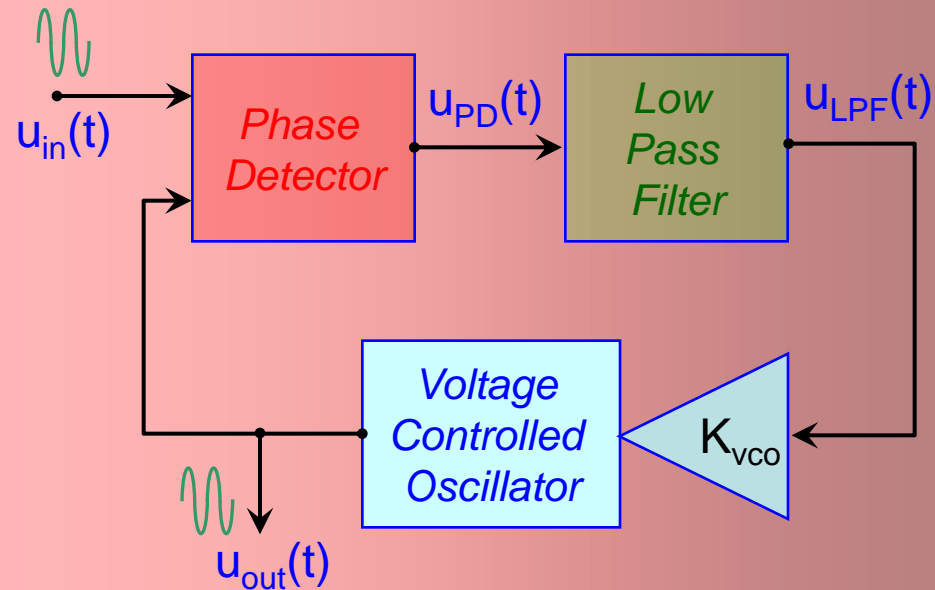
Some issues with modeling frequency modulation

- You could read about anything and learn something but if you really want to learn try it yourself and make your own mistakes. If you go to a movie or read a novel, I bet you wouldn't like someone to tell you beforehand how it ends. I believe that the current educational system promotes lack of confidence. You are always told to study more, get "better", gain "experience", gain "skills", read books, read research papers, ask the "experts", get a higher degree, get a Ph.D., get an MBA, work in groups. People live with the wrong impression that they are lacking the internal power to do much because they were conditioned this way by the system. Just like being healthy erodes the profits of the "health system" as an institution, using your mind is empowering you but it diminishes the importance of the educational system. The vast majority of times all you need to do is just close the door, sit down and think. It could save you weeks, months, or even years of beating around the bushes to solve ONE problem.

-Some time back I was attempting to model a frequency modulated wave for a PLL (the VCO) using two columns, a time series and of course the sinus function. Seemed straightforward, even trivial. At first I couldn't figure out why the result was not at all what I expected.

-After some struggle and digging I realized that it was important to replace the time column with a phase column calculated iteratively. More on this topic will be covered in a later presentation.
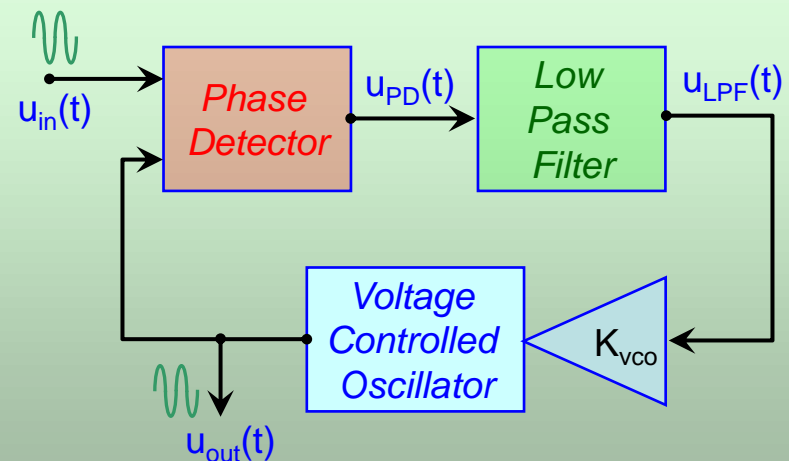
What would the two worksheet tables contain?

Input parameters:
-Input frequency-Input frequency step size
-VCO free oscillation frequency
-RC for the LPF
-KVCO-conversion gain
-Time step size

Calculated values:
-Input phase
-$u_{in}(t)$
-$u_{PD}(t)$
-$u_{LPF}(t)$
-Output phase
-$u_{out}(t)$

Spreadsheet implementation:

-Rename the second worksheet "PLL_a".

-There are four labels in the upper area (input parameters area).

-There are six labels in the bottom area (calculation area).

-You can use the same names or make your own.

-Create four buttons:

  =>"Fin" with a range of [-50, 50]

  =>"Delta_Fin" with a range of [1, 20]

  =>"K_vco" with a range of [0, 13]

  =>"RC" with a range of [0, 6]

-The macros associated with these buttons are:

```
Private Sub Delta_Fin_Change()
[B9] = Delta_Fin.Value / 20
End Sub


Private Sub Fin_Change()
[B11] = [B3] + [B9] * Fin.Value
End Sub


Private Sub K_vco_Change()
ArrVCO = Array(-10, -5, -2, -1, -0.5, -0.2, -0.1, 0.1, 0.2, 0.5, 1, 2, 5, 10)
[B7] = ArrVCO(K_vco.Value)
End Sub


Private Sub RC_Change()
ArrRC = Array(0.1, 0.2, 0.5, 1, 2, 5, 10)
[B5] = ArrRC(RC.Value)
End Sub
```
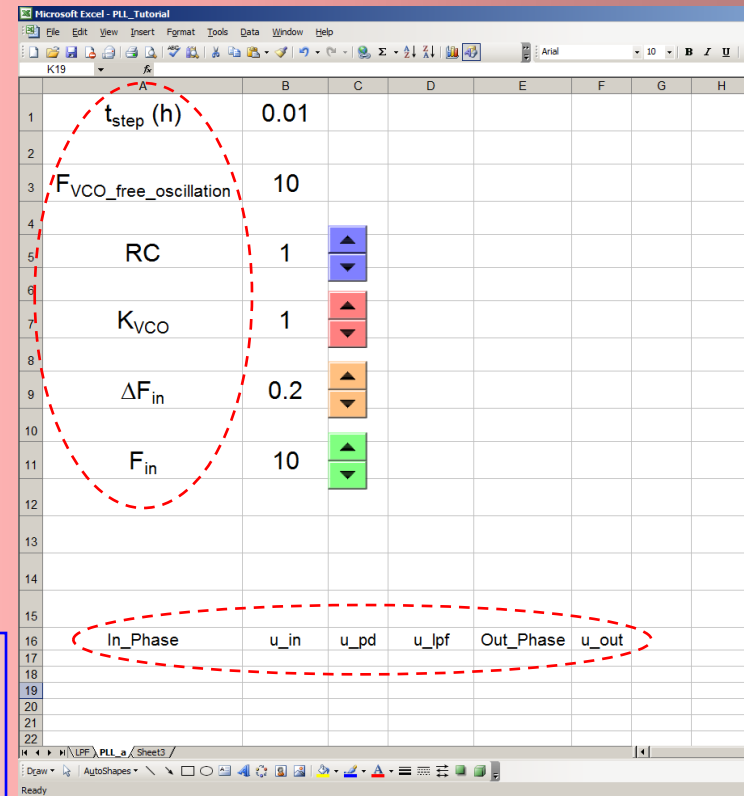
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	A	B	C	D	E	F	G	H
1	t_{step} (h)	0.01						
3	$F_{VCO\_free\_oscillation}$	10						
5	RC	1						
7	K_{VCO}	1						
9	ΔF_{in}	0.2						
11	F_{in}	10						
16	In_Phase	u_in	u_pd	u_lpf	Out_Phase	u_out		

–The last two macros use arrays to create a lookup table type of variation, the kind you can find in an oscilloscope.

–Notice that K_vco can go negative too. In this case we can see if the sign of the gain is an obstacle in the loop locking.

–Of course you can adjust the buttons and the macros to get different types of variations. I strongly encourage you to do so as an exercise.

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Implementing the calculation section

- The formulas will be calculated in the order shown by the red arrow. This is inspired by the shape of the signal path.
- It is very important to avoid circular a reference, which means a series of formulas where the last formula references the first hence resulting in a closed calculation loop.
- We need therefore to use the signal "$u_{out}(n-1)$" which is fed into phase detector as taken from the previous time step in order to avoid a circular reference.
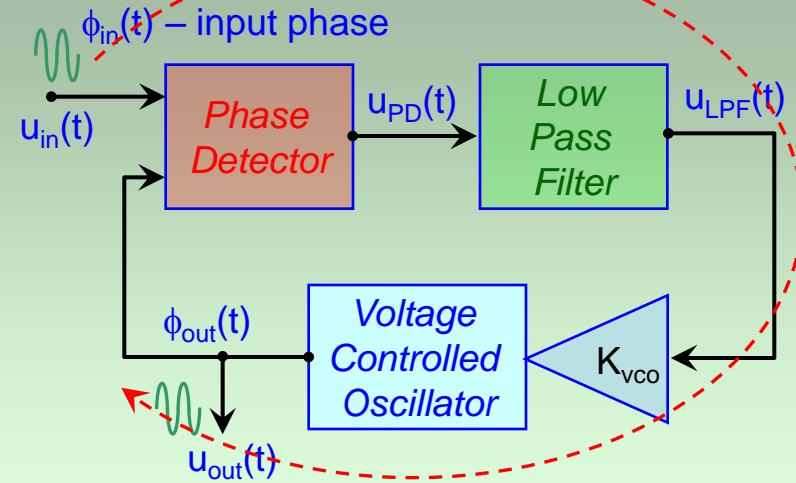
$$\varphi_{in}(n) = \varphi_{in}(n-1) + 2 \cdot \pi \cdot f_{in}(n) \cdot h$$

$$u_{in}(n) = \sin\big(\varphi_{in}(n)\big)$$

$$u_{PD}(n) = u_{in}(n) \cdot u_{out}(n-1)$$

$$u_{LPF}(n) = \frac{h \cdot u_{PD}(n) + R \cdot C \cdot u_{LPF}(n-1)}{R \cdot C + h}$$

$$\varphi_{out}(n) = \varphi_{out}(n-1) + 2 \cdot \pi \cdot \big(f_{VCO\_free} + u_{LPF}(n) \cdot K_{VCO}\big) \cdot h$$

$$u_{out}(n) = \sin\big(\varphi_{out}(n)\big)$$

The VCO frequency will deviate from its free oscillation value by an amount equal to: $\boxed{\Delta f_{VCO} = u_{LPF}(n) \cdot K_{VCO}}$

$\phi_{in}(t)$ – input phase

$u_{in}(t)$ → **Phase Detector** $u_{PD}(t)$ → **Low Pass Filter** $u_{LPF}(t)$

$\phi_{out}(t)$ **Voltage Controlled Oscillator** K_{vco}

$u_{out}(t)$

Where do the first and fifth formulas come from? By the definition, the frequency is:

in the discrete domain that approximates to:

$$freq(t) = \frac{1}{2 \cdot \pi} \cdot \frac{d\varphi(t)}{dt}$$

$$freq(n) = \frac{1}{2 \cdot \pi} \cdot \frac{\varphi(n) - \varphi(n-1)}{h}$$

During the short time step of course the above linear approximation holds true. By further developing the relationship we get:

$$\varphi(n) = \varphi(n-1) + 2 \cdot \pi \cdot freq(n) \cdot h$$

to be continued…