ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

Imperfections des Amplificateur opérationnel

6.1 Imperfections

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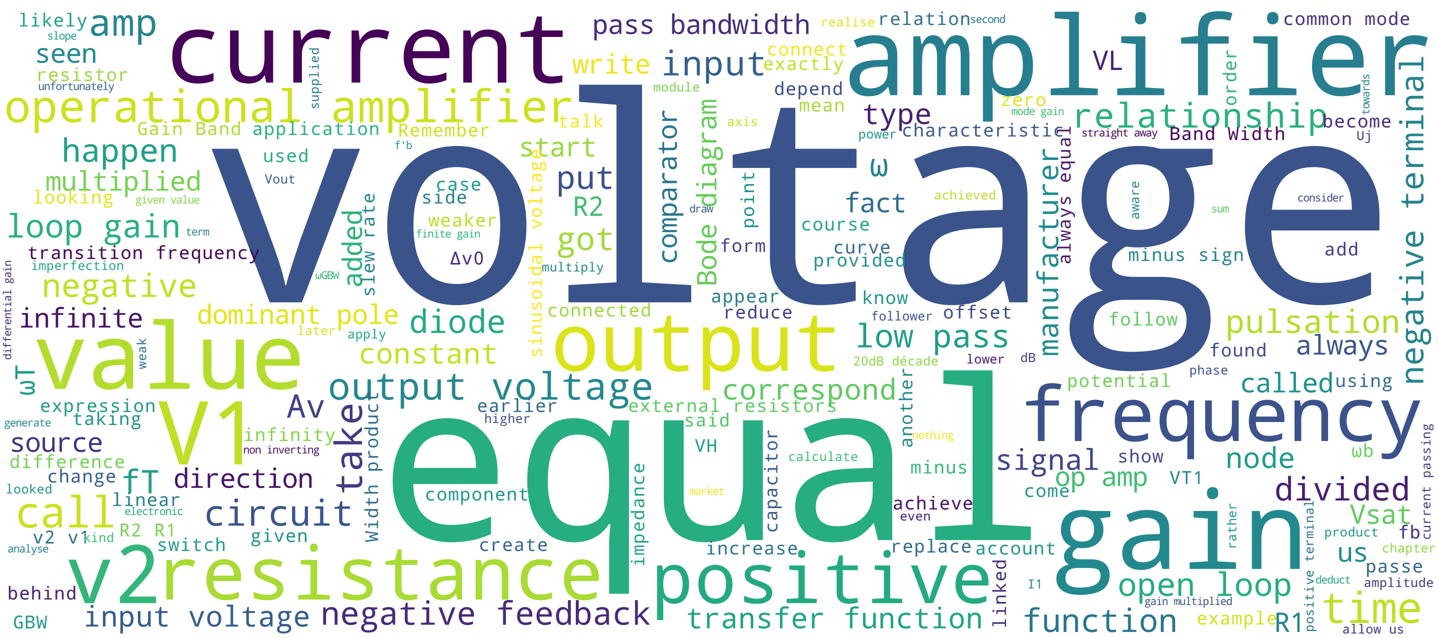


Video

EPFL

Hello everyone. Today, let's look at some of imperfections of the operational amplifier. Up until now, we have considered the operational amplifier to be an electronic component and we've said that it was perfect, meaning that it has infinite gain, that is is capable of a voltage that, at the output can be as much as that of the power supply, which has the same input voltage on both the positive and negative terminals and which takes no current at all from the positive and negative terminals. Yet, we will realise that this isn't exactly the case In this chapter, we're going to look at some of the imperfections, namely of the actual components which can be found on the market. You'll see that there are components, and when choosing an operational amplifier, we make a choice based on its imperfections. And its not possible to find an amplifier which has the best characteristics in all of its functions, for example the highest gain coupled with the widest possible bandwidth. So, in this chapter we will examine of all of the following points in turn: In order to look at the different limitations of an operational amplifier, we will look at them one by one.

Notes

Summary

0m 03s

Let's start by looking at the finite voltage gain of an open loop op-amp. So you will realise that the voltage gain of an operational amplifier isn't infinite. First, what is infinite voltage gain? What is the value which we consider to be high enough for it to be referred to as infinite? Same issue for frequency. We will see that frequency and gain are linked and that unfortunately, the op-amp can't follow just any odd input signal but will need to have a dominant pole that this dominant pole will lead us to lower the frequency in proportion to the gain, or rather to reduce the gain as the frequency rises. Similarly, we will look at another imperfection. We will see that the output voltage of an operation amplifier has a value and that this value, the higher the output voltage is, the higher the risk of a side effect, resulting in a linear output voltage. We're also going to talk about *slew rate*. This is the speed at which the output voltage will switch. Also, we'll see that there is a common mode. The common mode means that up until today, amps have had a positive and a negative terminal, and every time we have spoken about a differential gain, it has meant that the *V*+ minus *V*-, the voltage at the positive terminal and the voltage on the negative terminal have been multiplied by a differential gain.

Notes

Summary

1m 15s

So if you input the same voltage, you are bound to find an output voltage that equals zero. So if *V+* is equal to *V-*, it goes without saying that *V+* minus *V-* equals zero, so the output voltage has no gain. However, unfortunately, there will be a gain which we call a common mode gain, This means that even if you have the same signal on the positive and negative terminals, they will be short circuited. You'll see later on that there will be a gain and that this gain will multiply the same voltage and send back the same component multiplied by a gain which we call common mode gain. There will also be an imperfection linked to a difference in continuous voltage between the *V+* and the *V-*. which we will refer to as the *offset* voltage. This is the same for input impedance. We had stated that there wasn't any current passing through the amp, on the positive and negative terminals, We'll see that it depends on how the manufacturing of the electronics inside, what type of transistor has been used and that we are likely to have behind the positive and negative terminals, some form of current.

Notes

Summary

2m 50s

and that we are likely to have behind the positive and negative terminals, This current is likely to be very weak but it's there, and that we are likely to have behind the positive and negative terminals, This current is likely to be very weak but it's there, and it isn't the same on the positive terminal as on the negative terminal, which will lead us to talk about polarisation of current and *offset* current.

Notes

Summary

3m 52s

Gain fini en boucle ouverte

Electronique I

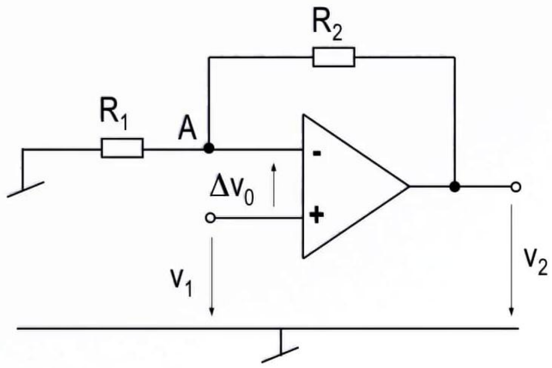
- Etape 1: Potentiel au nœud A

$$v_A = v_1 - \Delta v_0 = v1$$

$$v_A = v_1 - \frac{v_2}{A_v}$$

- Etape 2: Somme des courants nulle au nœud A

$$-\frac{v_A}{R_1} = \frac{v_A - v_2}{R_2} \rightarrow -\frac{v_1 - \frac{v_2}{A_v}}{R_1} = \frac{v_1 - \frac{v_2}{A_v} - v_2}{R_2}$$



$$\Delta v_0 = \frac{v_2}{A_v}$$

Avec A_v est le gain en boucle ouverte de l'amplificateur

The first imperfection of an operational amplifier is the finite gain of an amp. So, up until now, we had considered that an amplifier's gain *Av* was infinite. So each time, we've said that the gain was equal to infinity. And each time we've looked at the voltage difference between the positive and negative terminals compared to the output voltage, we've divided the voltage *v2* by infinity and we've said that *Δv0* is equal to 0. So what happens if this doesn't equal 0 because there is a finite gain? It's a given value that depends on the amplifier. So if you take the voltage of the node *A*, this voltage that appears here, we've always said that this voltage was equal to this one by the fact that *Δv0* is equal to 0. But now, we have to say that this is not the case. The voltage *v1* minus *Δv0* is the voltage that we'll see on the node *A*. So we will write the node *vA* as being the voltage *v1*, and this very *Δv0* as the difference that we've just discovered which is due to the fact that the voltage will be divided by a given value, that this value will be given to us by the manufacturer, and that we will call it i>Av.

Notes

Summary

4m 06s

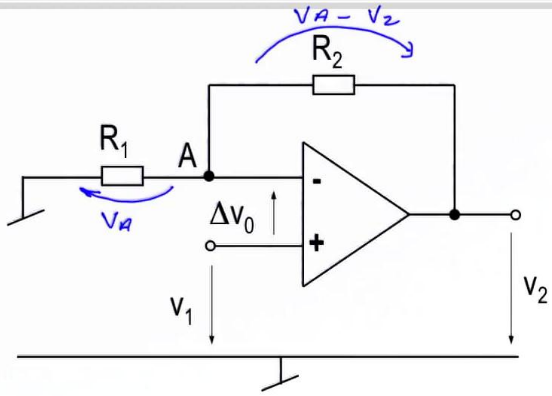
Gain fini en boucle ouverte

- Etape 1: Potentiel au nœud A

$$v_A = v_1 - \Delta v_0 = v1$$

$$v_A = v_1 - \frac{v_2}{A_v}$$

- Etape 2: Somme des courants nulle au nœud A



$$\Delta v_0 = \frac{v_2}{A_v}$$

$$-\frac{v_A}{R_1} = \frac{v_A - v_2}{R_2} \rightarrow -\frac{v_1 - \frac{v_2}{A_v}}{R_1} = \frac{v_1 - \frac{v_2}{A_v} - v_2}{R_2}$$

Avec A_v est le gain en boucle ouverte de l'amplificateur

Electronique I

So this *vA*, it will be *v1* minus a certain value of *v2* over *Av*. And we'll redo the same calculation each time. So we will say that there's a voltage which appears here, a voltage that we will call *vA*. And we're going to see a voltage that appears on that side and that voltage there, will be the voltage *vA* minus the output voltage *v2*. And by writing these two relationships, *vA/R1* this gives us the current that passes through this branch, is equal to *vA-v2/R2*, which is equal to the current passing through that branch there Of course, we also have the minus sign because the voltage is going in the opposite direction, which explains this minus sign. And we write down this relationship by replacing \i1}vA by its value. So I replace *vA* by what we had written here, which will allow us to find this relationship.

Notes

Summary

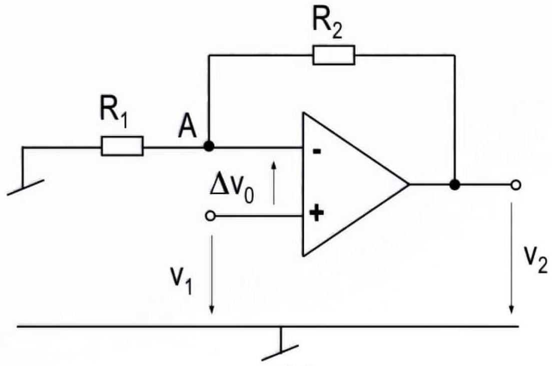
5m 20s

Description de l 'imperfection

- Commentaire

$$\frac{v_2}{v_1} = \frac{A_v(R_1 + R_2)}{(R_1 + R_2) + A_v R_1}$$

$$\frac{v_2}{v_1} = \frac{R_1 + R_2}{R_1} \cdot \frac{1}{1 + \frac{1}{A_v}\frac{R_1 + R_2}{R_1}}$$



$$\Delta v_0 = \frac{V_2}{A_V}$$

Avec A_V est le gain en boucle ouverte de l'amplificateur

Electronique I

So, here's the relationship of the voltage *v2* divided by *v1*, namely our amplifier's gain, taking into account the gain *v1* and simplifying the analytic expression that we derived earlier on from the fact that the voltage *vA* is equal to the sum of *Δv0* and this voltage *v1* whilst respecting the direction of the arrows. So we'll find that the gain *v2/v1* is equal to this formula here. If the gain *Av* had been infinite, this term would disappear and we would fall back on the relationship that we had at the start which is no other than the gain *1+R2/R1*. Now that this gain isn't infinite, now that we've got a finite value, if we need to calculate *v2/v1*, we must look at what the manufacturer has provided us with, which is the value *Av* and put it into this expression here. And here, we've got an exact expression of gain of *v2/v1*. And this is one of the amplifier's limitations and when there is even a small gain with the amplifier, we must take it into account This will give us the a relationship as follows *v2/v1*, which isn't merely proportional to the external resistors that we added ourselves.

Notes

Summary

6m 14s

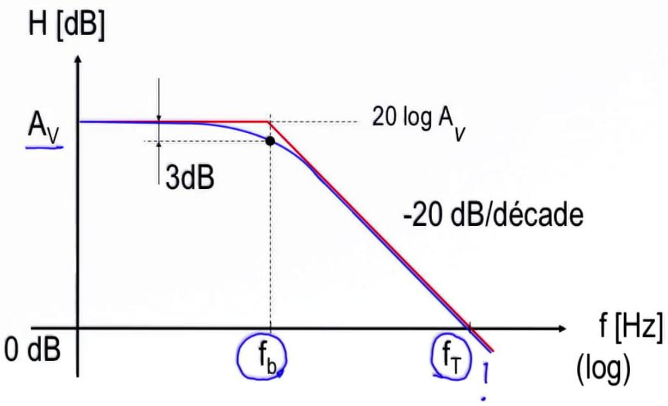
Réponse en fréquence

- A_v = gain de l 'AO en boucle ouverte
- *GBW = Gain Band Width product*

$$\omega_{GBW} = \omega_T = 2\pi f_T = A_v \omega_b$$

- Exemple numérique

$\omega_b = 2\pi\ 10$ Hz
$A_0 = 100'000$ (100dB)
f_T = GBW = 1 MHz
$\omega_T = A_0\, \omega_b = 2\pi\ 10^6$ rad/s



$$\underline{A}(j\omega) = \frac{A_V}{1 + \frac{j\omega}{\omega_b}} \approx \frac{A_V}{j\frac{\omega}{\omega_b}}$$

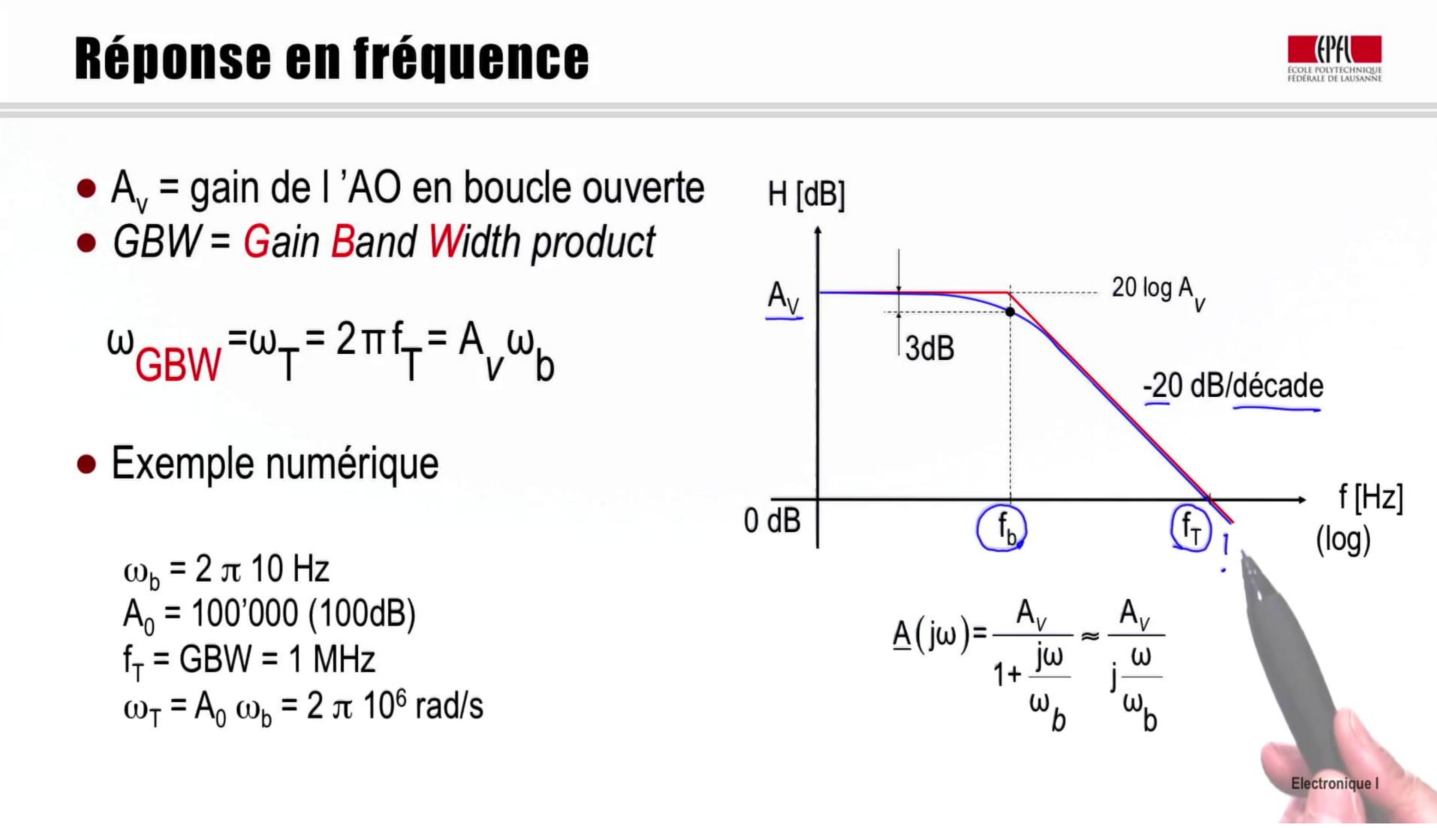
Electronique I

Here is a second imperfection of the amplifier: When we analysed the operational amplifier, we never mentionned the frequency. And if I show you this Bode diagram of an operational amplifier, I'm telling you that the gain that we looked at earlier, the amplifier's open loop gain that we called *Av*, and yes, this gain here is valid in a limited frequency bandwidth and this limited frequency bandwidth is given by a pass-band bandwidth presented by a dominant pole and the Bode diagram of an operational amplifier is a low-pass function, meaning that we've got a constant gain in the low-pass bandwidth up to the dominant pole that we call *fb*. And here, at this frequency we've got an attenuation of 3dB. And there's a frequency that we call the transition frequency. And this transition frequency is an important value in an amplifier, and that all manufacturers, when providing a value, will provide the value of the open-loop gain and of the frequency *fT* called the transition frequency And why refer to it as *fT*? It's the appropriate frequency when you apply a signal at the input that has a frequency *fT*, the voltage that you'll get at the amplifier's output is exactly the same as the voltage So you have a follower with your amp even if the amp isn't in negative feedback.

Notes

Summary

7m 37s

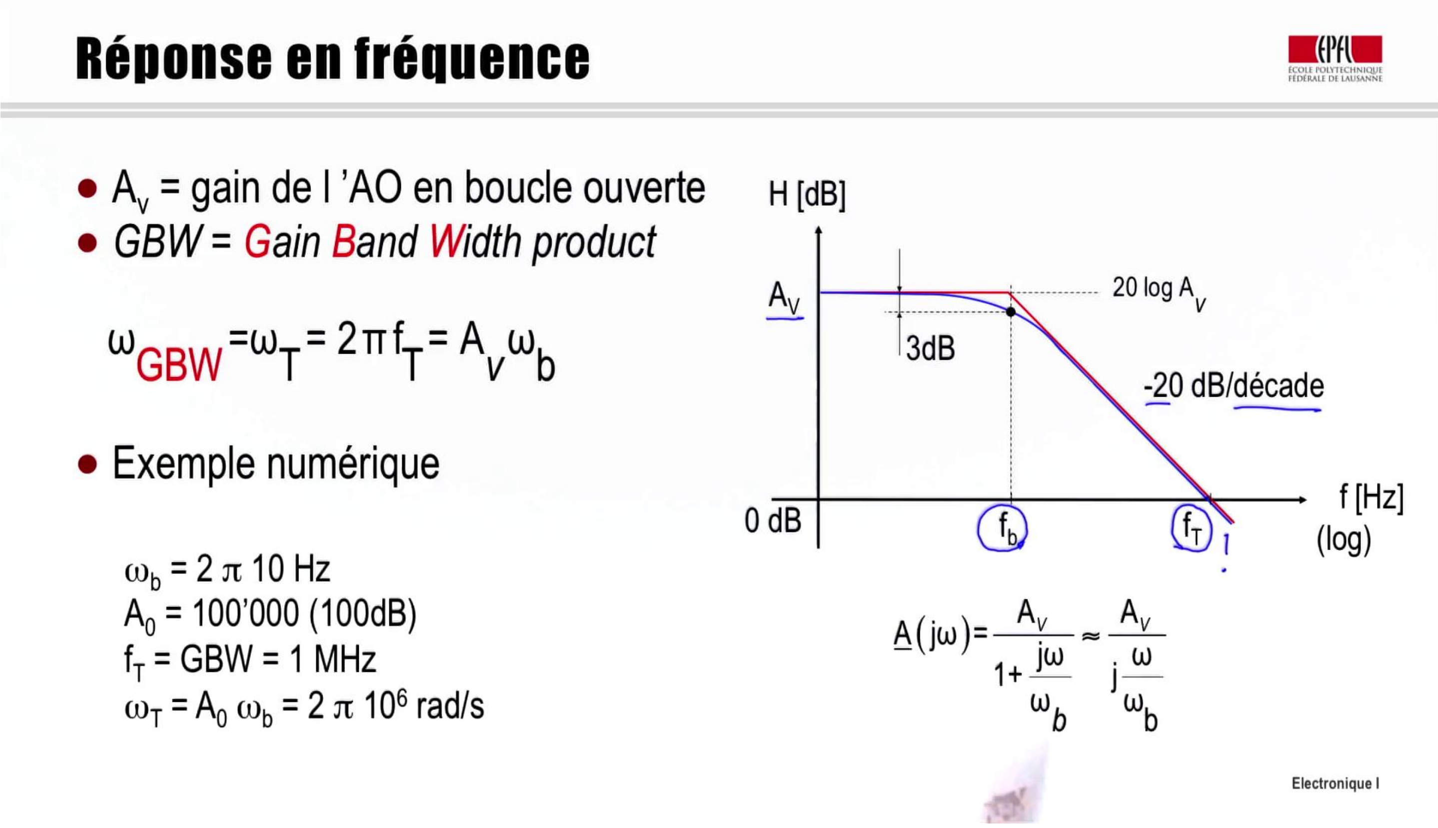


So you'll find, because of this characteristic that when you want to give it a certain gain when you change the frequency and you get to frequency equal to *fT*, you will see that the output voltage is equal to the input voltage. So in other words, an amplifier has an open-loop gain only for low frequencies. So here, we put *fb*, but when you see the value of *fb* is in the majority of low power amplifiers, you'll see that it's only a few hertz. So the open-loop gain which is supposed to be extremely high, even to infinity at first approximation, is in fact limited in frequency, which results in a gain that we call a DC gain, a gain that is quasi continuous voltage. And when the frequency starts to rise, independently from its negative feedback, and it will go down to around -20dB/décade independently from its negative feedback, the amplifier starts to reduce the gain and it will go down to around -20dB/décade the amplifier starts to reduce the gain until the point of the transition frequency. And from here instead of amplifying a signal, your amplifier dampens the voltage. So your output voltage will be weaker that your input voltage.

Notes

Summary

9m 18s

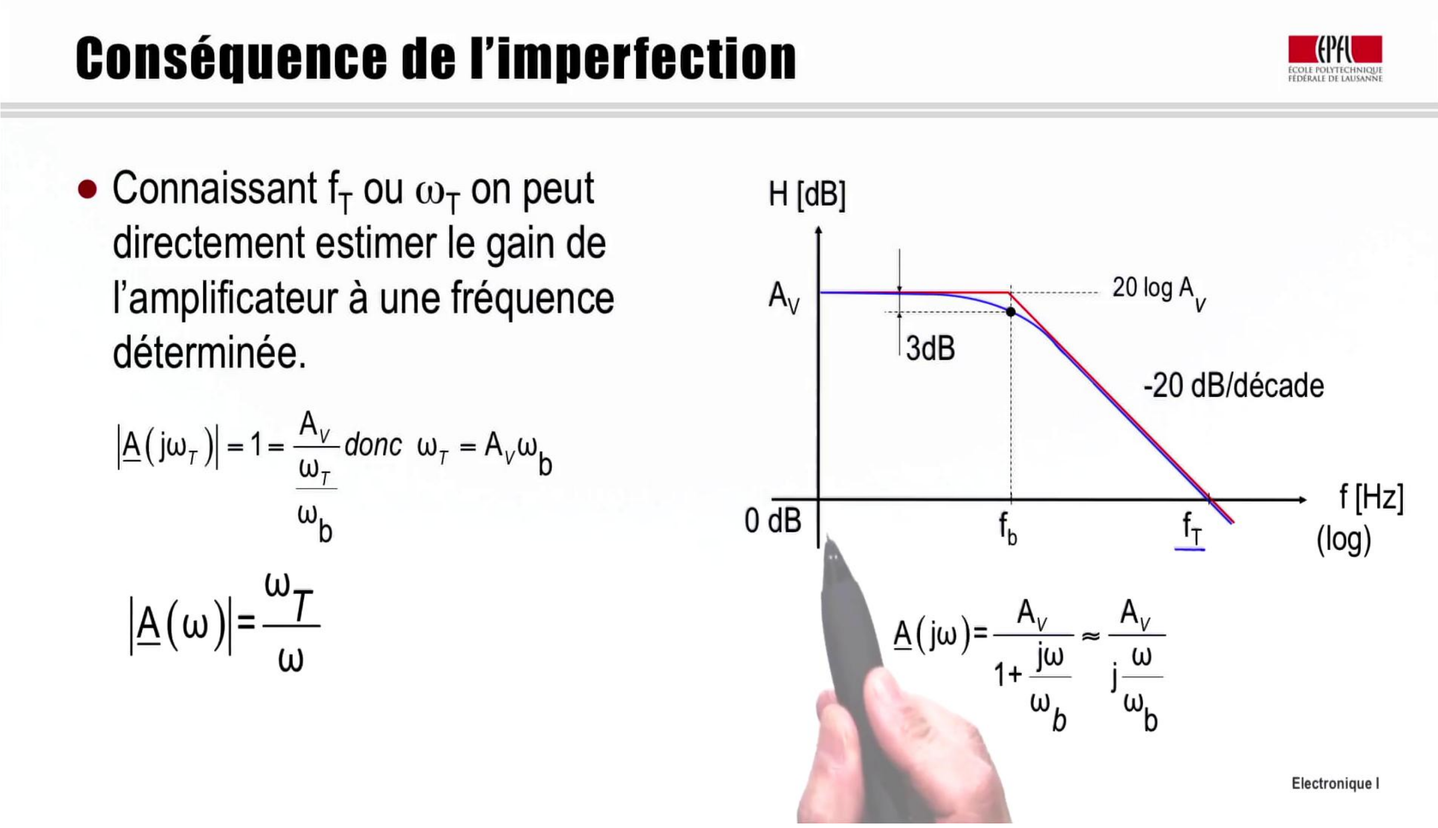


This is the transfer function of an operational amplifier As we've just seen, it is a low-pass filter that has an open-loop gain that we call *Av* divided by *1+jω/ωb* and *ωb* and corresponds to *2 π fb* which is the frequency of the dominant pole. If we consider that *ω* is very high and the the 1, the actual part added to this imaginary part when*ω* is very high, we can overlook the 1 or the actual part to the benefit of this complex part which is extremely high, and approximate the transfer function as if it's *Av* divided by *j* times *ω* over the *ωb*, which is the dominant pole. The *GBW*, or *Gain Band Width product*, corresponds to this pulsation *ωT* here, where we've put *fT*. So this frequency *fT* corresponds to a pulsation that we call *ωT*, but in practice, we call it *ωGBW* and I'll explain why we call it pulsation so that they can be provided by all manufacturers of operational amplifiers and provided in the format *ωGBW* and it's a very important concept because it's thanks to this pulsation, and thanks to the value *Av*, both of these supplied by the manufacturer, that we can deduct which gain will be achieved when we want to generate a feedback loop and give it an finite gain linked to external resistors.

Notes

Summary

10m 32s



So these two values will allow us to define the Bode diagram of our amplifier once in negative feedback. So if you take a digital example, I've shown here that up to around 10Hz, so a very, very low frequency for*fb*, this one here representing the gain, I have chosen an amplifier that shows a fairly high gain of 100 000 so we've got 100dB, and which has a transition frequency, so a frequency of *GBW* equal to 1 MHz. So here, the Gain Band Width product of our amplifier is *2π10^6*, taking into account the different values that I've given here. Let's return to this characteristic and look at the fact that this pulsation *ωT* will always be equal to the product of the open-loop gain multiplied by the dominant pole of your operational amplifier that we call the frequency *fb* and therefore a pulsation *ωb*. If you look at what's happening to this frequency here, or to the pulsation of *GBW*, the gain is equal to 1. So we've got 0dB on this axis. The output voltage is equal to the input voltage and we're talking about a gain equal to 1 because of this specification of the amplifier.

Notes

Summary

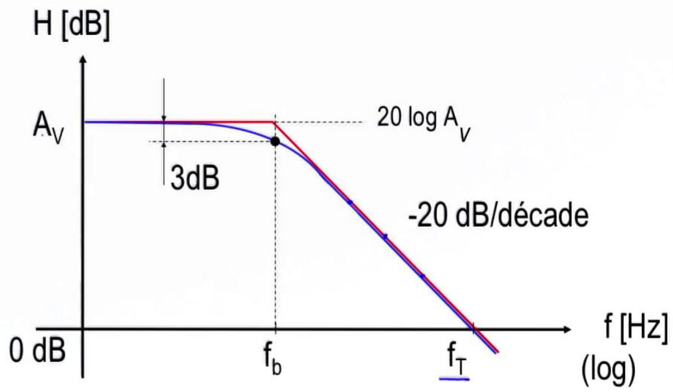
12m 17s

Conséquence de l'imperfection

- Connaissant f_T ou ω_T on peut directement estimer le gain de l'amplificateur à une fréquence déterminée.

$$\left|\underline{A}(j\omega_T)\right| = 1 = \frac{A_V}{\frac{\omega_T}{\omega_b}} \quad donc \quad \omega_T = A_V \omega_b$$

$$\left|\underline{A}(\omega)\right| = \frac{\omega_T}{\omega}$$



$$\underline{A}(j\omega) = \frac{A_V}{1+\frac{j\omega}{\omega_b}} \approx \frac{A_V}{j\frac{\omega}{\omega_b}}$$

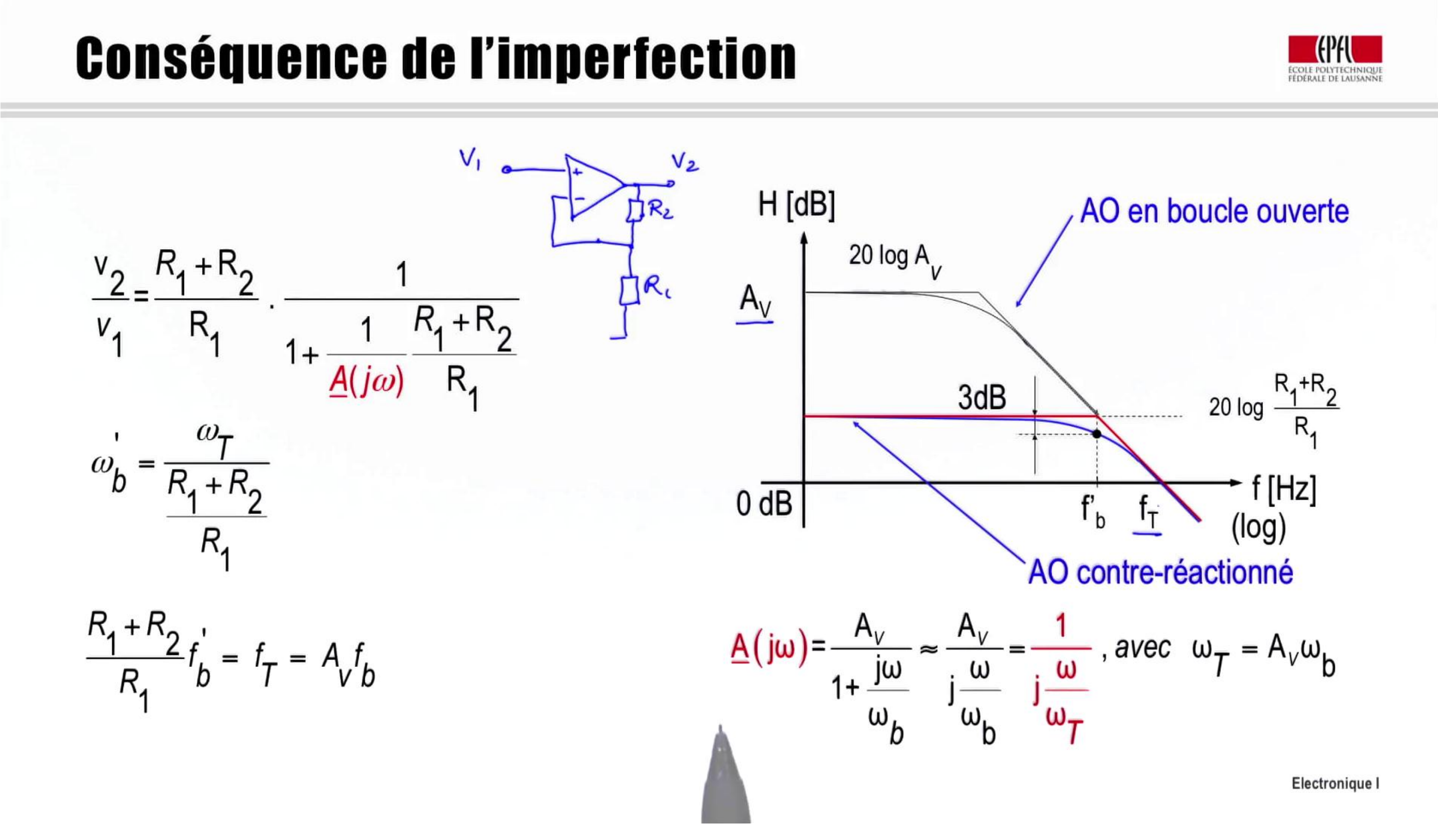
Electronique I

So when I replace ω by ωT, I should find a pulsation ωT divided here by the dominant pole of my amplifier, and that the open-loop gain at the numerator and all this should altogether give me a gain equal to 1 because it has become a follower. So if you develop this you'll find that ωT is equal to Av, open-loop gain, multiplied by ωb. So the gain band width product is equal to ωGBW, we can also call it ωT. And if you use this expression, it's the same as the demonstration, the value provided by the manufacturer, As the manufacturer supplies this value, you do not require the ωb because you can work it out for yourself Each time that you will put you amplifier into negative feedback because you'll find yourself in this range on the Bode diagram, all of which will give you a product gain times the Gain Band Width product is equal to the constant is equal to fT. So we can write down: for any type of pulsation of our operational amplifier, we will achieve a gain that is equal to ωT divided by the ω at which we are using our amplifier.

Notes

Summary

13m 45s



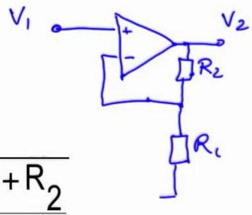
And now, here is what will happen with any kind of amplifier that you may use. with any kind of amplifier Any amplifier you may purchase will have an open-loop gain, that you may use. Any amplifier you may purchase will have an open-loop gain, and a transition frequency. You're going to put it in negative feedback. When it's in open-loop, you don't have to add external resistors. Let's imagine that you take your amplifier and turn it into a negative feedback amp in the following way. So, you add a resistor here and a second resistor there your output will depend on an input voltage that we call *v1*, a voltage output that we call *v2* and there's a resistor here that's called *R2* and another one that's called *R1*. Earlier on, we calculated the expression of the relationship *v2* over *v1* taking into account he amplifier's gain. And we' ve realised that the gain of this amplifier is nothing more than a transfer function. So I can replace this transfer function with its value, the one I've just found here.

Notes

Summary

15m 09s

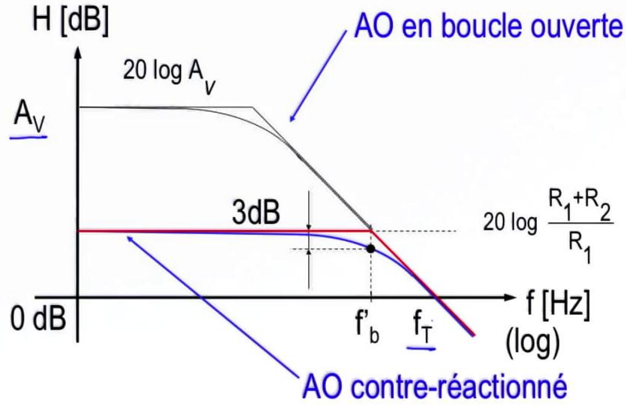
Conséquence de l'imperfection



$$\frac{v_2}{v_1} = \frac{R_1+R_2}{R_1}\cdot\frac{1}{1+\frac{1}{\underline{A}(j\omega)}\frac{R_1+R_2}{R_1}}$$

$$\omega_b' = \frac{\omega_T}{\frac{R_1+R_2}{R_1}}$$

$$\frac{R_1+R_2}{R_1} f_b' = f_T = A_v f_b$$



$$\underline{A}(j\omega) = \frac{A_V}{1+\frac{j\omega}{\omega_b}} \approx \frac{A_V}{j\frac{\omega}{\omega_b}} = \frac{1}{j\frac{\omega}{\omega_T}}$$, *avec* $\omega_T = A_V\omega_b$

Electronique I

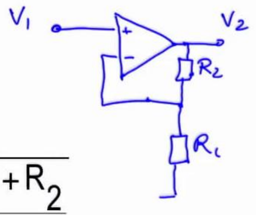
By simplfying it and considering that for fairly high ω I can overlook the 1 in favour of the complex number, and we can choose for any given pulse ω and we'll find that for *1/j(ω/ωT)*, when we replace the product that we've just found that everytime time, the gain product times the low-pass bandwidth is equal to ωT, by replacing this here, we are going to find this relationship that I've highlighted in red. And for any gain that you will realise with your amp using the two external resistors that you have added, you can deduct straight away the low-pass bandwidth which is linked to the limitation of the low-pass bandwidth of your amplifier supplied by the manufacturer in the form of *fT*. If you know this *fT*, you will always write down this expression when looking for this *f'b* value in order to identify the pulsation, or the frequency at which your amplifier will show a gain and a dominant pole, that the position on this asymptomatic diagram will be defined by the external gain of your amplifier that is caused by your two resistors, and that when you achieve a pulsation and you will meet the curve of your amp.

Notes

Summary

16m 16s

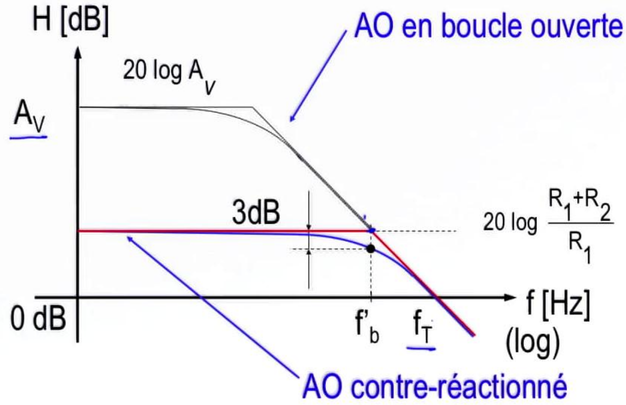
Conséquence de l'imperfection



$$\frac{v_2}{v_1} = \frac{R_1+R_2}{R_1} \cdot \frac{1}{1+\frac{1}{\underline{A}(j\omega)}\frac{R_1+R_2}{R_1}}$$

$$\omega_b' = \frac{\omega_T}{\frac{R_1+R_2}{R_1}}$$

$$\frac{R_1+R_2}{R_1} f_b' = f_T = A_V f_b$$



$$\underline{A}(j\omega) = \frac{A_V}{1+\frac{j\omega}{\omega_b}} \approx \frac{A_V}{j\frac{\omega}{\omega_b}} = \frac{1}{j\frac{\omega}{\omega_T}}, \ avec \ \ \omega_T = A_V\omega_b$$

Electronique I

So the amp is going to lower your signal by counts of 20dB/décade and it will lead you to see this filter function because of its original specification. Each time you will find the value of this *f'b* or express it as being *f'b*, the value which is here, multiplied by the gain that you have just realised via the external resistors, and is always equal to a constant, is equal to *fT* and which is always equal to *Av* multiplied by the *fb* of the amplifier before the negative feedback. And voilà, each time that you come to use an operational amplifier you can deduct yourselves the value of the low-pass bandwidth and that manufacturer has provided you with *fT*, you can deduct yourselves the value of the low-pass bandwidth that will be achieved when you generate a negative feedback with a gain of your choice depending on external elements. Be aware that this is a constant phenomenom because the product, the *GBW* of your amp is constant and always equal to its open-loop gain multiplied by *fb*.

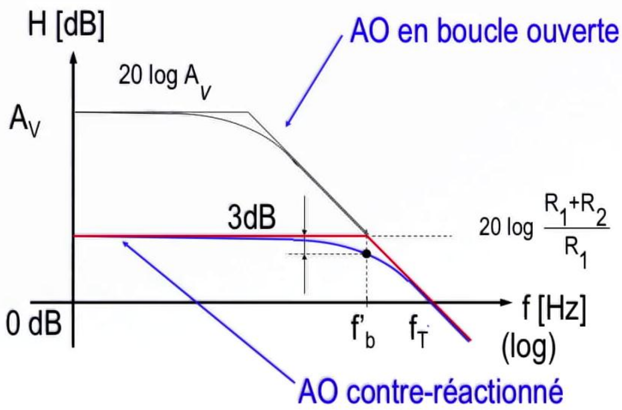
Notes

Summary

17m 38s

Résumé

- Plus faible est le gain en boucle fermée, plus large est la bande passante.
- Produit gain x bande passante = f_T



Electronique I

To summarise what we've just seen, the weaker the closed-loop gain, the wider the low-pass bandwidth. If you now look at this expression this is constant, which is supplied prior to using your amp, you can't go beyond *fT* and this *fT* has already been fixed in the manufacturer's specifications. So using this information you should straight away be in a position to calculate the gain which can be achieved with your amplifier depending on your signal and on the negative feedback that you have added. So we've just seen that an operational amplifier's gain and its low-pass bandwidth, are firmly linked and that every time we want to achieve a high gain, we have to increase the low-pass bandwidth along with it because we will always have the low-pass gain product of an amp equal to a constant pulse which is equal to this famous transition frequency, or the frequency that corresponds to what we have referred to as the *GBW* or the ω of *GBW*. So, each time that we purchase an amplifier on the market, or that we choose amplifiers that have an increasingly higher gain, be aware that they are weaker in frequency and that when you're looking for a wide bandwidth on an operational amplifier, unfortunately, you'll often have a weaker gain. These are compromises that you need to be aware of. and vice versa.

Notes

Summary

18m 41s