Mechanical Engineering Experiment (I) teaching manual

Unit 1 and 2-Introduction to basic laboratory instruments and operational amplifier

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Introduction

In the first two units, we will introduce some basic laboratory instruments and electrical elements which will be applied during this course. Experiments for the first two units will be separated into three parts. For the first part, students will practice applying a digital multimeter and a power supply and distinguish the characteristics of direct current (DC) voltage from alternating current (AC) voltage. In the second part, we will define several wave characteristics, and then practice applying an oscilloscope and a function generator to measure these characteristics of an artificial wave. For the last part, an important circuit element－operational amplifier (OP-amp) and its working principle will be introduced clearly. Students can observe its function through an inverting circuit.

Part 1-1. Voltage and current

Among all electronic products in your daily life, we always provide an energy source to drive or charge them. The energy source, which is the so-called “voltage”, must be familiar to you. When we plug electronic products into a socket, we create a circuit which has an electrical potential to drive electrons to your products. We can then define the <u>*electrical potential difference between two arbitrary points*</u> as “voltage” and is usually stated by the symbol *V* with the unit Volts. The movement of electrons then produce a “current”, which can be defined as the <u>*rate of flow of electric charge*</u>, and is usually stated by the symbol *I*. The current can be described by formula (1):

$$I = \frac{dq(t)}{dt} \qquad (1).$$

In formula (1), q(t) represents the quantity of electric charge which has the unit Coulomb (*C*, one electron carries $-1.602 \times 10^{-19} C$), while the unit for current is Ampere (*A*, *A*=*C/seconds*). For an ideal conductor, Ohm (1827) revealed that the voltage should be proportional to the current with a material constant *R*:

$$V = IR, \qquad \text{Ohm's law, (2).}$$

In formula (2), R represents the resistance of conductor and is a material constant, for those materials who disobey the Ohm's law, we define them as a non-ohmic material.

Since we already defined the current in formula (1), we can then distinguish the direct current (DC) from the alternating current (AC) by **Fig.** 1.1. A DC current represents a constant current so that $dI/dt = 0$, while an AC current possesses an alternating current which can be described by wave functions.

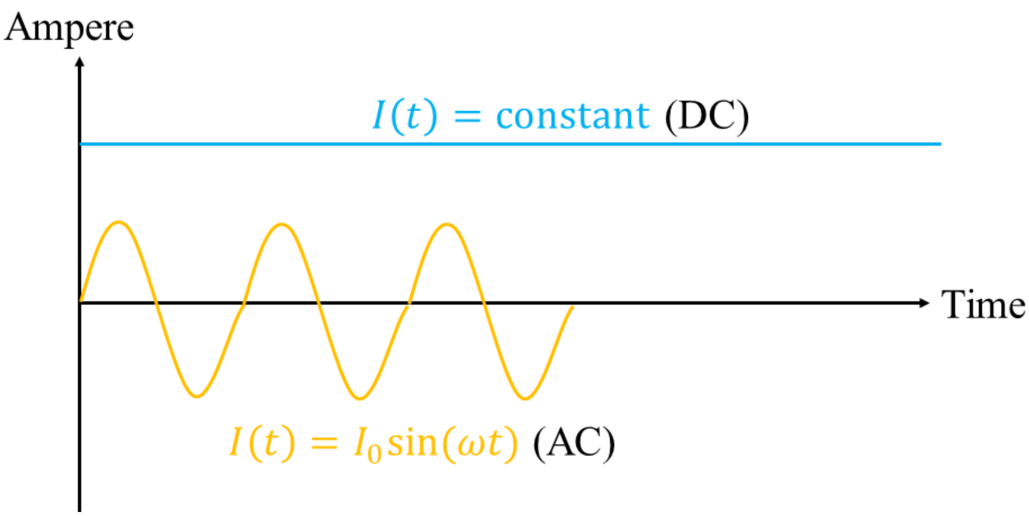


Figure 1.1. Definition of direct current (DC) and alternating current (AC).

Part 1-2. Equivalent estimations between AC current and DC current

Since we usually describe the AC current with a wave function, it is necessary to derive equivalent estimations between the AC current and the DC current. The first estimation is average current (I_{avg}). The average current of an AC current is defined as *the quotient area under a waveform with respect to its period*. Consider an AC current which can be described by a sinusoidal wave with a peak value I_0 and without any offset:

$$I(t) = I_0 \sin(\omega t) + offset; \;\; \omega = 2\pi/T\,, offset = 0 \qquad (3).$$

In formula (3), T represents the period of the wave function. The analytic expression of average current should then be:

$$I_{avg} = \frac{1}{T}\int_0^T I(t)dt = \frac{1}{T}\int_0^T I_0 \sin(\omega t)dt \qquad (4).$$

Since the sinusoidal wave is a symmetric function, let's consider half of the period ($T/2$) first. We can rewrite formula (4) as:

$$I_{avg}\ in\ half\ period = \frac{2I_0}{T}\int_0^{0.5T}\sin(\omega t)dt = \frac{2I_0}{T}\left(\frac{-\cos(\omega t)}{\omega}\Big|_0^{0.5T}\right) \quad (5).$$

With $T = 2\pi$ and recall from formula (3) that $\omega = 2\pi/T$, formula (5) can be calculated by:

$$I_{avg}\ in\ half\ period = \frac{I_0}{\pi}\{-\cos(\pi) + \cos(0)\} = \frac{2I_0}{\pi} \approx 0.637I_0 \quad (6).$$

From formula (6), we can infer that for a sinusoidal wave function without any offset, the average current in the first half period will be 0.637 times of its peak value I_0.For the latter half period, we can easily calculate from the same procedures and obtain a negative value -0.637I_0. Therefore, the total average current over one period for a non-offset sinusoidal wave will be zero. A schematic diagram for the definition of average current is shown in **Fig.** 1.2.

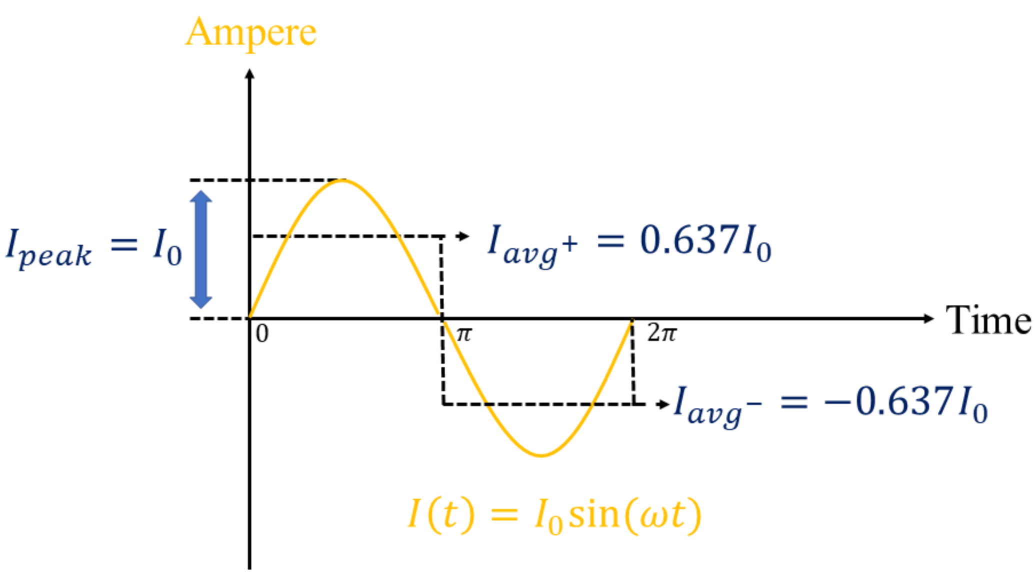


Figure 1.2. The average value of an alternating current (AC) over half period.

The second estimation is called the root-square-mean current (I_{RMS}), which is also known as the effective current (I_{eff}). To understand what is *RMS* current, we need to define the electric power first. The electric power is defined as the *<u>rate of consumed energy in a circuit</u>*. For a DC current under a certain resistance, the power can be described as $P_{DC} = I_{DC}^2 R$. Follow the same method, we can easily infer that the power for an AC current will be:

$$P_{AC} = I^2(t)R = I_0^2\sin^2(\omega t)R \quad (7).$$

The *RMS* value of an AC current is then defined as *<u>the average AC power which can produce **the same heating effect** as the equivalent DC power under the same resistance R</u>*, that is:

$$P_{RMS} = \overline{P_{AC}} = I_{RMS}^2 R \quad (8).$$

Again, we need to derive an equivalent estimation between I_{RMS} and I_{DC}. Let's assume we have an AC current as shown in formula (3). Follow the similar definition for average current, we can define the average power as the quotient area of instant AC power over a period *T*:

$$\overline{P_{AC}} = \frac{1}{T}\int_0^T P(t)dt = \frac{1}{T}\int_0^T I_0^2 \sin^2(\omega t) R dt \quad (9).$$

With $T = 2\pi$, $\omega = 2\pi/T$, and $\sin^2(\omega t) = \{1 - \cos 2(\omega t)\}/2$, formula (9) can be rewrote as:

$$\overline{P_{AC}} = \frac{I_0^2 R}{T}\int_0^T \sin^2(\omega t)dt$$

$$= \frac{I_0^2 R}{2\pi}\left\{\int_0^{2\pi} \frac{1}{2}dt - \int_0^{2\pi} \frac{\cos(2t)}{2}dt\right\}$$

$$= \frac{I_0^2 R}{2\pi}\left\{0.5t - 0.25\sin(2t) \Big|_0^{2\pi}\right\}$$

(10).

Since integrating for any sinusoidal function over a completer period 2π will be zero, formula (10) will be:

$$\overline{P_{AC}} = \frac{I_0^2 R}{2} \quad (11).$$

Combine formula (8) with formula (11), the *RMS* value for the AC current is:

$$I_{RMS}^2 R = \frac{I_0^2 R}{2}, I_{RMS} = \frac{I_0}{\sqrt{2}} \approx 0.707 I_0 \quad (12).$$

From formula (12), we can infer that for a sinusoidal wave function without any offset, the *RMS* value will be 0.707 times of its peak value I_0.A comparison between the *RMS* value of AC current and the average current is shown in **Fig.** 1.3.

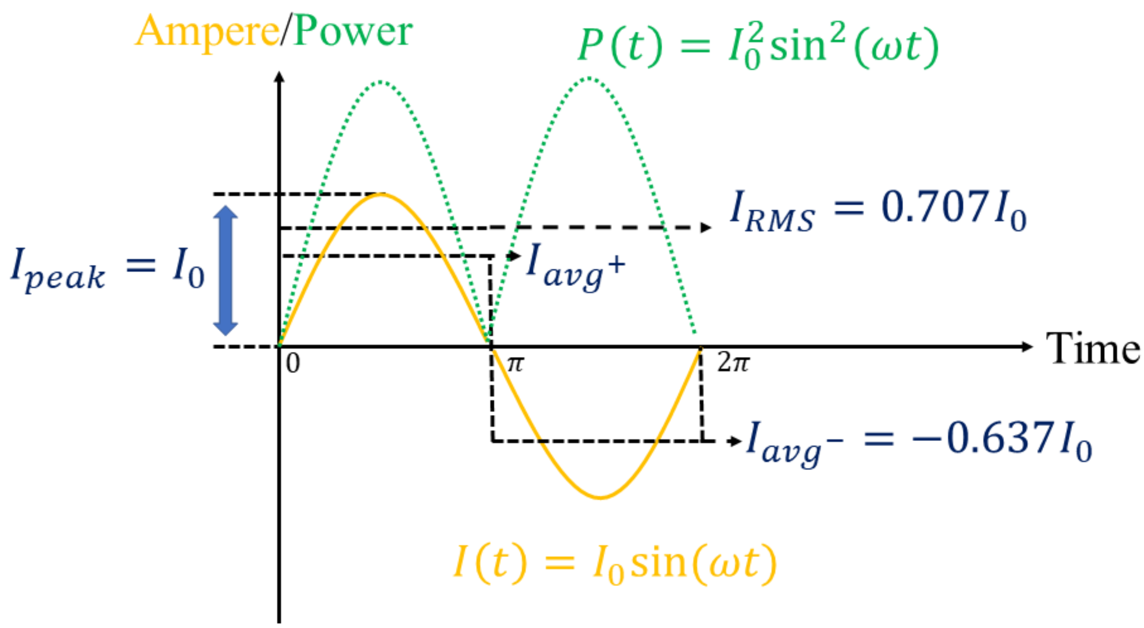


Figure 1.3. The *RMS* value of an alternating current (AC).

At last, we can derive the *RMS* value of a general AC current with an offset $I_1$and a peak value I_2: $I(t) = I_1 + I_2\sin(\omega t)$. Follow the definition of average power shown in formula (9), we know:

$$\overline{P_{AC}} = \frac{1}{T}\int_0^T P(t)dt = \frac{1}{T}\int_0^T I^2(t)Rdt = \frac{R}{T}\int_0^T\{I_1^2 + I_2^2\sin^2(\omega t) + 2I_1I_2\sin(\omega t)\}dt \qquad (13).$$

With $T = 2\pi$ and $\omega = 2\pi/T$, formula (13) can be rewrote as:

$$\overline{P_{AC}} = \frac{R}{2\pi}\{I_1^2t + 0.5I_2^2t - 0.25I_2^2\sin(2t) - 2I_1I_2\cos(t)\big|_0^{2\pi}\} \qquad (14).$$

Since integrating for both sinusoidal and cosine function over a completer period 2π will be zero, formula (14) can be simplified:

$$\overline{P_{AC}} = I_{RMS}^2R = I_1^2R + 0.5I_2^2R \qquad (15).$$

The offset I_1 of formula (15) is a constant current, so we can treat the first term I_1^2R as the DC power, while the second term $0.5I_2^2R$ is the *RMS* power from a non-offset wave as shown in formula (11). We can then conclude that for a general current function which can be departed into a DC component and an AC component, the *total RMS power will be the summation of power from each component*. For an ideal conductor which has the same resistance *R*, formula (15) can be simplified by the Ohm's law so that the voltage relation will be:

$$V_{RMS}^2 = V_{DC}^2 + V_{AC,RMS}^2 \qquad (16).$$

Part 1-3. Digital multimeter and power supply

To measure the current and the voltage of electrical elements within a certain circuit, or measure the resistance for a conductor; digital multimeter is one of the most common laboratory instruments. The currently applied multimeter for this course and its matching wires are shown in **Fig.**1.4. Matching wires will be inserted into junctions of multimeter and touch elements with probes (or crocodile clips), instant readings will then reveal on the screen with a desired unit, which is set by the central dial.

Figure 1.4. The multimeter and the matching wires (probes or crocodile clips).

To activate a circuit or an electrical element, we usually apply a power supply in laboratory instead of applying the AC voltage from wall sockets. Because the safety voltage limitation of experimental instruments, which protects them from overload, are usually much smaller than the official AC voltage (110V or 220V).

A DC power supply can offer DC current and voltage with much smaller magnitudes (usually less than 10A and 60V, respectively). There is also an AC-to-DC power supply which can convert the official AC voltage to a desired DC magnitude. The currently applied DC power supply of our lab is shown in **Fig.**1.5. More operation guides for digital multimeter and power supply will be provided in the later laboratory manual.

Figure 1.5. The currently applied power supply of our course.

Part 2-1. Measurement of wave characteristics

In the previous part, we apply a sinusoidal function to describe current and voltage. In part 2, we will introduce two commonly applied wave functions: the triangle wave and the square wave. There exist many analytical expressions for triangle wave and square wave. Here we are going to introduce the Fourier series approach, which describes both waves with an infinite summation series of sinusoidal function. Symmetric triangle wave and square wave with *period: 2π* and *peak value: 1* can be approached by formula (17) and (18), respectively:

$$f(x) = \frac{8}{\pi^2}\sum_{n=1,3,5\ldots}^{\infty}\frac{-1^{0.5(n-1)}}{n^2}\sin(nx) \tag{17}$$,

$$f(x) = \frac{4}{\pi}\sum_{n=1,3,5\ldots}^{\infty}\frac{1}{n}\sin(nx) \tag{18}$$.

Derivation details for both formulas will not be included in this manual, but can be obtained in the reference [5] and [6]. Moreover, a wave simulator is provided in the reference [7], which reveals the transient wave forms for both waves with different amounts of summation terms (n) in formula (17) and (18). Results of the wave simulator are shown in **Fig.** 2.1(a) and (b), the red line represents the superposed wave while the blue one indicates the ideal wave.

(a) (b)

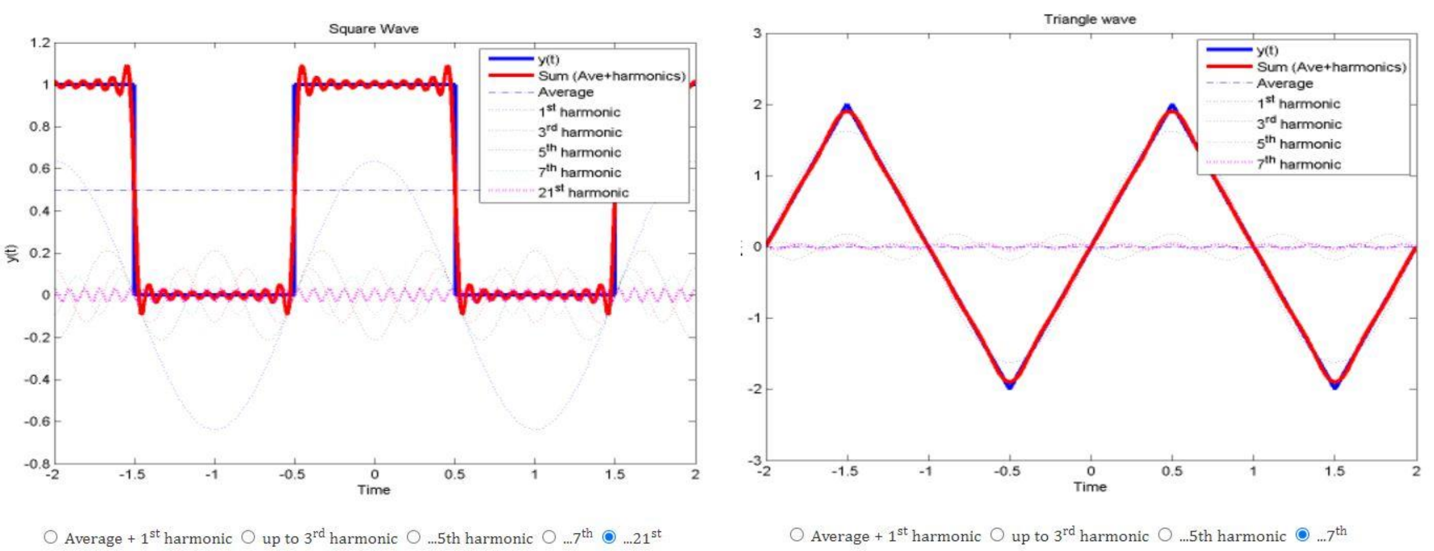


Figure 2.1. (a) The superposed square wave with 21 summation terms, and (b) The superposed triangle wave with 7 summation terms.

For a wave function, we usually describe its wave characteristics with the following parameter list. We will separate the wave characteristics into two groups: the voltage-relevant group and the time-relevant group.

Voltage-relevant

1. Peak voltage (V_p or $V_{\max}$): The most positive magnitude of a wave with respect to the ground. Ground usually indicates the zero-voltage reference.
2. Minimum voltage ($V_{\min}$): The smallest magnitude of a wave with respect to the ground.
3. Peak to peak voltage (V_{pp}): The voltage difference between peak voltage and minimum voltage.
4. Average voltage ($V_{average}$ or V_{DC}): The time-averaged voltage within a period. For a symmetric superposed wave function, the average voltage will be the offset part: $\underline{\boldsymbol{I_1 R}}$ + $I_2 R\sin(\omega t)$.
5. AC voltage (V_{AC}): The AC component of a superposed wave $I_1 R$ + $\underline{\boldsymbol{I_2 R}\,\mathbf{sin}(\boldsymbol{\omega t})}$.
6. *RMS* voltage (V_{RMS}): The voltage for a superposed wave which produces the same heat as the equivalent DC voltage. It will be the summation of DC component and AC component: $I_1^2 R + 0.5 I_2^2 R$.
7. Crest factor (*CF*): Crest factor of a wave is defined as V_p/V_{RMS}. Crest factor offers an estimation on the maximum consumed power of different waves with respect to the *RMS* voltage. Here is a simple example, consider a sine wave with the same peak voltage as a triangle wave, you can derive a different *RMS* value for the triangle wave follow formula (9) to (11). Therefore, they will produce different crest factor.

Comparisons between different voltage-relevant characteristics are shown in **Fig.** 2.2.

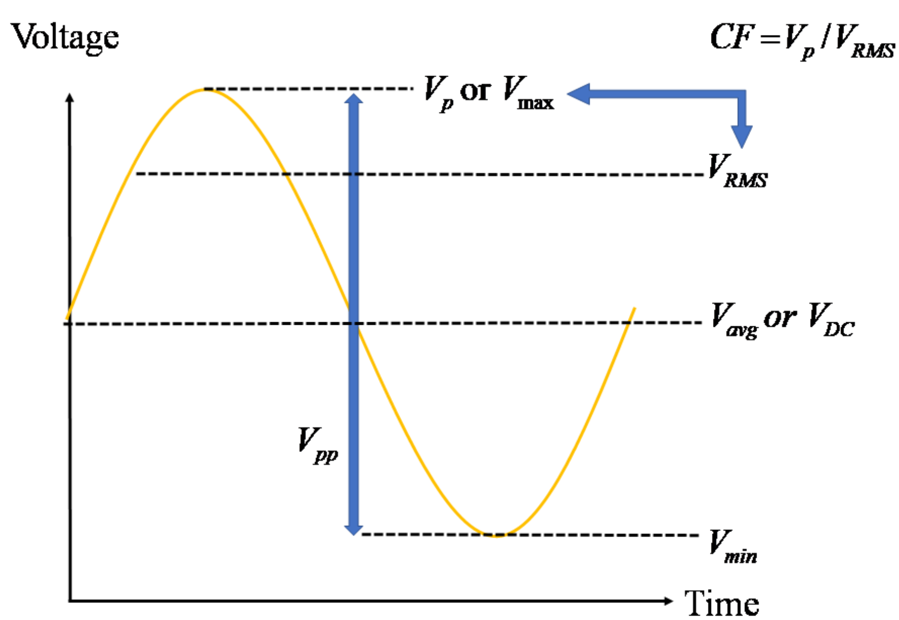


Figure 2.2. Definitions of voltage-relevant characteristics in a symmetric wave.

Time-relevant

1. Period (T): The time over which the wave function completes one cycle.
2. Frequency (f): Frequency of a wave is defined as reciprocal of the period: $f = 1/T$.
3. Phase / Phase difference: The elapsed time of a point with respect to the start instant ($t = 0$) or any reference points of a wave function.
4. Rising time: The time taken by a wave to ascend from a specific low value to a certain high value. Here we defined the interval as 10% to 90% of an assigned peak value.
5. On-time (T_{on}): The time for which the wave is in its "on" state, which is usually defined as the duration of a wave after exceeds 50% of its peak value and descends back to the same magnitude.
6. Duty cycle (D): Estimated by T_{on}/T. A higher duty cycle of a wave indicates a higher average voltage.

Comparisons between different time-relevant characteristics are shown in **Fig.** 2.3.

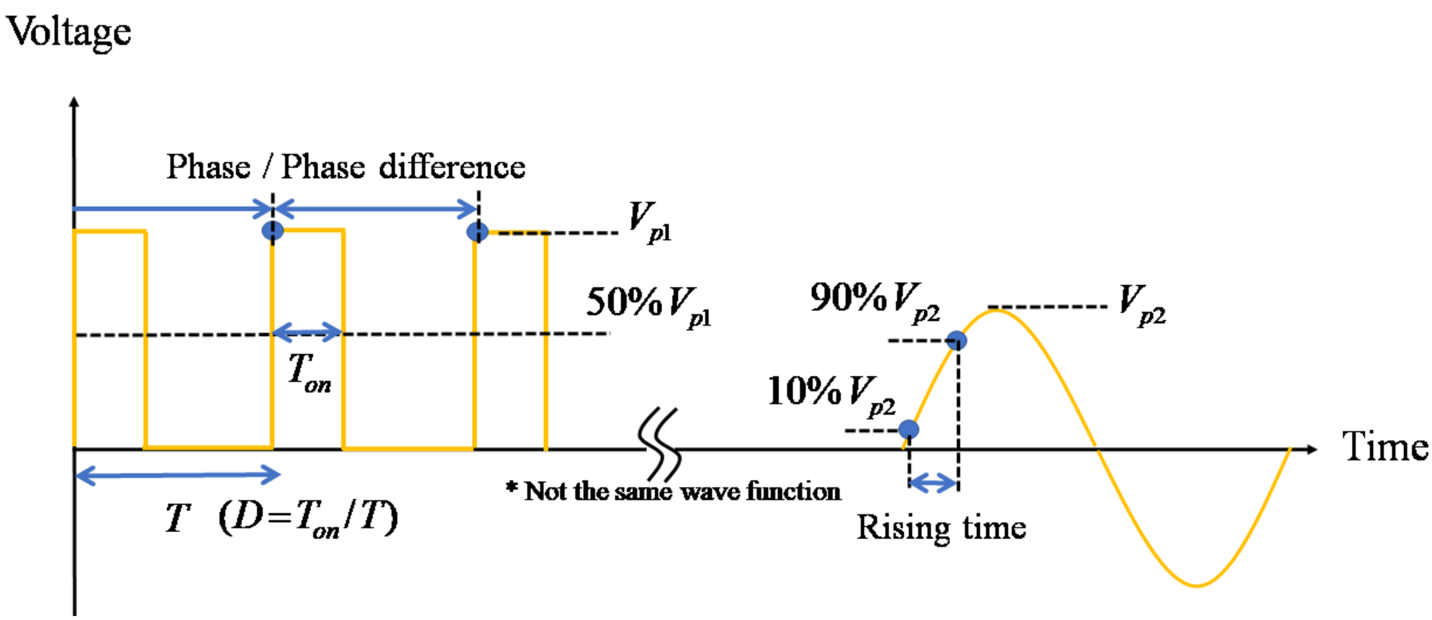


Figure 2.3. Definitions of time-relevant characteristics in a wave.

Part 2-2. Function generator and oscilloscope

In section 2-1, we have learned both the triangle wave and the square wave can be superposed analytically by sinusoidal functions. To produce different types of analog signal, function generator is a frequently applied laboratory instrument. During our experiment units, we apply function generator *GFG-8020H* as shown in **Fig.** 2.4(a). We can alter the signal type (square, triangle, or sinusoidal) with assigned frequencies (100 Hz~2.5M Hz). Moreover, we can also define the duty, the offset, and the amplitude, or even produce *TTL* signals. *TTL* signals will not be applied during our course, but you can learn more about this kind of signal in reference [11]. To connect function generator with other instruments, we will apply the *BNC* wires with a clip (or *BNC*) head as shown in **Fig.** 2.4(b).

(a) (b)

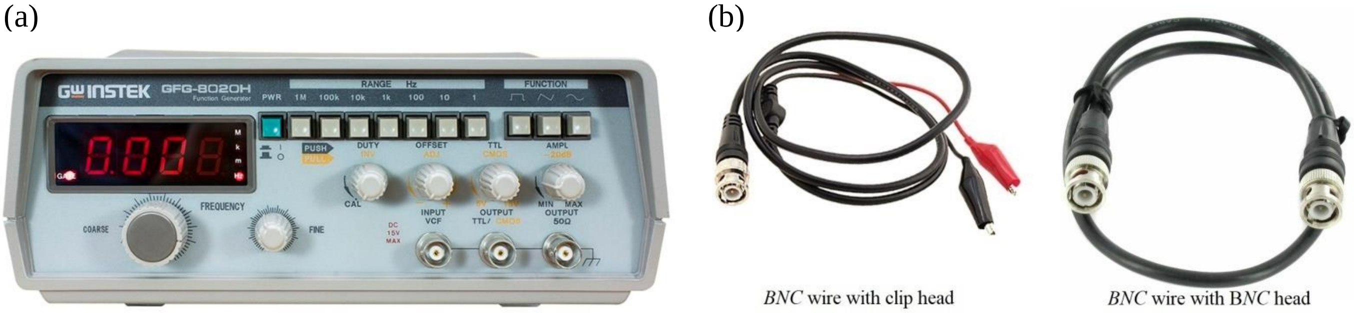


Figure 2.4. (a) The *GWG-8020H* function generator by GW Instek corp., and (b) different BNC wires.

To observe the resulting signals produced by the function generator, oscilloscope will be applied to connect with the output junctions of function generator by a *BNC-BNC* wire as shown in Fig 2.4(b). In the oscilloscope, we can adjust our observation scale for both amplitude (the *y*-axis) and time (the *x*-axis) to measure the wave characteristics precisely, and the results will be shown on the main screen. It should be noted that the oscilloscope can only measure wave characteristics of a signal segment <u>*contained in the main screen*</u>. Therefore, a proper scale adjustment to obtain correct measurement is necessary. More operation guides for function generator and oscilloscope will be provided in the later laboratory manual and our laboratory oscilloscope is shown in **Fig.** 2.5.

Figure 2.5.The *GOS-1152A-U* oscilloscope by GW Instek corp.

Part 3-1. What's an operational amplifier?

In the last part, we will introduce an important electrical element in modern circuit design: operational amplifier (OP-amp). An operational amplifier is applied to enhance the input potential difference with certain assigned output gain, which is typically larger than 10^5. In laboratory, we can create any equivalent gains via a simple circuit.

An 8 pins operational amplifier LM 741 and its circuit symbol are shown in **Fig.** 3.1. V_{input} represents the input potential difference while V_{output} is the resulting enhanced output. Besides, LM 741 requires an external source to activate and is marked by V_{supply}, which is usually ignored in a circuit diagram.

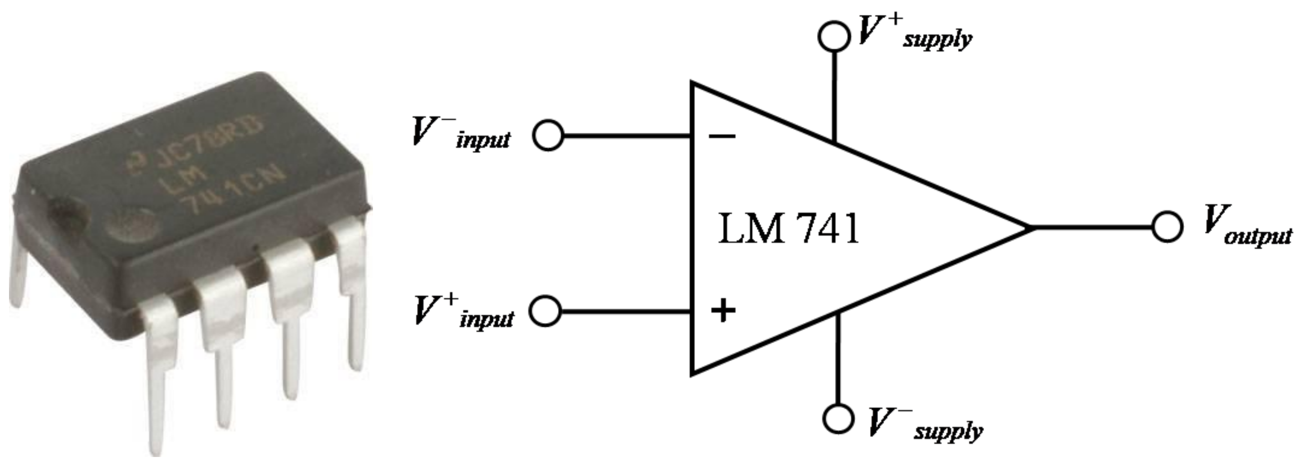


Figure 3.1. The LM 741 operational amplifier (left) and its circuit symbol (right).

Part 3-2. Derivation for an inverting circuit

In this week experiment, we will introduce one of the special applications of LM 741, which is known as the inverting circuit and observe its influence on input signal. Moreover, we will add a low pass filter to the inverting circuit to observe its effect. To fully understand the working principle of inverting circuit, let's begin with two basic rules: Kirchhoff's current law (*KCL*) and Kirchhoff's voltage law (*KVL*). Consider a circuit diagram as shown in **Fig.** 3.2, which contains a voltage source and three electrical elements marked by *A*, *B*, and *C*, respectively, each element possesses a voltage difference ($V_A, V_B,$ and V_C) and a working current (I_A, $I_B,$ and I_C).

Kirchhoff's current law (*KCL*) defines <u>*the net current through a node must be always zero*</u>. For example, for the node 1 which locates at the upper junction between three elements, we can assume the current direction as indicating by the arrow direction, *KCL* assigns a positive value for the inflow current and a negative value for the outflow current, therefore, apply *KCL* to node 1 we can obtain:

$$I_{\mathrm{A}} - I_{\mathrm{B}} - I_{\mathrm{C}} = 0 \tag{19-a}$$

A similar relation could also be obtained by applying *KCL* to node 2:

$$-I_A + I_B + I_C = 0 \tag{19-b}$$

Readers should be noted that in *KCL*, there are no restrictions for current directions, we will finally obtain a positive magnitude for the correctly assumed direction while a negative magnitude for the opposite one.

As for Kirchhoff's voltage law (*KVL*), it defines *the algebraic summation of voltages should be zero within any closed paths*. A closed path can be defined as a loop within a circuit. The red arrows in **Fig.** 3.2 reveal three loops for this circuit, two internal clockwise loops and an external counter-clockwise loop. *KVL* for the left clockwise loop can be described as:

$$-V_s + V_A + V_C = 0 \tag{20-a}$$

and for the right clockwise loop will be:

$$-V_C - V_B = 0 \tag{20-b}$$

at last, for the counter-clockwise loop:

$$V_B - V_A + V_s = 0 \tag{20-c}$$

Like *KCL*, loop direction for *KVL* can be defined freely, **but** *KVL* requires a strict definition on voltage. For a potential difference which already defines both end (positive vs. negative) specifically, the *KVL* voltage will be **positive** if the loop passes the element **from its positive end to negative** end (V_A, and V_C of formula (20-a), V_s of formula (20-c)), and will be negative in the opposite way.

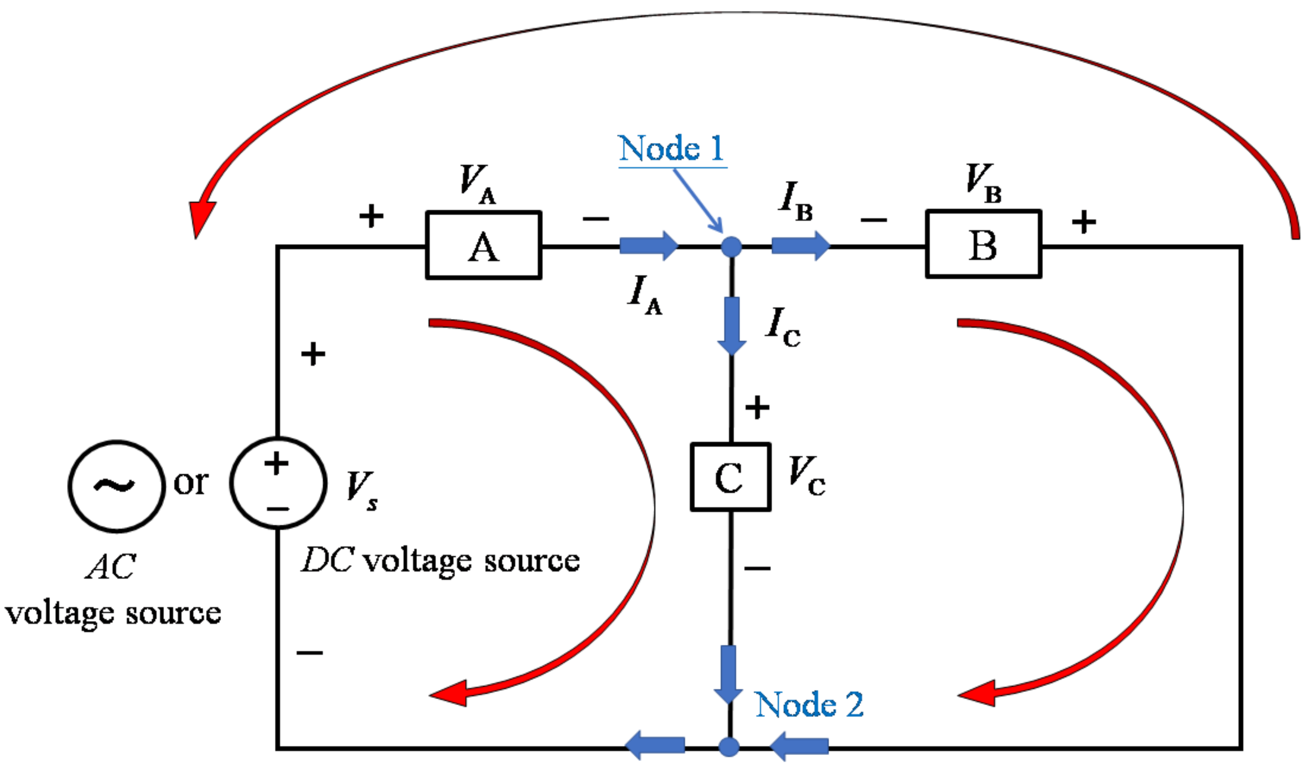


Figure 3.2. A circuit diagram example with a voltage source (*DC* or *AC*), three electrical elements (A, B, and C) with the potential difference (V_A, V_B, and V_C) and the current (I_A, I_B, and I_C) through them. The three red arrows indicate the imaginary loops applied to *KVL*.

A typical inverting circuit with an operational amplifier is shown in **Fig.** 3.3. GND represents the ground of circuit, which provides the zero-voltage reference. V_{input} and V_{output} indicate the input voltage and the resulting output voltage, respectively. Two constant resistances R_1 and R_2 and their passing current I_1 and I_2 are also marked on the diagram. We assume the operational amplifier creates a potential difference V_{op} with an inflow current I_{op}. Readers should be noted that both the V_{op} and the I_{op} **are not from external power supply**. We can draw two imaginary loops, and two nodes at the entrance and the exit of operational amplifier. The first loop contains the input voltage V_{input}, the resistance R_1, and the potential difference of operational amplifier V_{OP}. Apply *KCL* to the left node and *KVL* to the left loop, we can obtain the following formula, respectively:

$$I_1 - I_{OP} - I_2 = 0 \quad \text{(21-a)},$$

$$-V_{input} + I_1 R_1 - V_{OP} = 0 \quad \text{(21-b)}.$$

Recall formula (2) that we apply the Ohm's law to describe the potential difference across the resistance R_1. For an ideal operational amplifier which is assumed to have infinite input impedance[a] and zero output impedance, both the inflow current I_{OP} and the divided voltage V_{OP} are zero. Formula (21-a) and (21-b) can then be simplified to:

$$I_1 - I_2 = 0 \quad \text{(22-a)},$$

$$-V_{input} + I_1 R_1 = 0 \quad \text{(22-b)}.$$

Now, let's apply *KCL* to the right node and *KVL* to the upper loop. We can obtain:

$$I_{OP} + I_2 - I_{\text{out}} = 0 \quad \text{(23-a)},$$

$$V_{OP} + I_2 R_2 + V_{output} = 0 \quad \text{(23-b)}.$$

We already knew both I_{OP} and V_{OP} are zero, we can then conclude from formula (22-a), (22-b), and (23-b) that:

$$I_1 - I_2 = 0 \quad \text{(24-a)},$$

$$-V_{input} + I_1 R_1 = 0 \quad \text{(24-b)}.$$

$$I_2 R_2 + V_{output} = 0 \quad \text{(24-c)}.$$

At last, we can derive the relation between the input voltage and the output voltage that:

$$V_{output} = -\frac{\mathrm{R}_2}{\mathrm{R}_1} V_{input} \quad \text{(25)}.$$

** If your feel struggle to relate the circuit diagram with *KCL* and *KVL*, try questions Q2 of **Preview Questions (Latter week unit)** first.

(a): For an electrical element, we usually apply impedance *Z* to describe its ratio of working voltage and current. That is, *Z = V/I.*

From formula (25), we can conclude that for a superposed input source: $V_{DC} + V_{AC}$, the resulting output from an inverting amplifier will be: $-\frac{R_2}{R_1} * (V_{DC}+V_{AC})$. We can then create any desired <u>*gain*: R_2/R_1</u> by installing proper resistances.

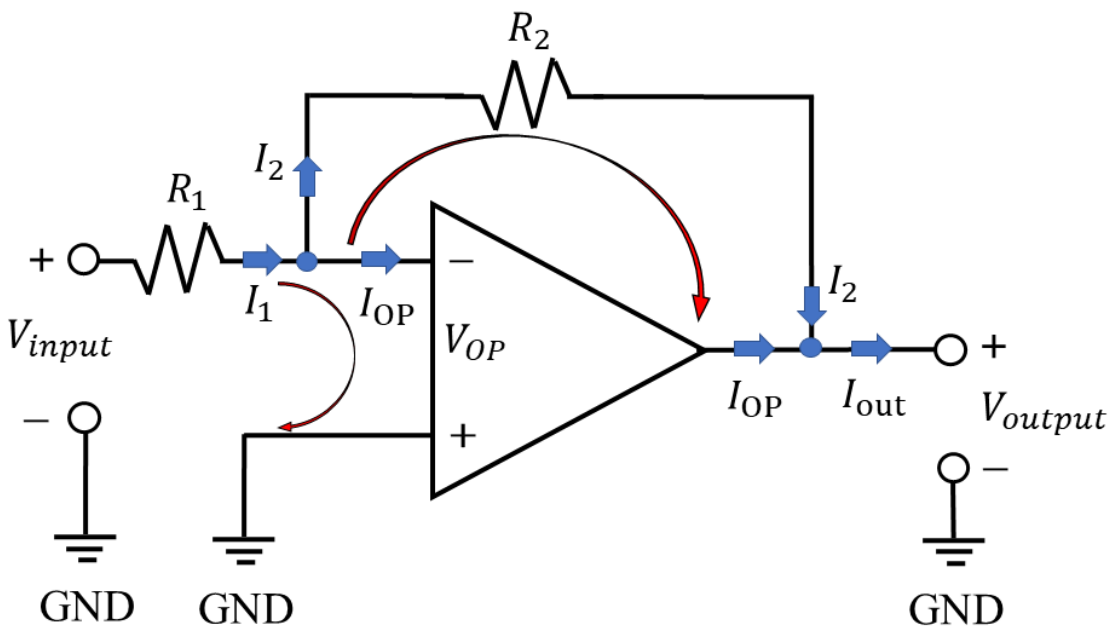


Figure 3.3. A circuit diagram example for inverting operational amplifier.

Part 3-3. Bandwidth and Low pass filter

In the previous section, we had derived the gain for an inverting circuit. In this section, we will introduce an important parameter for electrical elements to estimate its effective input frequency range. For an ideal operational amplifier, we expect it can work under all input frequency ranges and always produce a constant gain; however, the output gain for operational amplifier will descend gradually with increasing input frequency. If we define the decibel (dB)[b] of the output gain (A_o) can be described by:

$$dB = 20\log(A_o) \qquad (26).$$

A typical dB-input frequency curve for non-ideal inverting amplifier is shown in **Fig.** 3.4. We usually define the cutoff frequency as the frequency at which the output gain descends $3dB$ **<u>from</u>** the initial gain dB_0, the cutoff frequency is also known as the bandwidth. Typically, we will operate an inverting circuit only within its bandwidth to ensure its efficiency. As the input frequency increasing, the output gain keeps descending, and we will define the unit-gain frequency as the frequency at which decibel drops to zero. The unit-gain frequency indicates the upper limit for an inverting circuit to maintain its function.

[b] You may already learn the decibel in acoustics, but it is not the same concept in electronics.

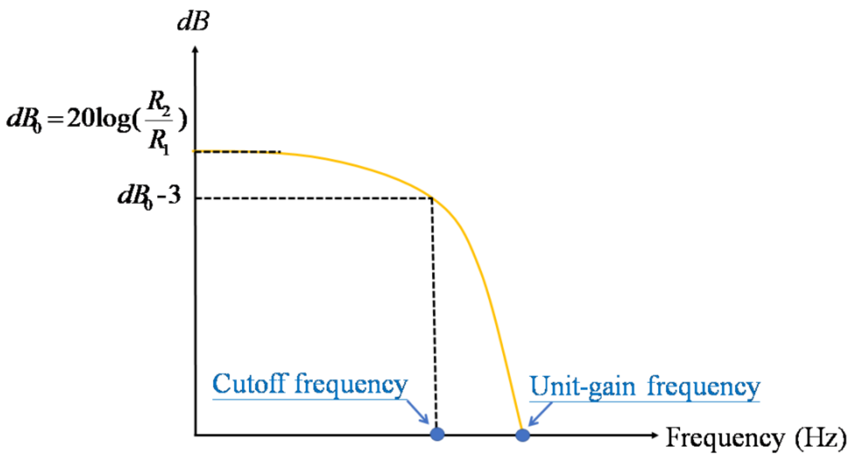


Figure 3.4. Decibel (*dB*) to frequency curve for inverting circuit (not a real scale).

Ideally, the *dB*-frequency curve is constant once the applied resistances are determined. However, for some certain purposes we may need to alter the bandwidth without replace any electrical elements. To achieve this, we usually add a filter to the original circuit. During the second unit experiment, a low pass filter will be applied. The low pass filter consists of a resistance and a capacitance. You are probably familiar with a resistance, but may seldom have dealt with a capacitance. Before we introduce the low pass filter circuit, let's begin with the function and working principle for a capacitance.

Capacitance is designed for energy storage and usually consists of two conductors with dielectric material between them. The capacitance stores energy in electric field while the passing current (*I*) is driven by a potential difference (*v*). Capacitance[c] (*c*) is described by the unit Farad (*F*) which can be estimated by Coulomb over volts (*C/v*). Recall from formula (1) which describes the relation between Coulomb and current, we can combine formula (1) with capacitance so that:

$$I = \frac{dq(t)}{dt} = \frac{d(cv)}{dt} = c\,\frac{dv}{dt} \quad \text{** in this formula, all the symbol } c \text{ belongs to capacitance.} \quad (27).$$

If we treat the capacitance as a constant, the outflow current of capacitance can then be described by formula (27). The most important characteristic for capacitance is that it provides a backup power source for electrical elements. Consider a capacitance in a circuit with a steady potential difference, it is then fully charged and produces zero current (since $dv/dt = 0$). When the circuit is switched off suddenly (now $dv/dt \neq 0$), the capacitance will then produce an outflow current for a while instead of shutting down your instrument immediately.

If we add a low pass filter to the output voltage V_{output} in **Fig.** 3.3, we can produce a new cutoff frequency which can be estimated by formula (28):

$$f_{cutoff,low\ pass} = \frac{1}{2\pi Rc} \quad (28).$$

[c] Do not confuse the symbol of capacitance (*c*) with the coulomb (*C*).

Derivation for formula (28) will not be included in this manual but is listed in reference [9] and [10]. The low pass filter diagram which reveals its connection with inverting circuit output and its effect on the original *dB* curve are both shown in **Fig.** 3.5.

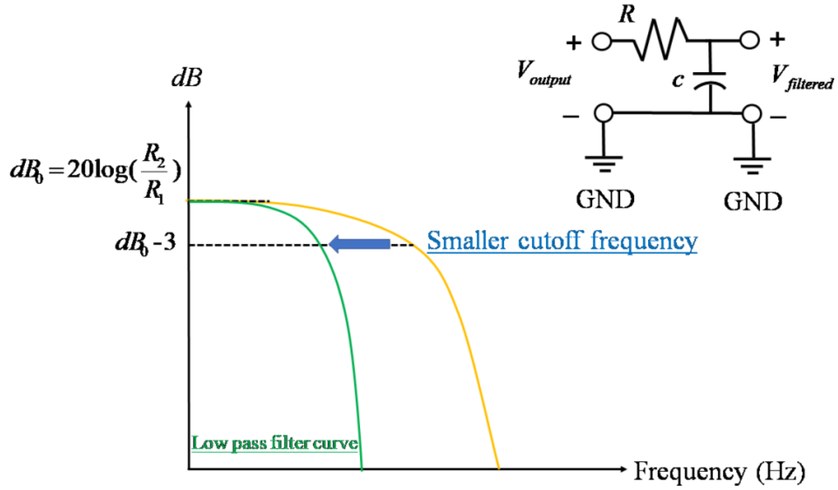


Figure 3.5. Decibel (*dB*) to frequency curve for inverting circuit with a low pass filter (not a real scale).

Reference

* The following reference list contains some free internet resources which may help you to establish a basic or advanced understanding for the theories revealed in this manual.

[1] Current vs Voltage - Difference and Comparison | Diffen

[2] Ohm's law - Wikipedia

[3] RMS Voltage of a Sinusoidal AC Waveform (electronics-tutorials.ws)

[4] What is a crest factor and its importance

[5] Traingle wave-Fourier series

[6] Square wave-Fourier series

[7] Triangle wave and square wave simulator

[8] Kirchhoff's Voltage Law and the Conservation of Energy (electronics-tutorials.ws)

[9] Capacitance reactance

[10] Low pass filter

[11] More about TTL signal

Laboratory Manual

Unit 1: Introduction

In the first week experiment, we will produce a superposed signal by using the function generator, and observe its wave characteristics from the oscilloscope. Besides, we will apply the multimeter to validate the voltage relationships between the DC component and the AC component.

Function generator

Oscilloscope

Digital multimeter

Figure I. Appearance of all applied instruments.

Experimental outlines and procedures

Experimental outlines for unit 1 are concluded in the following list. You can check the detailed procedures, instrument operation, and important notes in the following contents for each outline.

■ Check the matching wires for instruments are correct – *Page 18.*

■ Turn on the function generator and set a 1k Hz sine wave without offset – *Page 19.*

■ Turn on the oscilloscope to measure wave characteristics of your wave – *Page 19.*

■ Record the wave characteristics from both of the oscilloscope and multimeter and fill Table 1 – *Page 20.*

■ Repeat step 2 and 3 with different waves to complete Table 1.– *Page 21~22.*

■ In-class discussion: importance of proper oscilloscope scale. – *Page 21~22.*

Step 1: Check the matching wires for instruments are correct.

1.1: Check the matching wires follow the descriptions and figures below:

(a)Function generator: Output→BNC T-splitter→BNC-BNC wire (to oscilloscope)

→BNC-clipper wire (to digital multimeter)

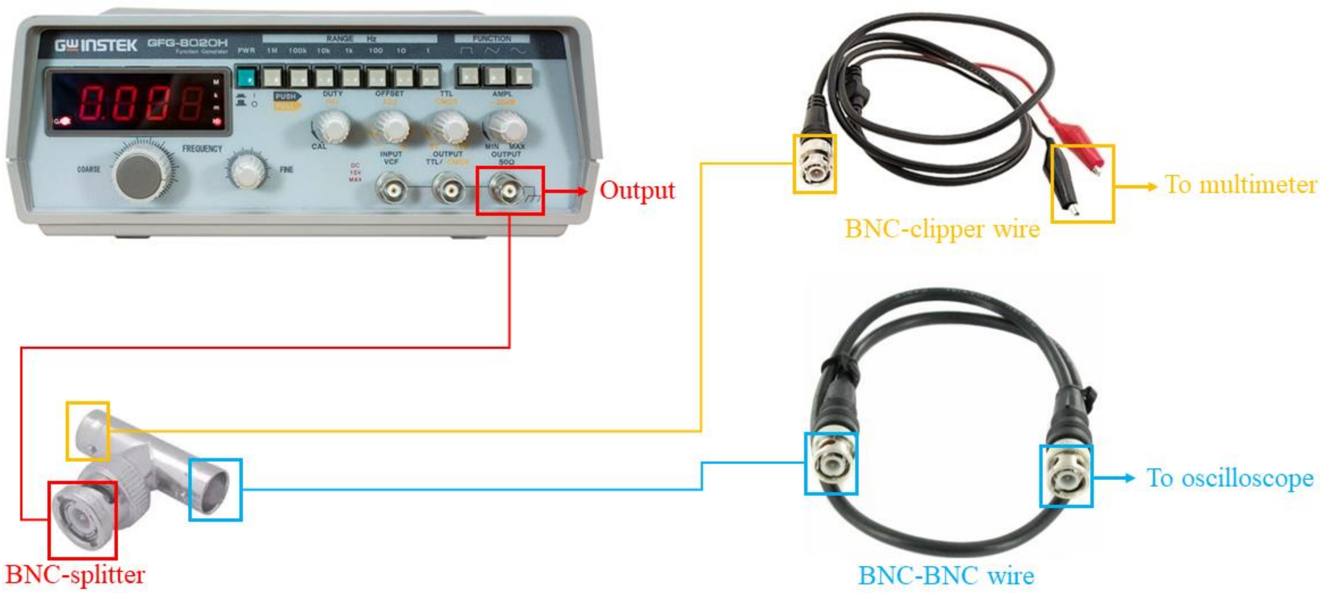


Figure II. Wiring for function generator.

(b)Oscilloscope: Input→BNC-BNC wire (from function generator)

(c)Multimeter: $V\Omega Hz$ junction→BNC-clipper **red** wire (from function generator)

COM junction →BNC-clipper **black** wire (from function generator)

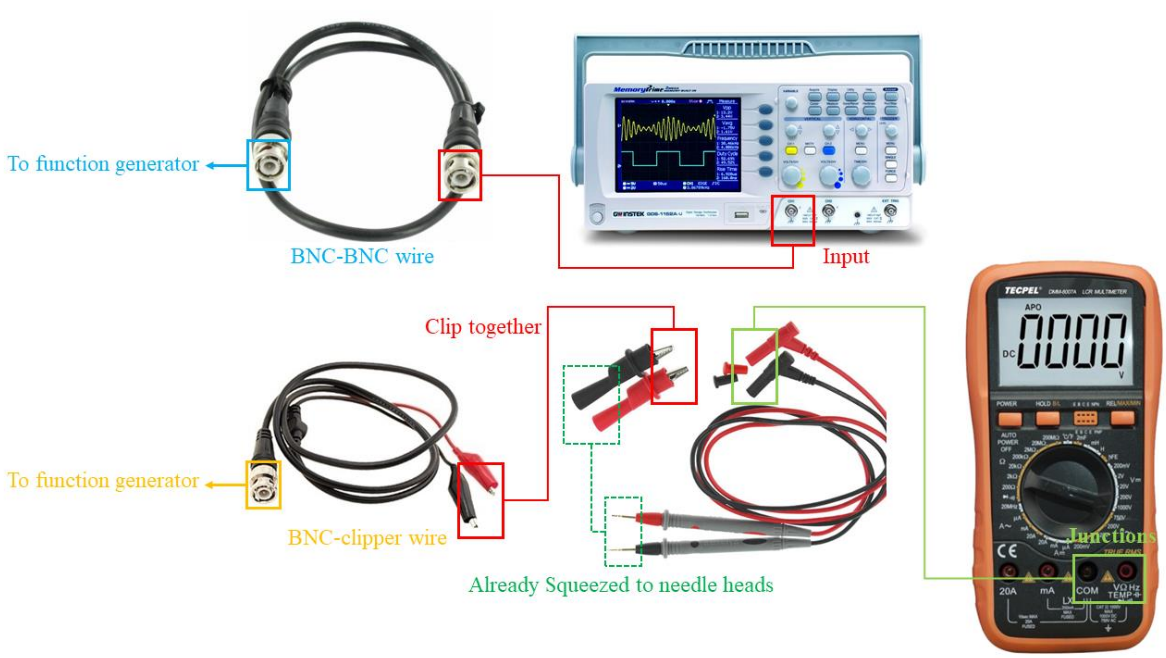


Figure III. Wiring for oscilloscope and multimeter.

Step <u>2, 3, and 4</u>: Turn on the function generator and set a 1k Hz sine wave without offset, you may need to operate the oscilloscope simultaneously to observe your wave.

<u>2.1:</u> Generate the assigned wave follow the operational sequences below:

2.1.1: Turn on the function generator with correct settings

2.1.2: Turn on the oscilloscope with correct settings

During 2.1.1~2.1.2, please generate a 1000 Hz sine wave **<u>without</u>** offset. (With $V_{max}\sim 2V$)

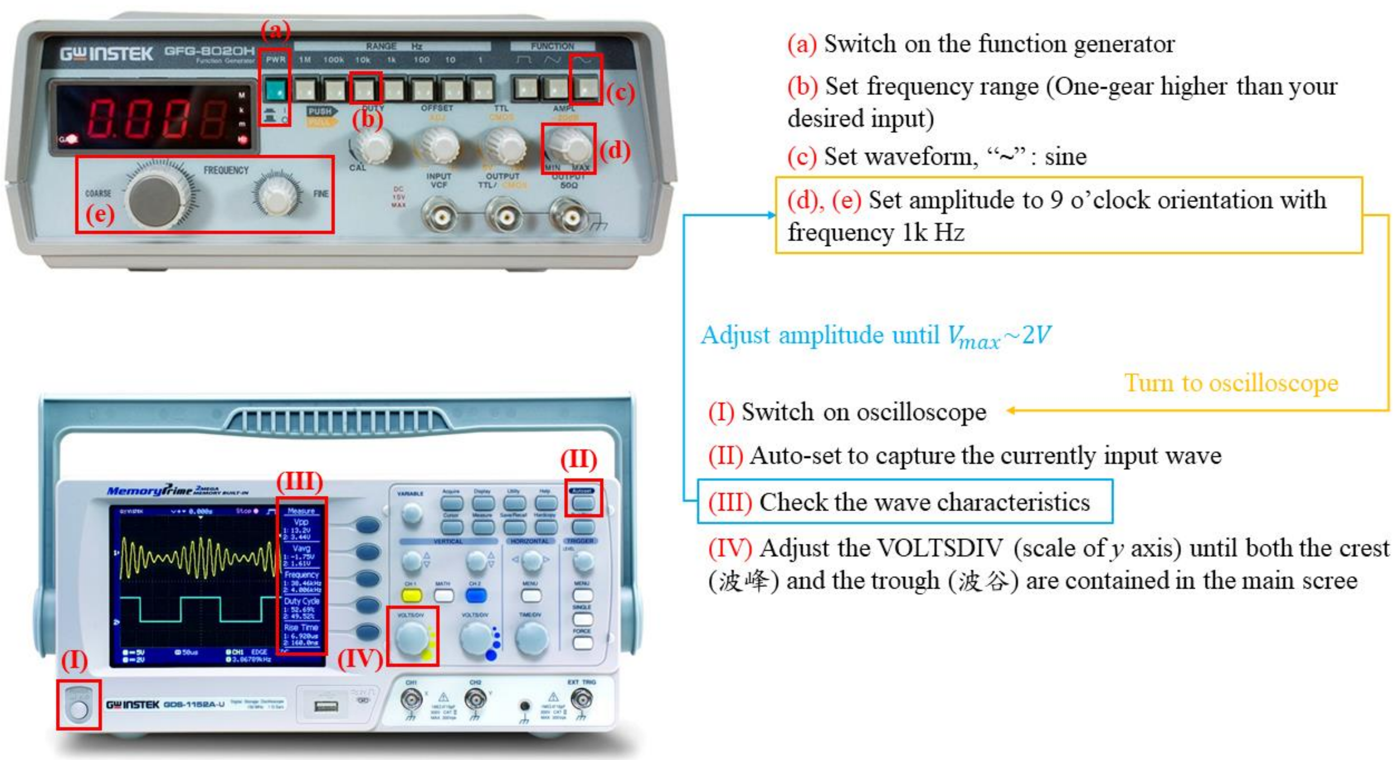


Figure IV. Generate a 1k Hz sine wave and reveal its wave characteristics.

<u>3.1:</u> Fill the second row, from the first to the fourth column of Table 1:

Table 1. Experiment recordings for wave characteristics

	V_{max}	V_{pp}	V_{RMS}	$V_{average}$	$V_{DC,multimeter}$	$V_{AC,multimeter}$
Sinusoidal with $1V$ offset						
Sinusoidal without offset						
Square with $1V$ offset						
Square without offset						

Step 4: Record the wave characteristics from multimeter

4.1: Apply multimeter by following the operational sequences below and fill Table 1 again:

(a) Switch on the multimeter

(b) Rotate the central dial to the DC voltage gear. The gear magnitude should be larger than V_{avg}. Fill the $V_{DC,multimeter}$ slot of Table 1

(c) Rotate the central dial to the AC voltage gear. The gear magnitude should be larger than V_{RMS}. Fill the $V_{AC,multimeter}$ slot of Table 1

Figure V. Measure the wave characteristics by multimeter.

Table 1. Experiment recordings for wave characteristics

	V_{max}	V_{pp}	V_{RMS}	$V_{average}$	$V_{DC,multimeter}$	$V_{AC,multimeter}$
Sinusoidal with 1V offset						
Sinusoidal without offset						
Square with 1V offset						
Square without offset						

Step 5: Produce an offset 1V wave

5.1: Now, follow the following operational guides to produce an offset wave with $V_{avg} \sim 1V$.

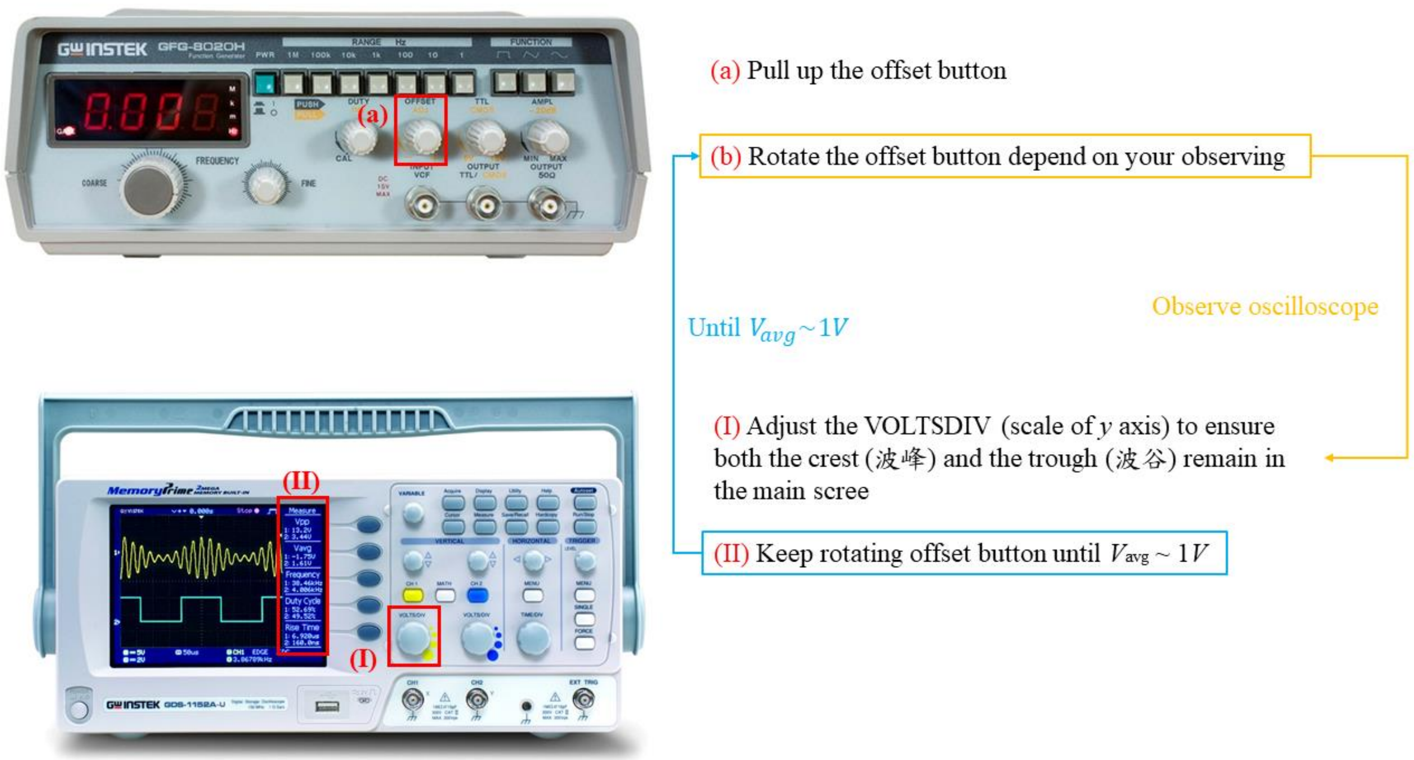


Figure VI. Generate an offset wave and reveal its wave characteristics.

5.2: Observe your oscilloscope and fill the first row, from the first to the fourth column of Table 1:

Table 1. Experiment recordings for wave characteristics

	V_{max}	V_{pp}	V_{RMS}	$V_{average}$	$V_{DC,multimeter}$	$V_{AC,multimeter}$
Sinusoidal with $1V$ offset						
Sinusoidal without offset						
Square with $1V$ offset						
Square without offset						

5.3: Repeat step 4.1 to complete the last two columns of first row:

Table 1. Experiment recordings for wave characteristics

	V_{max}	V_{pp}	V_{RMS}	$V_{average}$	$V_{DC,multimeter}$	$V_{AC,multimeter}$
Sinusoidal with $1V$ offset						
Sinusoidal without offset						
Square with $1V$ offset						
Square without offset						

Step 6: Complete the rest of Table 1 by yourself.

6.1: Square wave button of function generator: 

Table 1. Experiment recordings for wave characteristics

	V_{max}	V_{pp}	V_{RMS}	$V_{average}$	$V_{DC,multimeter}$	$V_{AC,multimeter}$
Sinusoidal with 1V offset						
Sinusoidal without offset						
Square with 1V offset						
Square without offset						

Step 7: In-lab practice and discussion

7.1: Produce an arbitrary non-offset square wave and record its initial rise time.

7.2: Rotate the TIMDIV button to descend the TIMEDIV scale (from *ms*, μs, to *ns* scale). Record each rise time. Does the rise time remain unchanged?

Laboratory Manual

Unit 2: Introduction

In the second week experiment, we will establish an inverting circuit with LM741 operational amplifier and learn to build a complete circuit on a breadboard with a power supply. By monitoring differences between the input signal and the output signal observed from oscilloscope, we can establish the *dB*-frequency curve for our inverting circuit. At last, a low pass filter will add to the inverting circuit and its influence on cutoff frequency will be revealed.

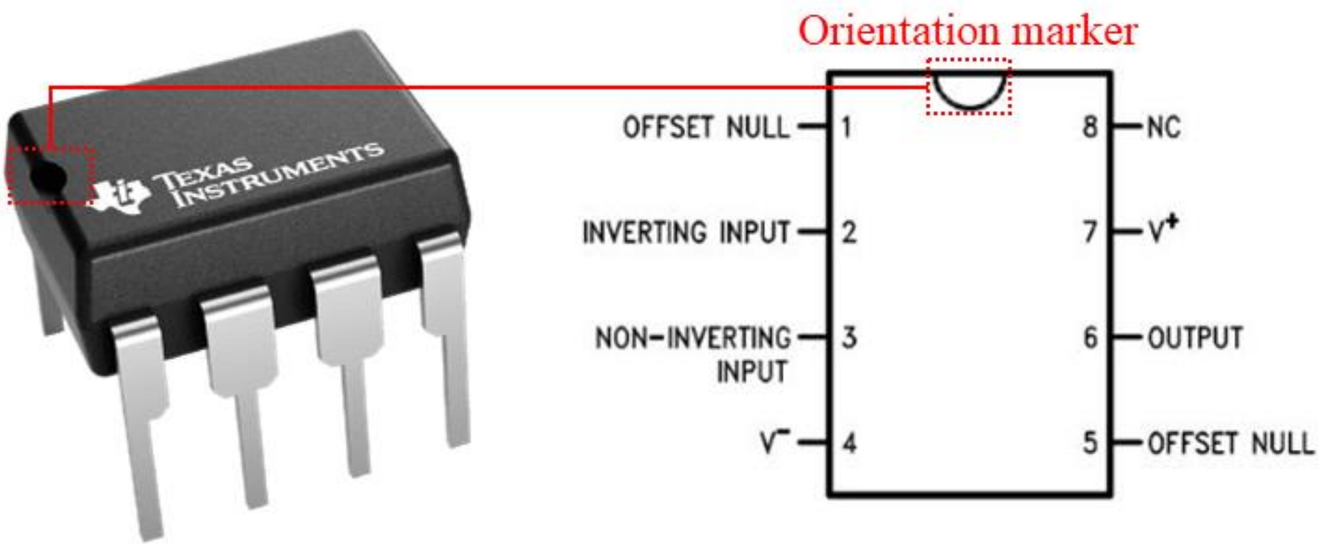


Figure I: LM741 operational amplifier with pin numbers.

Experimental outlines and procedures

Experimental outlines for unit 2 are concluded in the following list. You can check the detailed procedures, instrument operation, and important notes in the following contents for each outline.

■ Identify the inverting circuit and the breadboard – *Page 24.*

■ Check the matching wires for instruments are correct– *Page 25.*

■ Apply the function generator to input signal and the oscilloscope to observe output signal– *Page 26.*

■ Activate LM741 by power supply and fill Table 2 with increasing input frequencies– *Page 27~29.*

■ Modify your circuit by adding a low pass filter, repeat step 4– *Page 30~31.*

Step 1: Identify the inverting circuit and the breadboard.

1.1: Check the inverting circuit diagram below and compare with Fig. 3.3 to make sure you understand how to establish and modify it.

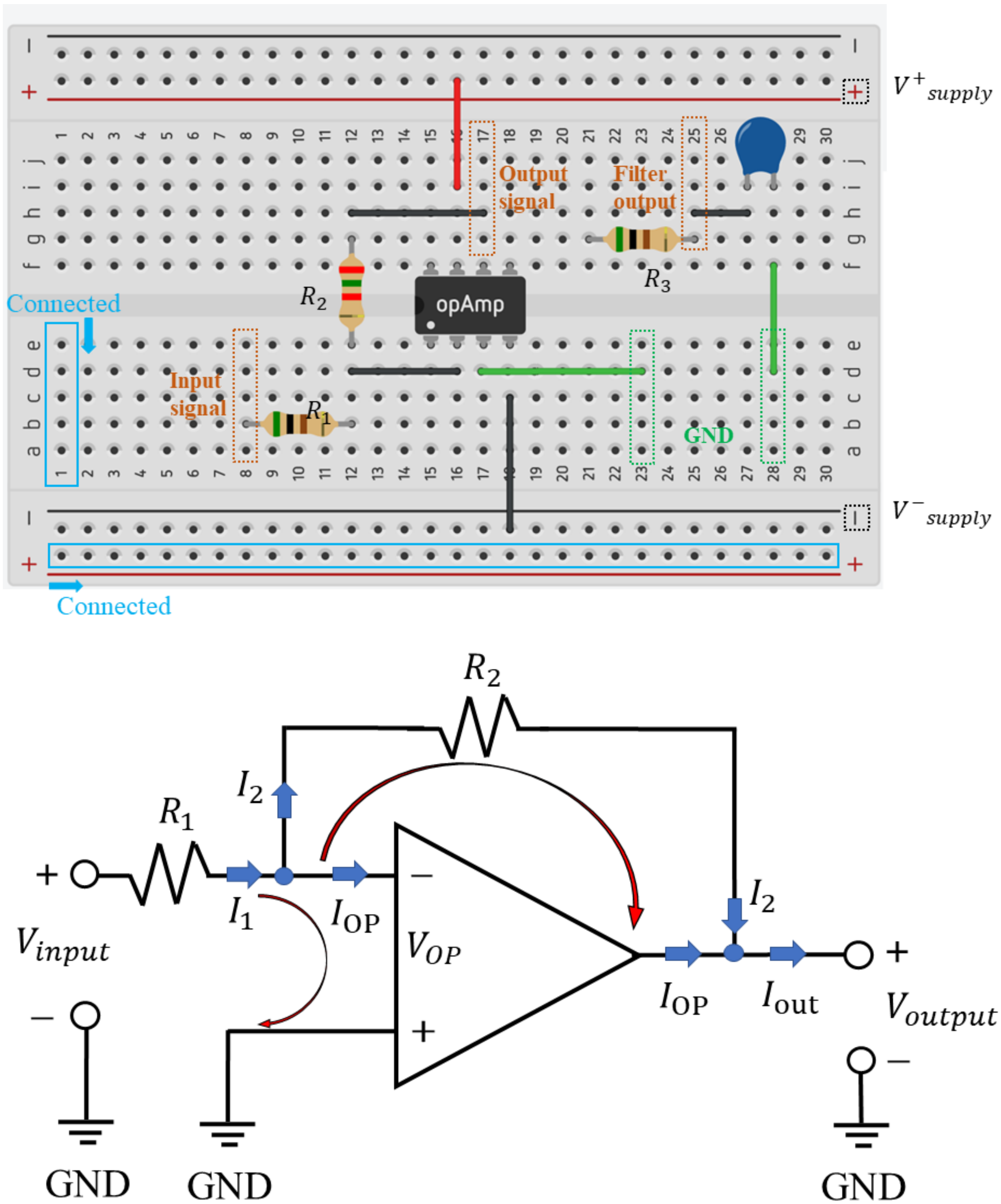


Figure II. Inverting circuit diagram, practical vs. theoretical. $R_1 = R_3 = 500\Omega$, $R_2 = 2500\Omega$.

Step 2: Check the matching wires for instruments are correct.

2.1: Check the matching wires follow the descriptions and figures below:

(a)Function generator: Output→BNC T-splitter→BNC-BNC wire (to oscilloscope)

→BNC-clipper wire (to input of circuit)

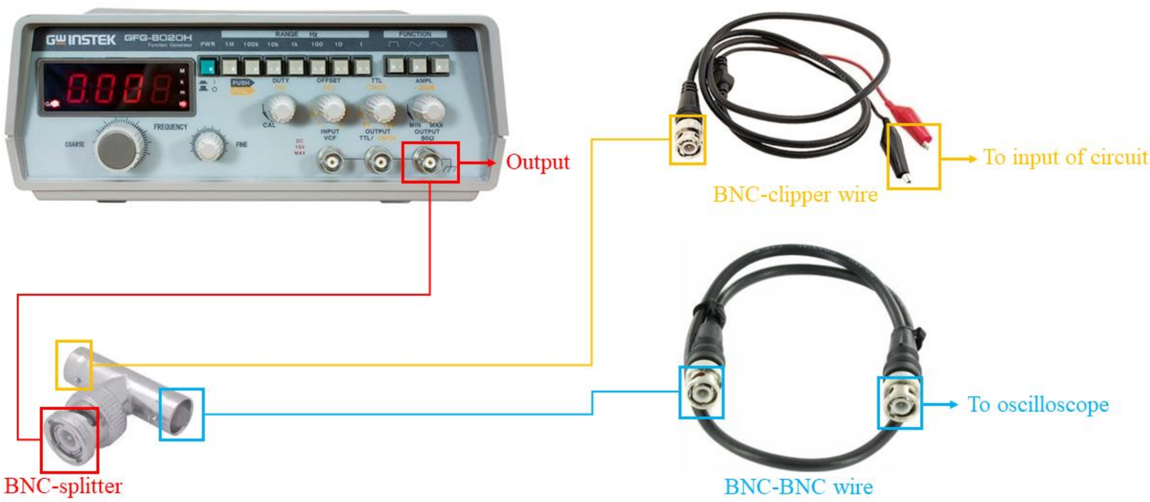


Figure III. Wiring for function generator.

(b)Oscilloscope: Input 1→BNC-BNC wire (from function generator)

Input 2→BNC-clipper wire (from inverting circuit)

(c)Inverting circuit: *Column 08* →BNC-clipper **red** wire (from function generator)

Column 23 →BNC-clipper **black** wire (from function generator (GND))

Column 17 →BNC-clipper **red** wire (output to oscilloscope)

Column 23 →BNC-clipper **black** wire (output to oscilloscope (GND))

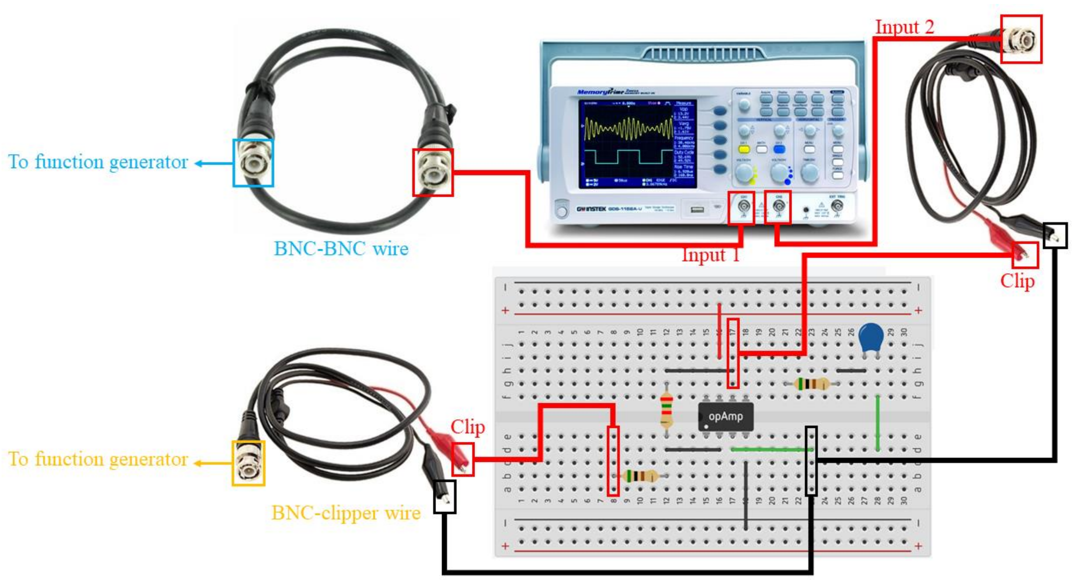


Figure IV. Wiring for inverting circuit.

Step <u>3</u>: Apply the function generator to input signal and the oscilloscope to observe output signal.

<u>3.1:</u> Generate the assigned wave follow the operational sequences below:

3.1.1: Turn on the function generator with correct settings

3.1.2: Turn on the oscilloscope with correct settings

During 3.1.1~3.1.2, please generate a 1000 Hz sine wave with no offset.

(With V_{pp}~$2V$, V_{avg}~$0V$)

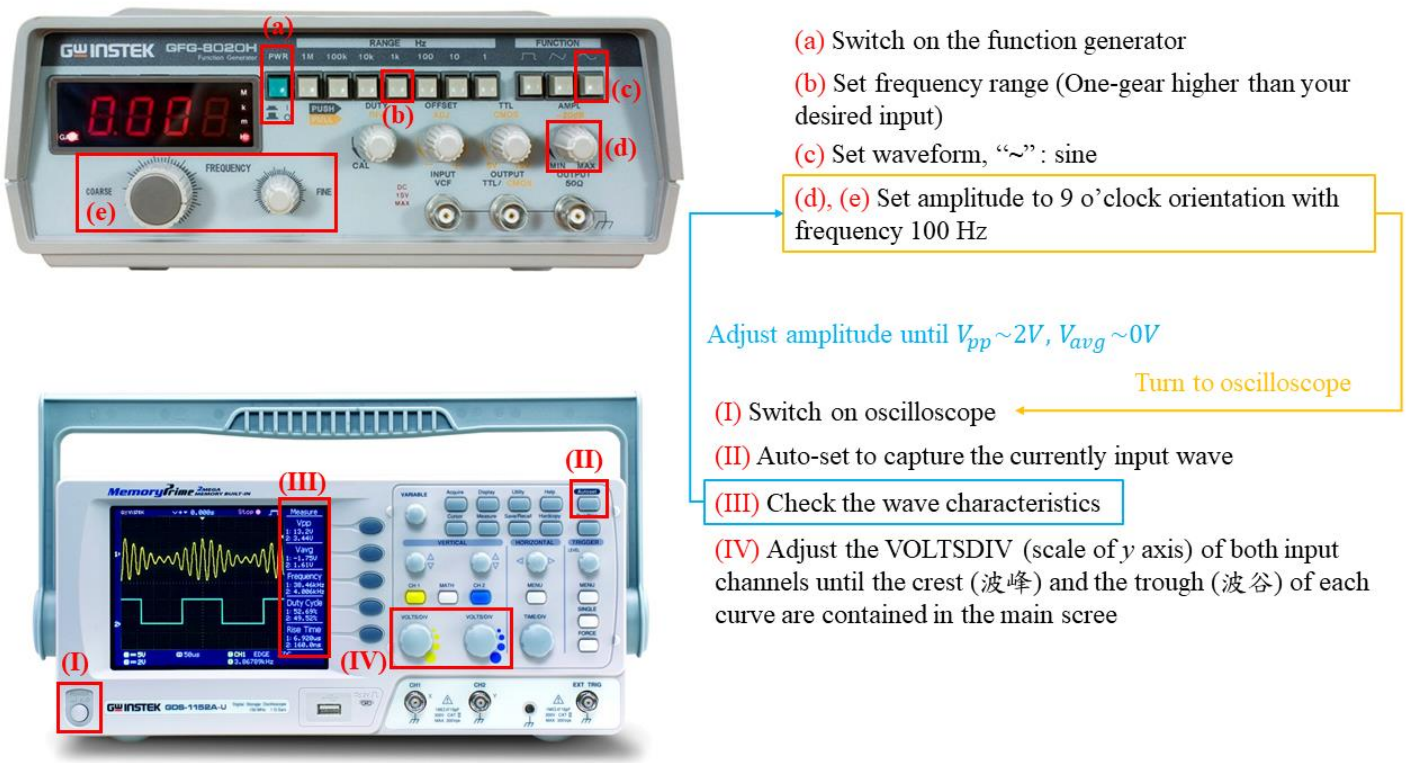


Figure V. Generate a 1000 Hz sine wave with assigned characteristics.

<u>NOTE</u>: Here you should observe two identical curves on your oscilloscope. Call for help if you are not sure about how identical they should be.

Step 4: Activate LM741 by power supply and fill Table 1 with increasing input frequencies.

Safety NOTE: This procedure has potential risk to endanger your personal safety, read all RED words very carefully before activate LM741.

安全警示:本步驟有危及個人人身安全的風險，務必確保閱讀清楚所有紅色字體再啟動 LM741。

4.1: Set your power supply magnitude and connect with inverting circuit: DO NOT press the OUTPUT button in this step.

(a) Power supply: **red** to CH1 +, **one black** to CH2 －, **the other black** to CH1 －

(b) Inverting circuit: *Row* + → CH1 +

Row － → CH2 －

Column 23 → CH1 － (GND)

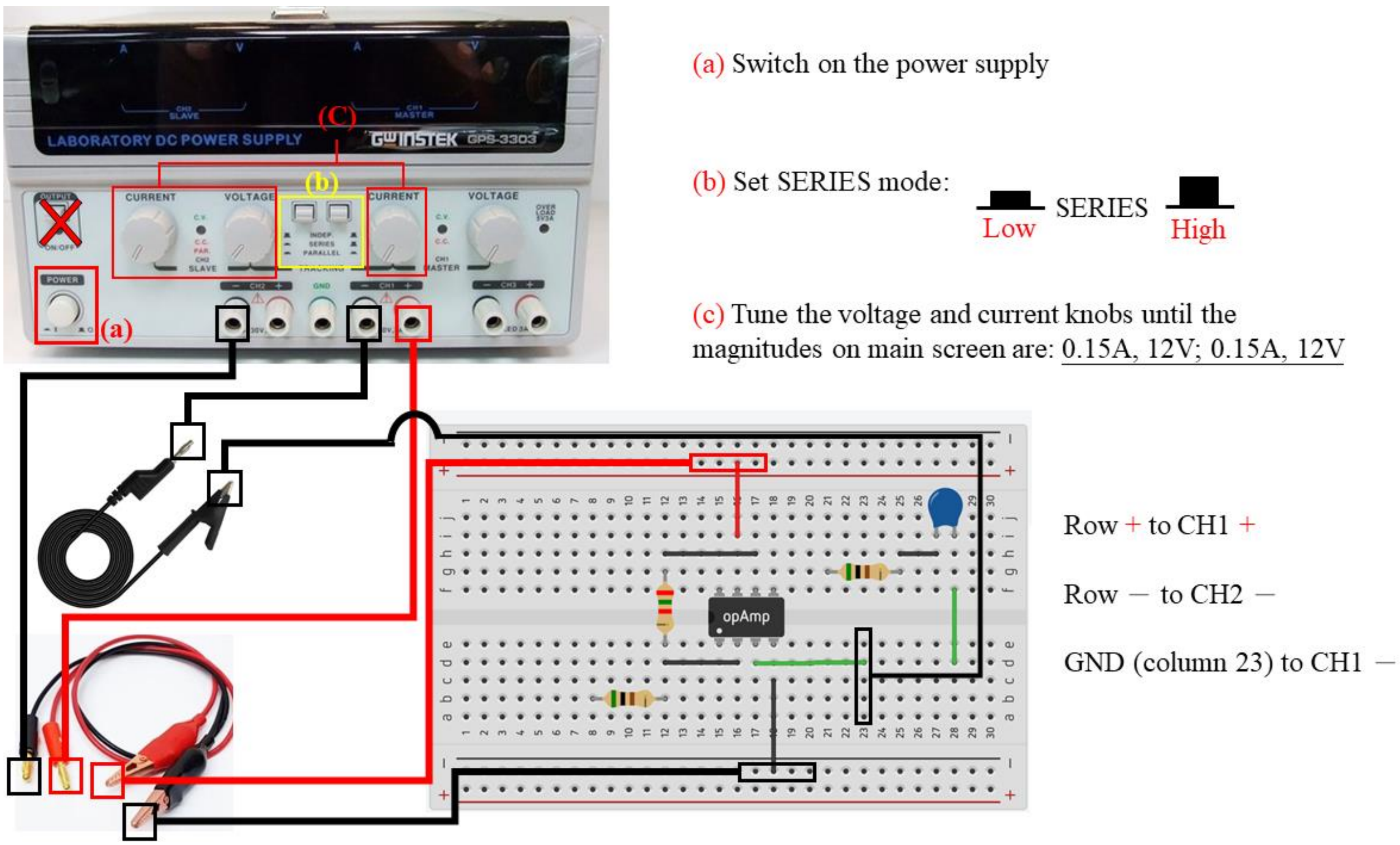


Figure VI. Setting for power supply and wiring with inverting circuit.

4.2: Press the OUTPUT button, fill Table 2 with increasing input frequencies:

(a) During the OUTPUT is ON, never touch any circuit components!

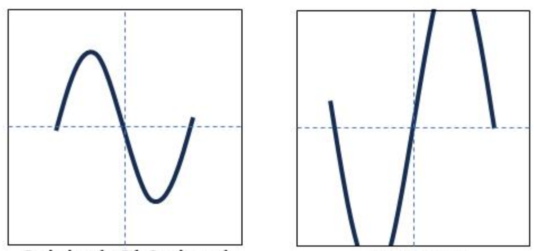
(b) When the c.c. indicator is activated (red light), shut down your power supply immediately.

(c) Your Ch2 signal of oscilloscope will experience a sharp jump, adjust VOLTSDIV of Ch2 until you can measure its characteristics.

(a) Press output

(b), (c) Shut down the power supply immediately if one of the lights is red (c.c. mode)

(d) Adjust the VOLTSDIV scale of CH2 signal until its wave characteristics are revealed



Original Ch2 signal

Ch2 signal
after LM741 is just activated

Figure VII. Activate LM741 and the corresponding signal response.

(d) Increase your input frequency from function generator and fill the first two columns of Table 2 (without low pass filter).

NOTE: Do not fill the table with a constant frequency interval, follow the in-lab instruction to learn how to “span” the frequency.

Table 2. Experiment recordings for OP enlarge ratio.

Frequency (Hz)	$V_{pp,CH2}/V_{pp,CH1}$	Frequency (Hz)	$V_{pp,CH2}/V_{pp,CH1}$ (Low pass)

Step 5: Modify your circuit by adding a low pass filter, repeat step 4.

Safety NOTE: This procedure has potential risk to endanger your personal safety, read all RED words very carefully before deal with LM741.

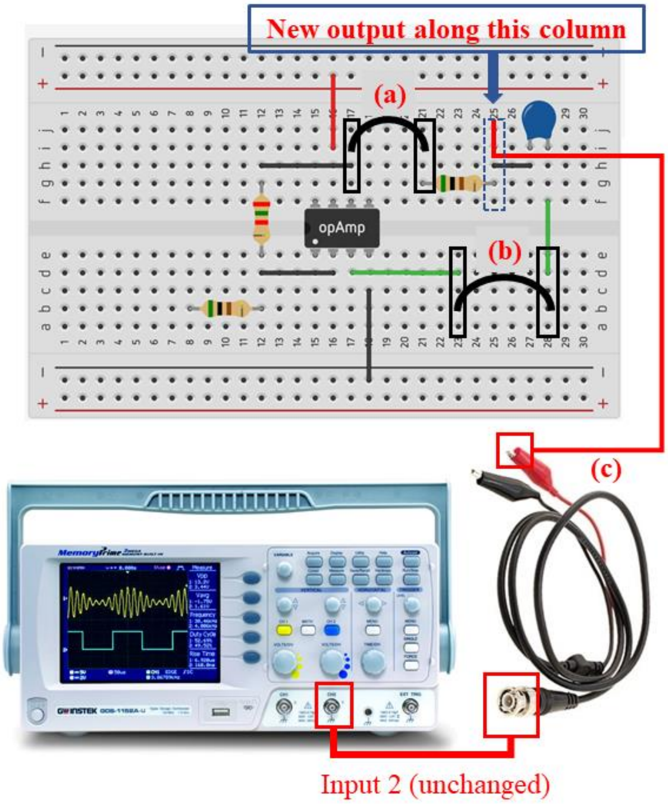
安全警示:本步驟有危及個人人身安全的風險，務必確保閱讀清楚所有紅色字體再操作 LM741。

5.1: Turn off your output button. Connect the low pass filter.

(a) Remove the original output and connect it with the output of low pass filter.

(b) Connect the original GND to that of the low pass filter.

(c) Remember to connect the Ch2 of oscilloscope with the low pass filter output.



(a) Remove the original output wire and apply a single wire to connect column 17 and 21. Also apply a single wire to column 25 as the filter output.

(b) Apply a single wire to connect column 23 and 28 (GND of low pass filter).

(c) Remember to alter the input 2 of oscilloscope to the output of low pass filter.

Figure VIII. Wiring for low pass filter.

5.2: Turn on your output button. Fill Table 2 with increasing input frequencies:

(a) During the OUTPUT is ON, never touch any circuit components!

(b) When the c.c. indicator is activated (red light), shut down your power supply immediately.

(c) Increase your input frequency from function generator (start from **50 Hz**) and fill the last two columns of Table 2 (with low pass filter).

(d) You should observe a very significant drop of cutoff frequency. The filter resistance and capacitance is 500 Ω and 470 nF, respectively.

Table 2. Experiment recordings for OP enlarge ratio.

Frequency (Hz)	$V_{pp,CH2}/V_{pp,CH1}$	Frequency (Hz)	$V_{pp,CH2}/V_{pp,CH1}$ (Low pass)

Preview Questions－Former week unit, 0.625% for each question:

Q1: (Part 1-1, page 1~2). Assume there is an electric charge with its quantity equals to 10 Coulomb. This charge passes through an element in 2 seconds. If this element follows Ohm's law and has a resistance 5Ω, calculate the current and voltage across this element, respectively.

Q2: (Part 1-2, page 2~3). Calculate the average current magnitude within a period for an AC current which follows the wave function (List your calculation details):

$$I(t) = 2\sin(2t) + 6.$$

Q3: (Part 1-2, page 3~5). Calculate the *RMS* current magnitude within a period for an AC current which follows the same wave function of Q2. (List your calculation details)

Q5: (Part 1-3, page 6). Why do we usually set a power supply in a laboratory instead of connecting instruments with wall sockets directly?

Q6: (Part 2-1, page 7~8). Calculate the crest factor of the wave function in Q2. (List your calculation details)

Q7: (Part 2-2, page 8~9). Consider the definition of rise time, what does the rise time for the wave function in Q2? (List your calculation details)

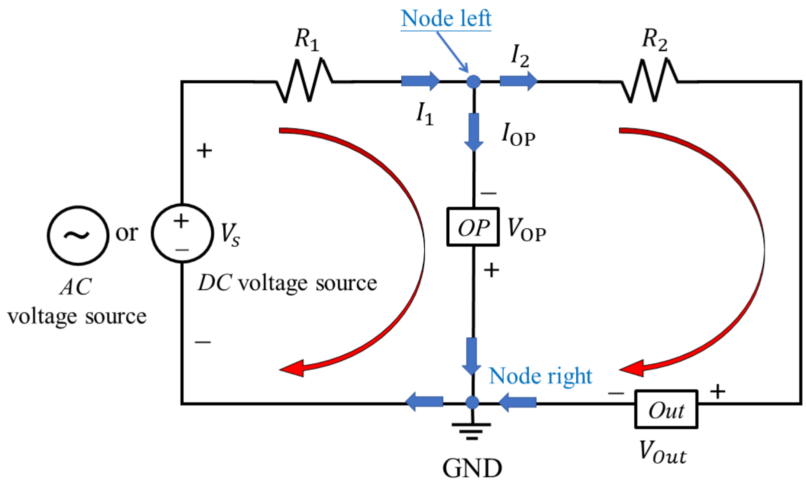
Q8: (Part 2-2, page 9~10). Consider a function generator, what type of square wave does it produce in your opinion? (ideal or superposed?). Describe your opinion clearly.

End of the former week preview Questions

Preview Questions—Latter week unit, 1% for each question:

Q1: (Part 3-1, page 11). What's the function of an OP-amp? For an OP-amp circuit diagram, what source should you connect to the positive and negative sign of **Fig.** 3.1? (The voltage needs to be enhanced or the voltage applied to activate OP-amp?)

Q2: (Part 3-2, page 11~12). Consider the following circuit diagram, please apply *KCL* to both the node left and node right, and apply *KVL* to both the left and right loop. Write down four explicit relations. ** Note that there is always an energy consuming of current after passing a resistance, therefore, we can mark a positive voltage symbol "+" at the entrance of resistance while a negative "—" at its exit. ** You can compare your result with inverting OP if set both *Iop* and *Vop* are zero.



Q4: (Part 3-3, page 14~15). Consider **Fig.** 3.3. If R_1 = 500Ω, and R_2 = 2500Ω. Calculate its gain and initial decibel, respectively. And write down its cutoff decibel magnitude.

Q5: (Part 3-3, page 15~16). Consider a low pass filter which applies a $470nF$ capacitance and a 500Ω resistance, what is the theoretical cutoff frequency? (n = 10^{-9})

End of the latter week preview Questions

Review Questions:

Q1:

(a) 0.5%. By your collected data in Table 1. Estimate and report the value: $V_{average}^2 + V_{AC,multimeter}^2$ for all four rows.

(b) 0.5%. If we define the results from Q1(a) as $V_{RMS,measure}^2$, estimate and report the error between $V_{RMS,measure}^2$ and V_{RMS}^2 of Table 1. The error could be estimated follows the equation:

$$Measurement\ error = \frac{V_{RMS,measure}^2 - V_{RMS}^2}{V_{RMS}^2} \times 100\%$$

(c) 0.5%. Repeat Q1(a) and Q1(b) but replace $V_{average}^2$ by $V_{DC,multimeter}^2$. Which instrument (oscilloscope vs. digital meter) provides a better approach with respect to V_{RMS}^2 ?

(d) 2%. (**Research by yourself**) Explain the physical meanings of crest factor clearly. And calculate all crest factors from Table 1. Does the experimental result match with your explanation?

(e) 2%. (**In-class discussion**) Explain why the rise time changes with different TIMEDIV scales?

Q2:

(a) 2.5%. (**Reveal-by-plot**) By your collected data in Table 2. Plot the dB－frequency curve for inverting circuit and low pass filtered circuit, respectively.

(b) 2%. Identify and report the two different bandwidths (with vs. without filter) of our OP-amp. Does the experimental cutoff frequency of low pass filter match its theoretical value? Estimate and report the error by:

$$Measurement\ error = \frac{f_{cutoff,exp} - f_{cutoff,theory}}{f_{cutoff,theory}} \times 100\%$$

End of review questions