MANCHESTER 1824
The University of Manchester

Phase-sensitive demodulation and low-pass filtering
Lab manual

2017

1. Aims

- To learn the principle of phase-sensitive demodulation (PSD) and low-pass filtering
- To gain knowledge on electronic circuit design from experiment
- To be familiar with the traditional lab equipment
- To gain practical skills by building and testing electronic circuits using real components on a bread-board

2. Sessions

You MUST complete all experiment within 2 sessions, 3 hours in each session. No extra time out of the sessions can be arranged. We will record each session you attend. If you have any special reason for not being able to attend a scheduled session, you MUST inform the lecturers 2 weeks in advance so that another session may be arranged for you with a different group. **If you do not attend all lab sessions, your report will not be marked according to the School's regulation, and you will lose 20% of your final mark for this course module.** During the lab sessions, you can ask demonstrators to help. But DO NOT ask demonstrators to build circuits for you. It is your own work.

3. Equipment/components for experiment

You should have the following equipment/components as listed in Table 1. For details of the components, please read Appendix 1. For details of the equipment, please read Appendix 2.

Table 1: Equipment/components

Equipment/component	Model/value	Quantity
Triple DC power supply (±15V and +5V)	digimess HY3003-3	1
Function generator with sine-wave and square-wave (TTL) outputs	TTi TG315	1
Digital oscilloscope	Agilent DSO-X 2012A	1
Digital multi-meter (DMM)	Millennium DM441B	1
Bread-board		1
Op-amp	μA741	3
SPST quad switch	DG412	1
Inverter	74LS04	1
Resistors	10 kΩ, 160 kΩ	
Trimmer (i.e. adjustable resistor)	0-200 kΩ	1
Capacitors	0.1 μF	6

4. Principle of PSD

PSD is commonly used in signal conditioning circuits for data acquisition. Basically, two AC signals (sine-wave or square-wave) of the same frequency are input to a PSD and the output of PSD is not only the function of the amplitudes of the two signals, but also the phase difference between the two input signals. The output of a PSD consists of a DC component and high frequency harmonics. A low-pass filter (LPF) is needed to eliminate the harmonics and the remaining DC signal is the measurement.

In principle, if the phase difference between the two input signals is 0°, the output of the PSD should be positive. If the phase difference is changed to 180°, then the polarity of the output will change, from positive to negative. If the phase difference is either 90° or 270°, the output will be zero.

4.1 Overall arrangement for experiment

Fig. 1 shows the overall arrangement. A function generator (TTi TG315) is used to provide a sine-wave voltage and a square-wave voltage at the TTL level, i.e. 0-5 V. Note that the sine wave and the square wave from the function generator have 90° difference. The sine-wave signal goes through a phase shifter, which is constructed by an op-amp, so that the phase difference between the sine wave from the output of the phase shifter and the original square wave from the function generator can be adjusted.

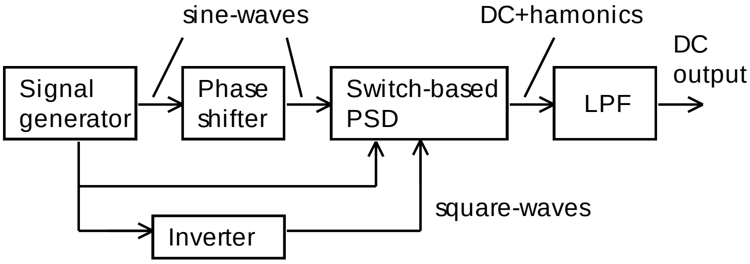


Fig. 1 Overall arrangement for experiment

In Fig. 1, there are 4 circuits to be built. Please follow the sequence.

(1) Phase shifter
(2) Inverter
(3) Switch-based PSD
(4) LPF.

The other units, which are needed for your experiment, are standard equipment, including

(1) Function generator, which supplies two signals: a sine wave and a synchronous square wave at the TTL level
(2) Triple DC power supply with ±15V and +5V outputs, providing power to all integrated circuits (IC)
(3) Digital oscilloscope
(4) DMM.

4.2. Phase shifter

Fig. 2 shows a phase shifter circuit, which is constructed using an op-amp (μA741). It has a unity gain and can give a phase shift between 0° and nearly -180°. The phase shift can be calculated by

$$\phi = -2\tan^{-1}(\omega CR) \tag{1}$$

where $\omega = 2\pi f$ and f is the input signal frequency (Hz).

The trimmer R in Fig. 2 has 3 pins. You should use the middle pin and either side pin. By adjusting R, you can vary the phase shift.

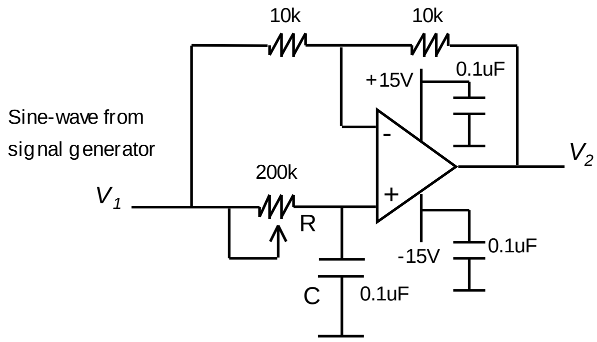


Fig. 2 Phase shifter circuit

4.3 Switch-based PSD

Fig. 3 shows a switch-based PSD circuit. It consists of an op-amp (μA741) and a single CMOS switch IC package (DG412) with 4 CMOS switches in it. The four CMOS switches are used to implement the demodulation process and these switches are controlled by two complementary square-wave signals, one from the TTL output of the function generator and the other from an inverter (74LS04). The two complementary square-wave signals drive

- *either* switches S2 & S3 to be closed (ON) and switches S1 & S4 to be open (OFF)
- *or* switches S2 & S3 to be open (OFF) and switches S1 & S4 to be closed (ON).

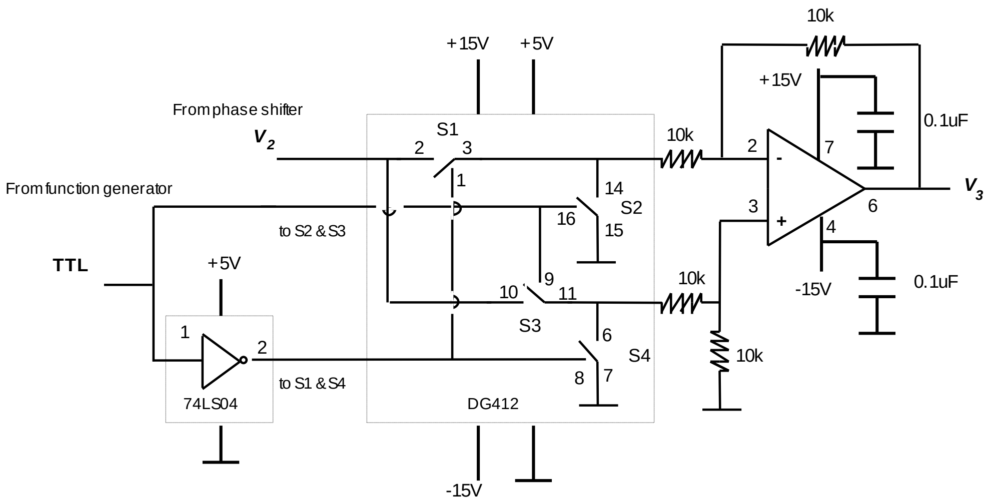


Fig. 3 Switch-based PSD circuit with pin numbers indicated

When S2 & S3 are closed (ON) and S1 & S4 are open (OFF), the PSD circuit functions as a unity-gain non-inverting amplifier. This is equivalent to multiplying the input signal by +1.

When S1 & S4 are closed (ON) and S2 & S3 are open (OFF), the PSD circuit functions as an inverting amplifier. This is equivalent to multiplying the input signal by -1. Because this type of PSD relies on switching function, it is called switch-based PSD.

4.4 LPF

Following the switch-based PSD, an LPF is used to remove high frequency harmonics. The remaining DC signal is then a function of *both* the two amplitudes *and* the phase difference between the sine wave and the square wave. Note that the square wave signal is used as a reference. With the switch-based PSD, the output of the LPF is

$$\overline{V} = \frac{2A}{\pi}\cos\phi \tag{2}$$

where, A is the magnitude of the sine wave, and ϕ is the phase difference between the sine wave and the square wave.

Fig. 4 shows a simple 1st order LPF circuit.

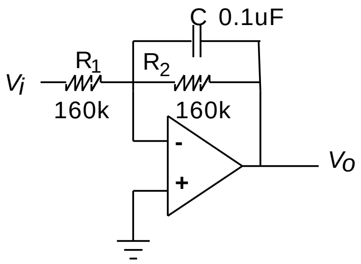


Fig. 4 1st order LPF circuit

The cut-off frequency of this filter is

$$f_o = \frac{1}{2\pi RC} \tag{3}$$

If R = 160 kΩ and C = 0.1 μF, then the cut-off frequency $f_o \approx$ 10 Hz, which is sufficiently low to eliminate the high-frequency harmonics. Because of the same input and feedback resistors used, the gain of the LPF circuit at low-frequency is 1.

Note that in your circuits, you use 3 op-amps. You should use 0.1 μF decoupling capacitors connected between the power supply pins (+15V and -15V) of each op-amp and ground to avoid coupling problems. Otherwise, you may see spike noise and/or very low frequency oscillation.

Session 1

5. Set up equipment

To avoid confusion, please use different colour as follows.

- +15V (**Red**)
- -15V (**Green**)
- +5V (**YELLOW**)
- GND (**Black**)

Please follow the procedure to set up your power supply (see Fig. 5).

(1) Without connecting any wires, switch on the power supply.
(2) Choose the series outputs using the two buttons in the middle. In this mode, the right side is a Master supply and the left side is a Slave supply.
(3) Adjust both current limits to maximum by turning the knobs clock-wise to the end.

(4) Adjust the output voltage of the Master supply to 15V. You will see that the Slave supply follows the Mater supply to be 15V, too.
(5) Switch off your power supply.
(6) Connect the analogue ground (ground for +15V) and the digital ground (ground for +5V) terminals together using a **BLACK** lead, and then connect this common ground to all other ground: function generator, DMM, oscilloscope and bread-board, as shown in Fig. 6. Note that in the series mode, the negative terminal of the Master (ground for +15V) and the positive terminal of Slave have been connected together internally. Therefore, you do not have to connect those two terminals externally.
(7) Connect power supplies (+15V, -15V, +5V) to your bread-board: **RED** for +15V, **GREEN** for -15V, **YELLOW** for +5V and **BLACK** for ground.
(8) Without connecting to any circuit, switch on the power supply, the voltage meters on the power supply panel should display 15V and 15V.
(9) Check all power supply outputs on bead-board using your DMM to make sure that they are +15V, -15V, and +5V.
(10) Switch off the power supply.

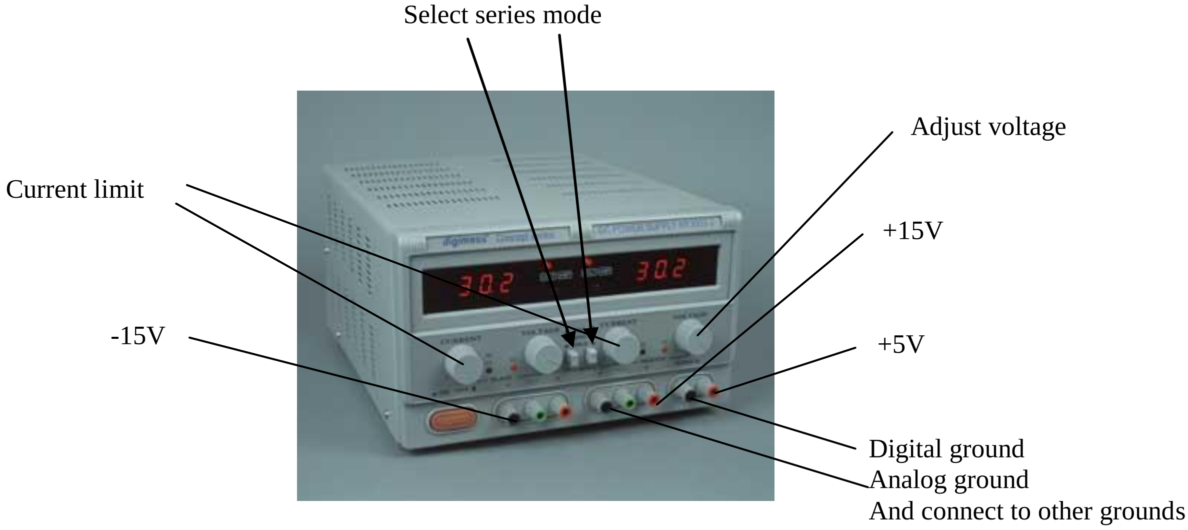
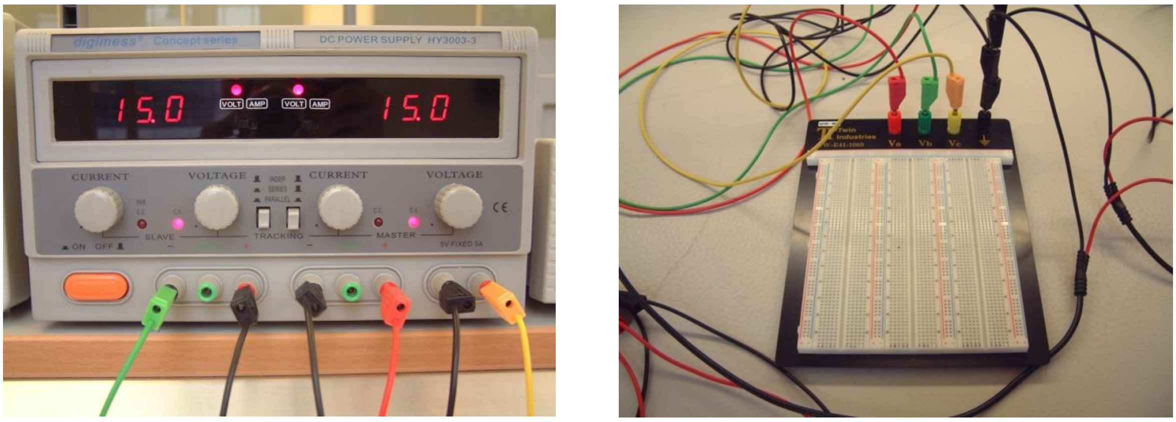


Fig. 5 Set up power supply

Fig. 6 shows the arrangement of the equipment. Please keep the positions of all equipment. Fig.7 shows the detailed connections between the power supply and the bread-board.

Fig. 6 Equipment positions



(a) Power supply (b) Bread-board

Fig. 7 Connections between power supply and bread-board

5. Experiment procedure

Now you are ready to start your experiment following the steps. The detailed circuits have been given above.

(1) Switch on your function generator. Adjust the frequency of the sine wave to 1 kHz and the amplitude of the sine wave to 2 $V_{p\text{-}p}$. Note that if you choose attenuation by pushing the far right button, it is much easier to adjust the amplitude. Examine the two waveforms using your oscilloscope. Now you can save your oscilloscope screen, showing the two signals, on your USB memory. **Note that in your report, you MUST add scales and units for each axis and indicate amplitudes, to make a scientific drawing. Otherwise, you will lose marks.**

(2) Add all pin numbers to the phase shifter circuit shown in Fig. 2 and then build the circuit. Note that each time you should build and test ONE circuit only, rather than building all circuits and test all of them together. You MUST be very careful to make connections. Otherwise, you may burn your components and/or waste time to re-check your circuits. In the past, almost all problems students had are wrong connections. **Before you switch on the power supply, please ask a demonstrator to check your power supply connections (not your circuit)**.

(3) Connect the sine-wave signal from the function generator to your phase shifter. Examine the input and output signals of the phase shifter, using your oscilloscope. Adjust the trimmer *R* in Fig. 2 to check the range of phase shift.

Measured range of phase shift: ______________________

(4) Place 74LS04 on your breadboard and connect 5V power supply to the chip. Connect the square-wave signal from your function generator to 74LS04. Examine the two square-wave signals from the inverter and the function generator, using your oscilloscope. Your oscilloscope screen showing the two signals can be saved to your USB memory. The two signals should be complimentary.

(5) Add missing pin numbers to the PSD circuit shown in Fig. 3 and then build the circuit. Note that for your CMOS switch DG412, you need three power supplies, +15V, -15V and 5V. Connect the sine-wave signal **from your phase shifter** (not the original sine wave from the function generator) and the two square-wave signals to your PSD. **Before you switch on the power supply, please ask a demonstrator to check your power supply connections.** Examine the output signal from the PSD against the square wave. Save your oscilloscope screen, showing the two signals, to your USB memory.

Session 2

(6) Adjust the phase shifter to make sure the phase difference between the output sine wave and the square wave is **either 0° or 180°**. Note that if the phase is 0°, the waveform should look like a signal from a full-wave rectifier (head up). If the phase is 180°, it should be head down. Save your oscilloscope screen, showing the output of the PSD against the square wave from the function generator, to your USB memory. **Note that you just need to show either 0° or 180°.**

(7) Adjust the phase shifter to make sure the phase difference between the sine wave and the square wave is **either 90° or -90°**. Save your oscilloscope screen, showing the output from the PSD and the square wave from the function generator, to your USB memory. **Note that you just need to show either 90° or -90°.**

(8) Add all pin numbers to the LPF circuit shown in Fig. 4 and build the circuit. Note that when you test the frequency response of your LPF circuit, you need to connect the input of the LPF circuit to the sine-wave signal of the function generator directly, NOT your PSD circuit. Switch on your function generator. Examine the amplitude-frequency response of the LPF circuit using the dual-track oscilloscope. Note that to draw a Bode plot you have to use a log scale for frequency in the x-axis and you have to calculate your amplitude response by $20\log\frac{output}{input}$. Because of the log-scale for frequency, you can choose the following frequencies for your test: 1, 2, 4, 6, 10, 20, 40, 60, 100, 200, 400, 600, and 1000 Hz.

(9) Find the cut-off frequency (-3 dB) by changing the frequency and write down the frequency and amplitude at this point.

Connect the LPF circuit to the output of your PSD, and measure the DC values using your DMM when the phase difference between the sine wave and square wave is 0º or 180º and 90º or 270º. Fill in the DC values in Table 2. Note that you just need two values for Table 2.

Table 2: DC value with different phase

Phase difference	0º/180º **	90º/270º **
DC value		

** Delete one as appropriate

7. Report

For your lab report, DO NOT write more than 6 pages (excluding an additional page for a complete circuit diagram). Please use the cover page template (page 10 in this document). On your cover page please include your name, your registration number, and the dates you attended your lab. In the main report, you should include

(1) Aims of the experiment (Use your own words. Do not copy from this manual)
(2) Draw a complete circuit diagram (**functional as shown in Figs. 2, 3 and 4, not layout**) **by hand** (because in the past some students made copy from other students), showing all individual circuits and connections between them, including all power supply, pin numbers and decoupling capacitors. DO NOT use Multisim to draw the circuits as the electronic drawing can be easily copied. **Note that only the circuit diagram should be drawn by hand and your report should be typed and printed. If you include an electronic version of your drawing (even hand drawing), you will lose mark.**
(3) Experimental results (**not simulation results**) and data analysis, including all waveforms captured and explanation. Note that you must add X-Y axis, scales and units and indicate amplitudes.
(4) Calculate the frequency response of your LPF and compare the calculated data with your measured results. List all results, including relative errors in percentage in Table 3.

Table 3: Frequency response of LPF

Frequency (Hz)	Input ($V_{p\text{-}p}$)	Measured output ($V_{p\text{-}p}$)	Theoretical output ($V_{p\text{-}p}$)	Relative error $= \frac{\text{Experimental value - Theoretical value}}{\text{Theoretical value}} \times 100\%$	Measured $20\log\frac{output}{input}$ (dB)	Theoretical $20\log\frac{output}{input}$ (dB)
1						
2						
4						
6						
10						
20						
40						
60						
100						
200						
400						
600						
1000						

(5) Draw Bode plots together according to both the experimental results and the theoretical values. Note that in a Bode plot, both x-axis and y-axis are in log scale.

(6) Answer the following questions:

Question 1: If -90° phase shift is required for a 1 kHz sine wave, calculate the resistor value of the trimmer *R* in Fig. 2 and show the detailed calculation procedure. Note that for engineering, 3 digits are sufficiently accurate.

Question 2: If you have seen 0° PSD signal, how can you obtain 180° PSD signal? Or if you have seen 180° PSD signal, how can you obtain 0° PSD signal?

Question 3: With a cut-off frequency of 10 Hz of the LPF as shown in Fig. 4, calculate how many times a 1 kHz signal is attenuated? If the cut-off frequency is increased to 100 Hz, how many times is the signal attenuated?

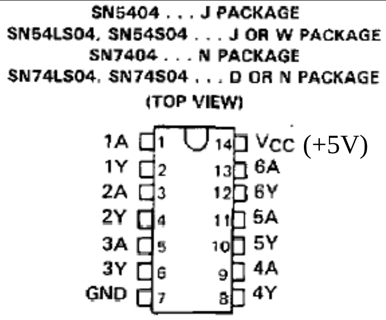
Question 4: What is the theoretical DC output of the above PSD if the phase angle is 60°.

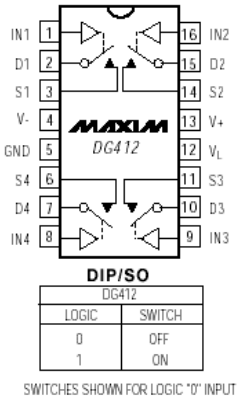
(7) Conclusions.

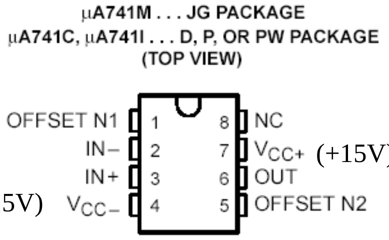
8. Marking scheme

Aspect	**Detail**	**Professional**	**Average**	**Poor**	**Very poor**
(1) Experiment results and analysis	• Good analysis of experimental results • Present results/graphs professionally with all scales and units	8	6	4	2
(2) Hand-drawing	• Clear hand-drawing of all circuit diagrams • Professionally presented	4	3	2	1
(3) English writing and layout	• Good English without oral language • Professional layout	4	3	2	1
(4) Answer questions	• Answer all questions independently	4 (1 mark for each question)			
Prior conditions	• Attended two lab sessions • Evidence that all experiments were completed • No copy from others, including lab instruction manual • No more than 6 pages • Submitted lab report on time. No mark for late submission				
Full marks	**20**				

Appendix 1: Details of components used for experiment

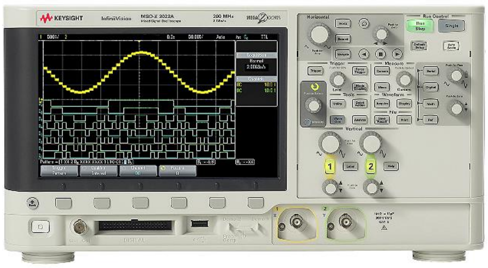
<table>
<tr>
<td>


(+5V)
74LS04
A -- input, Y -- output
</td>
<td rowspan="2">
(-15V)


(+15V)
(+5V)
DG412
</td>
</tr>
<tr>
<td>


(+15V)
(-15V)
µA741
</td>
</tr>
</table>

Appendix 2: Equipment

digimess HY3003-3 Power supply http://www.digimess.co.uk/datasheet/english/Digimess%20HYseries.pdf	
TTi TG315 Function generator http://www.ttid.co.uk/products-tti/generator/tg300.htm	
Agilent DSO-X 2012A digital oscilloscope http://www.keysight.com/en/pd-1945059-pn-DSOX2012A/oscilloscope-100-mhz-2-channels?&cc=GB&lc=eng	
Millennium DM441B Digital multi-meter http://www.sjelectronics.co.uk/acatalog/SJ_Electronics_DM441B_1354.html	

Coursework: PSD lab (ECDII – EEEN20025)

Name:	Group:
ID:	PCB / Breadboard (delete as appropriate)
Lab Date:	Report date:

R	
E	
D	
A	
total	