

## Laboratory Exercise 9.

(Last updated: 18/12/2013, Tamás Krébesz)

# Study of Analog Phase-Locked Loop (APLL)

## Required knowledge

- Operation principle of analog phase-locked-loop (APLL)
- Operation principle of the loop elements of APLL
- Operation ranges of a PLL
- Typical applications implemented by PLL (especially FM and FSK demodulators)

## Objective

The aim of the measurement is that students get familiar with the operation of the main blocks that build up a PLL, the design methods of PLLs based on Bode curves and theoretical results, measuring methods of PLLs and some typical applications. The measurement teaches some system level parameters of APLLs such as lock-in range, tracking range. Then some typical PLL based applications are measured (operation of FM/PM demodulators).

## References

The following reference/preparing materials available online via the web page of the Laboratory2 subject (<http://www.mit.bme.hu/eng/oktatas/targyak/vimia305/M09>):

- Lab2\_M9\_PLL\_application.pdf – **only pages 1-6**
- Lab2\_M9\_PLL\_slides.pdf

## Matlab help

- **help** *command*; Matlab description of *command*.
- **clear**; erase the variables and functions from memory.
- **load PD.txt**; load *PD.txt* ASCII file. It contains a matrix and it is the actual value of variable *PD*. The name of the file **.m** or **.mat** cannot be the same even without extension as the name of the file to be loaded.
- **y=PD(:,2)**; it loads the second column of the previously loaded file (that is *PD* variable now) to variable *y*.
- **x=PD(:,1)**; it loads the first column of the previously loaded file (that is *PD* variable now) to variable *x*.
- **figure**; figure window appears.

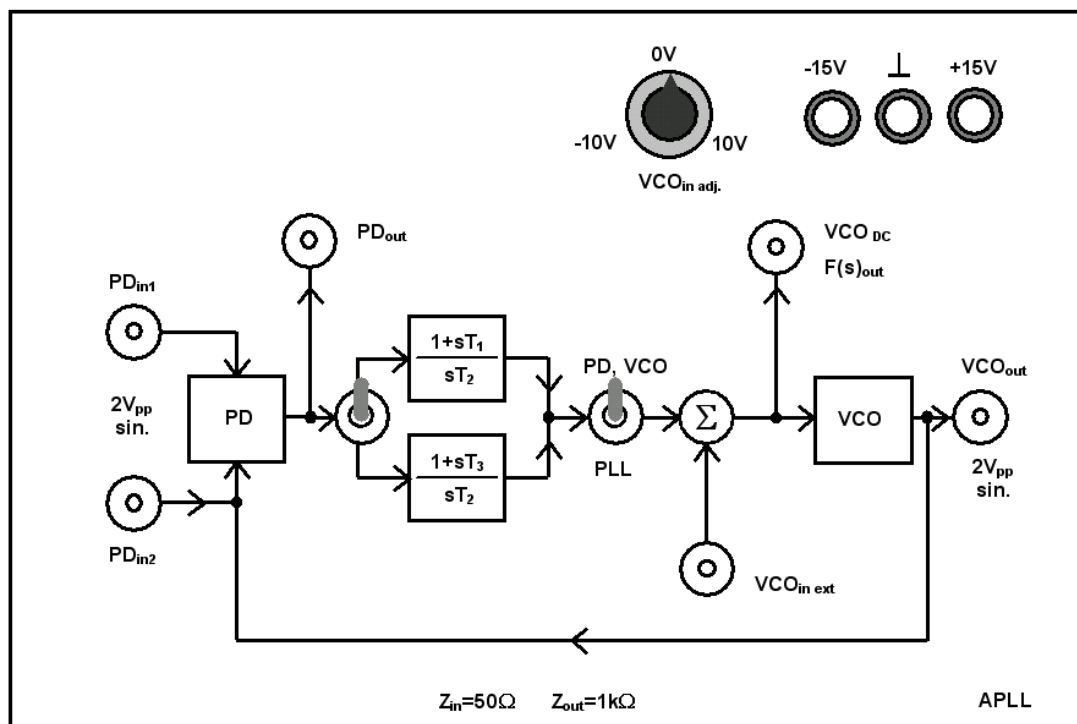
- **plot(x,y)**; plots y vector assigned to x vector (puts pairs  $x_i, y_i$  into the coordinate position x,y).
- **semilogx(x,y)**; the same as the previous except that this command uses logarithmic scale to x.
- **axis([xmin xmax ymin ymax])**; sets the maximum and minimum values for x and y coordinate axes.
- **grid**; puts such a grid to the coordinate system that fits to the axes.
- **xlabel('theta\_2[^\circ]')**; writes text to axis x.
- **ylabel('u\_d [ V ]')**; writes text to axis y.
- **title('PD curve')**; writes text to the top of the figure.
- **w=(100:10:100000)**; makes a w vector whose elements are in the interval from 100 to 100000 and the step between two consecutive elements is 10.
- **num=[K\*T1 K]**; factor of the numerator of transfer function  $(sK\tau_1+K)$ .
- **den=[1 K\*T1 K]**; factor of the denominator of transfer function  $(s^2+sK\tau_1+K)$ .
- **bode(num,den)**; returns the Bode curves.

### Measurement instruments:

Oscilloscope	Agilent 54622A
Power supply	Agilent E3630
Synchronizable function generators	Agilent 33220A-Option 001
Digital multimeter (6½ digit)	Agilent 33401A
Digital multimeter (3½ digit)	Metex ME-22T

## Test panel

Phase- locked loop (PLL) to be measured is built into a test panel. The terminals of the PLL can be accessed via BNC connectors. Test panel is shown by fig. 9-1.



9-1 Test panel

### **Power supply voltage:**

Set +15V and -15V on the power supply then connect the outputs of the power supply to the test panel inputs labeled +15V and -15V. Mind the polarity! The COMM output of the power supply has to be connected to the test panel input labeled  $\perp$ . For making connections use banana jack (also called split plug or banana pin/plug) and colored wires. It is a rule of

the thumb that red wire goes for + (now +15V) blue wire goes for – (now -15V) and common wire (or ground wire) goes for black (now COMM).

**Attention!**

***DO NOT connect any other input or output terminals of the test panel to the power supply to avoid the damage of the circuit!***

***Inputs of test panel:***

The inputs of test panel are the followings  $PD_{in1}$ ,  $PD_{in2}$  and  $VCO_{in\ ext}$  with BNC connectors.

*These inputs are matched to  $50\Omega$  therefore the output impedance of generators connected to this terminal have to be set  $50\Omega$ .*

*Parameters of signal to be connected to input  $PD_{in1}$ :*

- voltage: 2Vpp sine,
- frequency: from 75kHz to 105kHz,
- coupling: AC.

*Parameters of signal to be connected to input  $PD_{in2}$ :*

- voltage: 2Vpp sine,
- frequency: from 75kHz to 105kHz,
- coupling: AC.

*Parameters of signal to be connected to input  $VCO_{in\ ext}$ :*

- voltage: 1Vpp square,
- frequency: 100Hz,
- coupling: AC.

***Outputs of test panel:***

*The outputs of test panel are  $PD_{out}$ ,  $VCO_{DC}$   $F(s)_{out}$  and  $VCO_{out}$  with BNC terminals. These outputs are matched to  $1k\Omega$  that has to be considered during the measurements. (Output is protected against accidental shortcut by the  $1k\Omega$  resistor.)*

Signal parameters appearing at output  $PD_{out}$ :

- voltage: between -1V és +1V,
- frequency: from DC to 200kHz,
- coupling: DC.

Signal parameters appearing at output  $VCO_{DC}$   $F(s)_{out}$ :

- voltage: between -10V and +10V,
- frequency: from DC to 10kHz,
- coupling: DC.

Signal parameters appearing at output  $VCO_{out}$ :

- voltage: 2Vpp sine,
- frequency: from 78kHz to 102kHz,
- coupling: AC.

**Attention!**

**DO NOT connect any other input or output terminals of the test panel to the power supply to avoid the damage of the circuit!**

**Switch-over facilities of the test panel:**

1. The *applicable loop filter* can be chosen by the switch can be found between PD and loop filter.

Parameters of loop filter denoted by transfer function  $\frac{1 + s\tau_1}{s\tau_2}$  :

$$\tau_1 = 193 \cdot 10^{-6} \text{ [s/rad]}$$

$$\tau_2 = 43 \cdot 10^{-6} \text{ [s/rad]}$$

$$\zeta = 1$$

$$\omega_n = 11130 \text{ [rad/s]}$$

Parameters of loop filter denoted by transfer function  $\frac{1 + s\tau_3}{s\tau_2}$  :

$$\tau_3 = 45,2 \cdot 10^{-6} \text{ [s/rad]}$$

$$\tau_2 = 43 \cdot 10^{-6} \text{ [s/rad]}$$

$$\zeta = 0,25$$

$$\omega_n = 11130 \text{ [rad/s]}$$

2. Switch between loop filter and VCO is three states.

Switching toward label **PD**, **VCO** opens the loop to measure the elements of the loop unconnected from the loop (phase detector and VCO).

*Phase detector*

Reference signal should be connected to input PD<sub>in1</sub> of the phase detector while the other signal to be connected to input PD<sub>in2</sub>. Output signal of the VCO is switched off from the input of the phase detector by the switch (VCO output and PD input are not connected this way.) The output of the phase detector still can be accessed at PD<sub>out</sub>.

*VCO*

This state of the switch connects the potentiometer labeled VCO<sub>in adj</sub> to the input of the VCO. The potentiometer provides voltage from -10V to +10V. This voltage also appears at the BNC terminal labeled VCO<sub>DC</sub> for measuring purpose. The output signal of the VCO can be accessed at BNC terminal labeled VCO<sub>out</sub>.

**Attention!**

**Terminal VCO<sub>DC</sub> is not input, therefore do not connect the power supply or the generator to it!**

Switching to the middle position supports the free-running frequency of VCO.

The input of the VCO is unconnected from any input signal. The output signal of the VCO remains accessible at BNC terminal labeled  $VCO_{out}$ .

Switching toward label *PLL* closes the loop to measure the PLL.

In this position of the switch terminal  $PD_{in2}$  is unconnected from the phase detector and potentiometer is unconnected from the VCO input however the output signal of the VCO is now connected to the PD.

Reference signal should be connected to  $PD_{in1}$  input of the phase detector. The output of the phase detector is accessible at  $PD_{out}$ . The output of the loop filter is accessible at  $F(s)_{out}$ . The output of the VCO is accessible at  $VCO_{out}$ . External signal to the VCO can be connected via terminal labeled  $VCO_{in\ ext}$ .

## Laboratory exercises

### 1. Measuring of the loop elements of the APLL

The aim of the measurement is to introduce the measuring methods of the loop elements.

#### 1.1. Obtaining the PD curve

Set +15V and -15V on the power supply then connect the outputs of the power supply to the test panel inputs labeled +15V and -15V. Mind the polarity! The COMM output of the power supply has to be connected to the test panel input labeled  $\perp$ .

Connect test panel inputs labeled  $PD_{in1}$  and  $PD_{in2}$  to the outputs of the signal generators and to the oscilloscope. Connect output  $PD_{out}$  to Agilent 33401A multimeter that is set to voltage measurement.

Be careful! Reference signal goes to input  $PD_{in1}$  while the signal with altering phase goes to  $PD_{in2}$ . Switch between loop filter and VCO has to be in position labeled **PD, VCO**. (Now loop is opened and ready for measurements of loop elements.)

The phase of the signal connected to  $PD_{in2}$  has to be altered from  $-180^\circ$  to  $+180^\circ$ , the step between two consecutive phase value is  $10^\circ$ . The two signal generators have to be synchronized to each other. Read the output voltage of the PD using the multimeter connected to output  $PD_{out}$ . Record the phase and voltage values into a chart and plot it to have the PD curve (use Excel or Matlab). Calculate the transfer coefficient of the PD ( $K_d$ ). You have the necessary data for that.

Output voltage of PD is proportional to  $\theta_e$  phase error that is now  $\theta_e = -\theta_2$ .

Settings of the function generators:

- output impedance:  $50\Omega$ ,
- frequency: 90 kHz,
- amplitude:  $2 V_{pp}$ ,
- signal type: sine.

*Synchronization of phase generators and setting the phase:*

*Function generators can be synchronized by connecting External 10MHz Reference Output Terminal and External 10MHz Reference Input Terminal. Check if these terminals exist at the back.*

The reference signal should be connected to test panel input PD<sub>in1</sub> from the generator having synchronization cable at its *External 10MHz Reference Output Terminal*. Set the parameters given above at both function generators.

Set the initial phase at the function generator connected to input PD<sub>in2</sub> of the test panel as follows:

Push buttons in the following order **Utility** -> **Output Setup** -> **Adjust Phase** at the function generator. Set the signal phase of the function generator to have 0° phase difference to the signal of the other function generator. Check on the oscilloscope that the two signals are in the same phase. (The two signals overlap each other.) If it is so push button **Set 0 Phase** then this phase state is stored and this means the zero phase difference between the two function generators. Now write 90° on the function generator connected to input PD<sub>in2</sub>, set it, and push again button **Set 0 Phase**. As a result the reference signal becomes a sine while signal of the function generator connected to PD<sub>in2</sub> is a cosine (shifted with 90° to the reference). Obtain the PD curve between -180° and +180° as it was detailed before.

### 1.2. Obtaining VCO curve

Connect the VCO output to the oscilloscope and to the Agilent 33401A multimeter that is set to measure frequency. Output VCO<sub>DC</sub> should be connected to Metex ME-22T multimeter that is set to measure voltage. Set the switch between the loop filter and the VCO to position **PD, VCO**.

Adjusting potentiometer labeled VCO<sub>in adj</sub> (and this way the input voltage of the VCO) so that the frequency of the voltage appearing at the output of the VCO be changed by 2kHz in every measurement step. Measure the output frequency of the VCO by using Agilent 33401A multimeter and the input voltage of the VCO by using Metex ME-22T multimeter. Obtain the VCO curve from 80 kHz to 100 kHz with the resolution of 2 kHz (the frequency step between two consecutive frequency values is 2 kHz).

Record the frequency and voltage values into a chart and plot it to have the VCO curve (use Excel or Matlab). Calculate the transfer coefficient of the VCO ( $K_v$ ).

### 1.3. Calculating the free-running frequency of the VCO

Set the switch between the loop filter and the VCO into middle position and measure the frequency appearing at the output VCO<sub>out</sub>. Record it.

## 2. Obtaining the locking- and tracking ranges of the APLL

The aim of the measurement is to show the operating frequency ranges of the APLL.

### 2.1. Obtaining the locking range

Connect input PD<sub>in1</sub> to the output of the function generator and to CH1 of the oscilloscope then connect VCO<sub>out</sub> to Agilent 33401A multimeter set to measure frequency and to CH2 of the oscilloscope.

The switch between the loop filter and the VCO should be set into PLL position. The other switch between PD and the loop filter should be set into the upper position to

have loop filter with transfer function  $\frac{1+s\tau_1}{s\tau_2}$  in the loop.

Slowly change the output frequency of the function generator from 78 kHz to 90 kHz while continuously watching the oscilloscope waiting for the two signals be synchronized. (the frequency is the same and the phase difference between the two signals is  $90^\circ$ ). Then measure the upper locking frequency by changing the frequency of the function generator from 102 kHz to 90 kHz. Record the data.

As a final check use Lissajous measuring method. If phase locked state is valid a circle must be seen.

### 2.2. Obtaining tracking range

The connections are the same as before.

Slowly change the output frequency of the function generator from 90 kHz to 78 kHz while continuously watching the oscilloscope waiting for the two signals loose synchronization. Then measure the upper tracking frequency by changing the frequency of the function generator from 90 kHz to 102 kHz. Record the data.

As a final check use Lissajous measuring method.

## 3. Implementation of analog FM demodulator and obtaining its curve

The aim of this measurement point is to introduce some PLL based applications, furthermore to show some measuring methods of them.

Connect the input  $PD_{in1}$  to the output of the function generator, then the output  $F(s)_{out}$  to Agilent 33401A multimeter that is set to measure voltage.

The switch between the loop filter and the VCO should be set into PLL position. The other switch between PD and the loop filter should be set into the upper position to

have loop filter with transfer function  $\frac{1 + s\tau_1}{s\tau_2}$  in the loop.

Set the function generator as follows:

- output impedance: 50  $\Omega$ ,
- frequency: 90 kHz,
- amplitude: 2  $V_{pp}$ ,
- signal shape: sine.

Turn on FM modulation on the function generator and set the followings:

- signal shape: sine,
- modulating frequency: 100 Hz,
- deviation: 1 kHz.

Set the modulating frequency 100 Hz then push button **dB** to be the voltage displayed in dB. The so set voltage corresponds to 0 dB. Increase the modulating frequency of the function generator from 100 Hz to 6100 Hz with step 200 Hz and read the voltage displayed by the multimeter. This way you can obtain the transfer function of the FM demodulator. Using Excel or Matlab plot the transfer function. Measure the frequency corresponds to the -3 dB attenuation point. Give the frequency and the amplitude in dB at that point where the output of the FM demodulator provides the highest signal level.

Knowing the deviation and  $K_v$ , calculate the amplitude of the demodulated signal then compare the calculated and measured values to each other (amplitude should be given in volts).



#### 4. Implementation and measurement of digital FSK demodulator

The aim of this measurement point is to introduce PLL as a digital demodulator.

##### 4.1. Measurement in case of FSK with small deviation

Connect  $PD_{in1}$  to the output of the function generator then  $F(s)_{out}$  to the oscilloscope.

The switch between the loop filter and the VCO should be set into PLL position. The other switch between PD and the loop filter should be set into the upper position to

have loop filter with transfer function  $\frac{1 + s\tau_1}{s\tau_2}$  in the loop.

Set the function generator as follows:

- output impedance: 50  $\Omega$ ,
- frequency: 90 kHz,
- amplitude: 2 V<sub>pp</sub>,
- signal shape: sine.

Turn on FSK modulation on the function generator and make the following settings:

- modulating frequency (FSK Rate): 200 Hz,
- frequency hopping (Hop Freq.): 92 kHz.

Measure the signal by oscilloscope and save it into the measurement log.

##### 4.2. Measurement of FSK with big deviation (collapsing the locked state, generating locking transient)

Use the same measurement setup as in 5.1. but change the frequency hop to 97 kHz and measure the demodulated signal. Save the screen of the oscilloscope and explain why the locked loop collapsed and restart the locking transient.

Calculate the maximal deviation that still preserves the locked loop. Verify the calculation with measurement.