[Prolog] Analog Integrated Circuit, or analog IC, is designed specifically for analog signals. The term “IC” here means that we use microelectronic technology to put the amplification, filtering, circuit interface, etc., electronic circuits on a chip as modules. Analog signals’ voltages exist from the minimum \( V_{\text{min}} \) to the maximum \( V_{\text{max}} \) with \textbf{continuous} values between \( V_{\text{min}} \) and \( V_{\text{max}} \). Because of its linear amplification capability, analog IC is often also called linear IC, and is a masterpiece of electronic circuit design.

Operational Amplifier, or Op-Amp, is one of the most fundamental modules in analog IC. Op-amp sees a lot of applications thanks to its near ideal properties, low-cost and versatility. For EE 4429, we will start with a look at op-amp and its various applications.

[Related Knowledge] Op-amp’s internal construction is quite complex, and there are many different kinds of op-amps. Just Google LM741’s (a popular op-amp device) or LM555CN’s schematic diagrams and you will see why. The reason we like to use op-amp in analog IC designs is because of its simple input/output relation. As long as we are careful with its limitations, this simple I/O relation makes analyzing and designing op-amp application circuits relatively easy. Op-amp is mainly used in linear circuits, where the typical analog signals used are voice, temperature, pressure, velocity, EMG, etc.

Both small signal op-amps and power op-amps are commonly seen. It’s basically a DC-coupled voltage amplifier that exhibits differential input and single-ended output.

1. They have the following advantages when fabricated as IC:
   (1) small and light, (2) performance and stability, (3) reliability, (4) low-cost, (5) low power consumption.

2. Op-amp example:
   Below is a generic op-amp symbol. Often \( +V_{\text{cc}} \) and \( -V_{\text{cc}} \) are not shown in a circuit diagram. But remember to connect these two important pins!

   As you can see, a typical generic op-amp needs 5 pins, including:
   (1) Basic functional pins – non-inverting input \( V_{\text{in+}} \), inverting input \( V_{\text{in-}} \), output \( V_{\text{out}} \)
   (2) Power supply pins – \( +V_{\text{cc}} \) and \( -V_{\text{cc}} \)

   Many op-amps also come with additional pins for adjustment and compensation. For example, LM741 uses internal frequency compensation, while LM301A, LM308 and
LM709/C use external frequency (phase) compensation. Usually dedicated pins are allocated to do the compensation work.

3. 741 op-amp is a BJT based op-amp, and has existed since the 1960’s. It can come in an 8-pin dual-in-line, or DIP, package, a ceramic flat package, or a round metal can package. Each manufacturer has a different code. For example, LM means National Semiconductor, µA stands for Fairchild, MC for Motorola, etc.

4. Op-amp circuit background

Construction:

Typical op-amps consist of these modules: (1) differential amplifier, (2) current mirrors, (3) class A gain stage, (4) voltage level shifter, and (5) output buffering stage. Besides these modules, there is a current biasing module, providing the DC current needed to drive these 5 modules. Below is the schematic diagram of the BJT 741 op-amp IC.

You can see why this is a BJT based op-amp IC. Of course, if we look at the input and output equivalent circuits, we can simply this op-amp into the following circuit:
For small signals, we can simply the circuit in a similar way as follows:

5. Important properties of op-amps

When we use op-amp IC’s as basic elements of an analog circuit, we need to be aware of op-amp’s properties. These include ideal and non-ideal DC properties, AC small signal and large signal properties. These properties will “magnify” the difference between ideal and realistic op-amp based analog IC designs, as we employ more op-amps in the various modules in the design. As the semester goes on, we will become familiar with some of these important properties of the op-amp.

Extra tip on practical use of op-amps:

As an example, let’s look at LM301A.

On the left is the typical schematic for LM301A. However in practice, we need to do what is shown on the right hand side, plus:

1. Current voltages: dual current sources (±V_{DD}) or single current source (+V_{DD}, GND).
2. For high-speed op-amps without internal protective circuits, the time difference between dual current sources (i.e. +V_{DD} and −V_{DD}) should not exceed 1~2 seconds.
3. Adding some extra non-functional elements, such as the ones shown above, where C_1, C_2 are for the current source, C_C is for frequency compensation, R_3 is for
offset compensation and “zeroing” DC signals, and Ground (GND) which is better to be concentrated for a single point of grounding. The wiring required to add these non-functional elements should be minimized.

The experimental input sine wave or triangular wave frequency, $f_{\text{in}}$, should be between hundreds of Hz and thousands of Hz. Typically we use 1 kHz.

Here are some popular “cookbook” op-amp application circuits, drawn using LTspice. Can you verify that these circuits do work as designed? What do those “.commands”, such as “.include” and “.dc” mean? What about the “LM741.sub”?

**Summing Amplifier**

![Summing Amplifier circuit diagram]

**Difference Amplifier**

![Difference Amplifier circuit diagram]
Voltage Follower

```
.include LM741.sub

>V3 -15
>V2 15
>V1 5

 dc V1 0 5 .1
```

Op-amp Integrator

```
.include LM741.sub

>V3 -15
>V4 15
>V1 5

 PULSE(0 5 0 0 0 .5 1 1)

 tran 0 1 0 .01
```

Op-amp Differentiator

```
.include LM741.sub

>V3 -15
>V4 15
>C1 5p

 SINE(0 5 100)

 tran 0 1 0 .01
```
As can be seen, op-amp applications abound. The ones shown here are but a subset of the commonly seen op-amp application circuits.

Something to think about, once you have verified these circuits in LTspice to your satisfaction, how confident are you to reproduce the same results in hardware on the breadboard, using a combination of IC’s and discrete components?

Furthermore, given the LM741 DIP IC which everyone of you were handed one in the lab session, how would you go about turning these op-amp circuits into DIP IC’s that look just like the LM741 IC? What is the process involved in making that happen?