DC Servos - Tips, Traps & Applications

Rod Elliott - Elliott Sound Products

Elliott Sound Products	DC Servos

Updated March 2023

Main Index **Articles Index**

Contents

Introduction

A number of audio circuits use a DC servo circuit, with the idea being to remove all traces of DC from the output of a preamp or power amp. Apart from the (IMO) complete futility of making audio equipment DC coupled throughout, it's also potentially dangerous to loudspeakers in particular. Operating any audio gear with response to DC is asking for trouble, and it should be obvious that a DC servo will *not* (by definition) allow operation to DC. The idea that a DC servo removes DC but doesn't affect AC (at any frequency) is simply untrue. Unless the DC servo is set for an unrealistically low frequency (0.01Hz for example), it *must* and *does* affect the low frequency AC as well. At question here is whether this is more or less 'intrusive' than a couple of capacitors.

A good part of this has come from the stupid idea that "The best cap is no cap." The best cap is a cap that's been chosen to ensure that your loudspeaker drivers will never be subjected to DC or very low frequencies that aren't audible anyway. It will usually be polyester, sometimes people insist on polypropylene, and in many cases an electrolytic cap is used. Despite all the objections, provided the voltage across *any* capacitor is low enough, the distortion contributed is negligible. Phase shift is often stated as a 'good' reason to avoid using an input cap, but a DC servo can actually make it *worse*. It's easy to ensure that there is close to zero phase shift at any frequency of interest, simply by using a larger cap than normal.

When you include a DC servo system, it creates issues of its own, and these are rarely discussed by anyone. There is also additional complexity in the overall circuit, which is sometimes considerable. A power amplifier will run from fairly high voltage supplies (typically in excess of ±25V), but the DC servo needs an opamp, which requires a lower voltage (around ±15V maximum). That means additional regulation is needed, which may only include a couple of resistors and zener diodes, but may use regulator ICs instead. In a combined preamp and power amp, the DC servo(s) can be run from the preamp supplies, and now two supplies are needed for the power amp board(s) - operating voltages and servo supply voltages.

This all means that there are more parts, more connectors and (obviously) more things that can go wrong. If any part of the DC servo circuit fails, there's every chance that the circuit will develop a DC output as a result, and that may be sufficient to cause speaker failure in a fully DC coupled system. The chance of a capacitor failing in such a way as to cause the same problem is very small - so small as to be considered negligible in most cases.

For anyone who thinks that caps are 'evil' (hint; they aren't) the only way to ensure a low DC offset is to use a DC servo, but as you'll see these impose their own special constraints. In many cases, the servo may be more intrusive than using capacitors, and I can't see how this can be considered a sensible approach. However, DC servos definitely have their uses, and dismissing them out of hand would be just as silly as rejecting capacitors because they 'ruin' the sound (another hint; they don't).

It must be remembered that any DC servo system will be set up so that it can remove *small* amounts of DC offset - perhaps up to ±1V or so would be a sensible maximum. If a faulty preamp is connected with (say) 5V DC at its output, the DC servo system will not have enough range to remove that much, so the power amplifier will provide DC straight to the speakers (which will announce their displeasure by liberating 'magic smoke'.

Consider that just about every piece of music you listen to has already passed through countless capacitors within the recording process. Not just coupling caps, but those used for equalisation (whether vinyl or CD - EQ is almost invariably used during recording), and even in microphones such as capacitor (aka 'condenser') mics or any other that has electronic circuitry. It's unrealistic to imagine that every piece of equipment used for recording only contains capacitors with the most advanced dielectrics available, because the vast majority will include no such thing. It's equally unrealistic to assume that if no capacitors are used in the playback audio chain it will make anything sound 'better'.

By definition, an amp or preamp using a DC servo cannot reproduce DC. The servo will operate and remove (or *try* to remove) the DC component, but if it's large enough to saturate the servo opamp then DC will get through anyway. Everything has its limits, and no ideal devices exist, so the end result will always be a compromise.

This is *not* to say that the DC servo is 'pointless'. There are countless pieces of equipment that rely on a DC (or other) servo for their operation, and the purpose of this article is to provide useful information, and not to dissuade anyone from adopting a DC servo if it suits their purpose. When used for some *perceived* benefit (such as eliminating capacitors from the signal path), then the actual benefit may be far less than expected. All circuit building blocks have their place in electronics, and it's up to the designer to determine what is necessary to achieve the desired goals. If this includes a DC servo, then that's what should be used.

---

1 - DC Servo Operation

Before continuing, not everyone will know what a DC servo is or how it's used, so some explanations are in order. If a circuit has a DC error (i.e. some amount of DC output when it should be zero), a servo is used to provide just enough input offset to correct the output and set it to zero with no signal. The servo is almost always a fairly simple integrator, most commonly using a FET input opamp to allow low values of capacitance and high resistances. Some practical examples are shown further below.

The integrator is set up so that it provides negative feedback, but with very high DC gain to maintain a low final error. Even a 'pedestrian' opamp such as a TL071 has a DC open loop gain of at least 100,000 (100dB) and often more. The primary error term in the final system is the opamp's input offset voltage (typically 2-3mV, but usually less in practice). The overall open-loop gain (i.e. before feedback is connected) of an amplifier and servo for DC and *very* low frequency signals can easily exceed 120dB (1,000,000).

The DC servo provides a very large open-loop gain improvement over the amplifier circuit by itself. This is (by design) limited to sub-audible frequencies, and the additional DC gain provided by the servo's opamp is able to remove DC offset almost completely. By design, few power amplifiers have a high enough open loop (or DC) gain to be able to effectively eliminate any DC offset. The opamp (and associated integrator) ensure that there is more than sufficient DC gain to reduce overall DC offset to negligible levels.

Note: The ultimate limitation of *any* DC servo is the DC input offset voltage of the opamp used for the servo itself. For an opamp such as the TL072, the 'typical' input offset voltage is 3mV, and unless you include a DC offset control for the servo opamp, the main amplifier's output DC offset can be no better than this. I mention the TL072 because it's ideal for this purpose, having very low input current which minimises errors due to this factor. The integrator's input DC offset has been assumed to be *zero* for the following discussion, but it will rarely be so in practice.

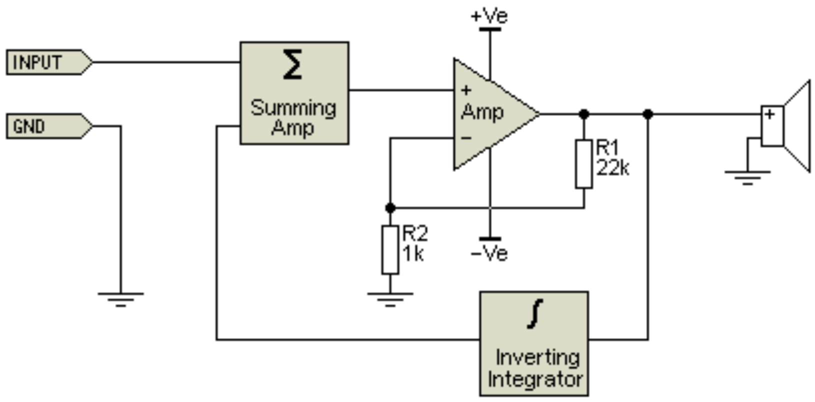

Figure 1 - Basic DC servo Principle

The basics of a DC servo are shown above. The integrator (∫) essentially ignores AC, and produces the integral (in simple terms, the average) of the output. If it happens to be some value of DC, then the output of the integrator will be just that, provided of course that the AC component is at a frequency high enough to be 'ignored' by the integrator itself. Note that the integrator is inverting. The input and integrator are then summed (∑) so that any DC at the amplifier's output is effectively cancelled.

The circuit has been shown connected to a loudspeaker (this site is mainly about audio after all), but in reality it can be any transducer, as may be used for scientific, medical, industrial or other application(s). DC servos are used in some unlikely places, but the same principles apply regardless. Because they *are* DC servos, much of the complex feedback loop stability criteria may not be necessary, but as you'll see below, just the addition of an input capacitor can mess that up badly.

---

2 - Inverting DC Servo

In Figure 2, there is an amplifier circuit (shown simply as 'Amp') and a DC servo circuit (shown as U1). If the amplifier shows any sign of DC at the output, this is integrated by U1, and that signal is applied to the amp's input to correct the offset. Let's say that the amplifier (for whatever reason) has an output DC offset of 620mV (corresponding to an input DC offset of around 27mV). While that won't hurt a loudspeaker (power into an 8 ohm driver is only 49mW) it may cause a small but unacceptable shift in the speaker cone's static position. In some other applications, it may be catastrophic (for example, driving a transformer).

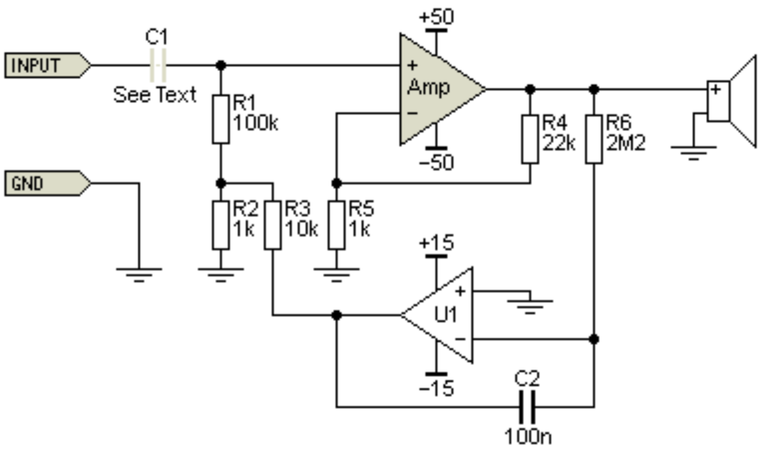

Figure 2 - Practical Inverting DC Servo

When the DC servo is connected, the initial DC is still 620mV, but the servo circuit reduces that to less than 1mV within a few seconds. After around 15 seconds (when the circuit has fully settled), the DC offset is about 100µV - a significant improvement. Any DC at the output of the amp is integrated by U1 (via R6 and the integration capacitor C2), and once settled the output of U1 applies exactly the right amount of DC offset to the input to force U1's output to (close to) zero. With the values shown (and a DC offset of -630mV without the servo), the servo's output voltage will be +300mV, and it feeds just enough correction to the amp's input to force the offset down to only 100µV. The (passive) summing point is the junction of R1, R2 and R3.

However, the circuit shown is now sensitive to the source resistance, which has to be in excess of 20k or the DC servo is unable to make the correction needed. U1 can supply a maximum output voltage of around 13V, and this can't force enough current through the bias network (R3, R2 and R1) to cope with low impedance inputs. This is obviously unacceptable, since most sources have an output impedance of close to 100 ohms, so the DC servo can't function. There's another problem as well, in that if the source is connected or disconnected while the amp is on, it takes time for the servo to reset itself to suit the changed conditions. With an audio system, the speaker will make a fairly loud 'thump' as the input is changed. You also can't use an input pot, because the DC will make it noisy (and it will cause more issues with source impedance).

One answer is to include C1 (shown greyed out) so the DC servo feedback path is isolated from the source. This has some unexpected consequences though, because there are *two* time constants involved in the feedback path, which cause some potentially serious issues. This means that we *do* need to concern ourselves with feedback loop stability. The graph below shows what happens if you use a 100nF, 1µF and 10µF cap for C1. With 10µF there's some bad ringing as the circuit settles, and this also shows up in the frequency response at very low frequencies. The frequency response shows a peak of more than 6dB at 0.36Hz, and although well below audibility, it *will* cause 'disturbances' when stimulated by the audio signal. If C1 is reduced to 100nF, settling time is as close to perfect as you'd ever need, but response is about 2dB down at 20Hz. This is almost certainly unacceptable.

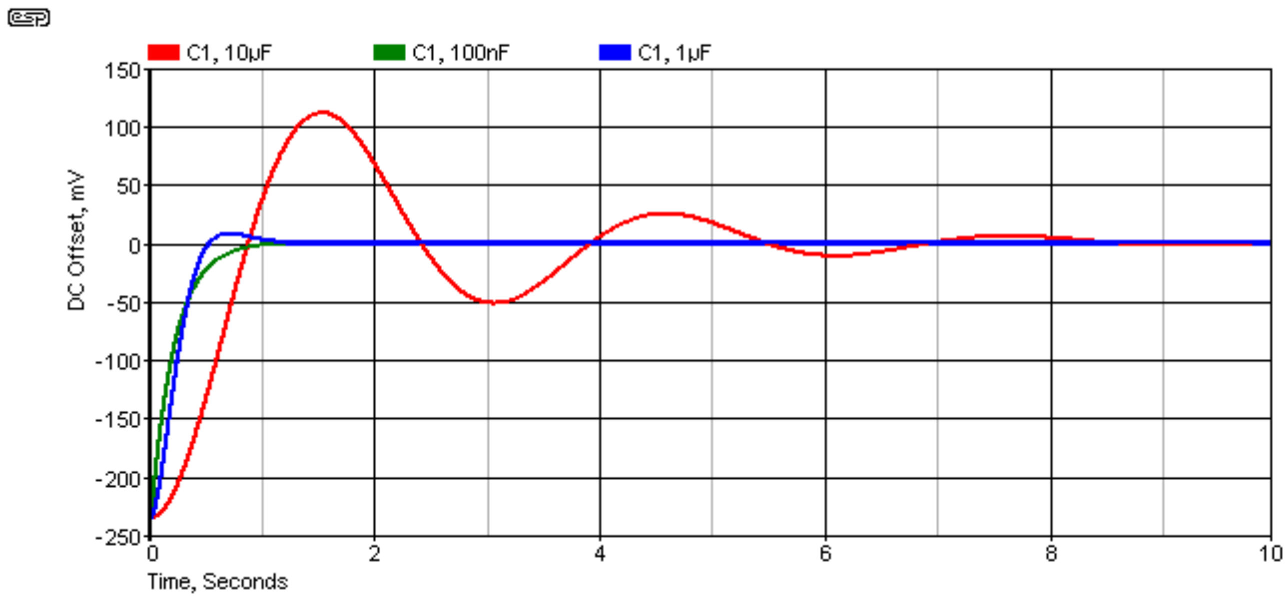

Figure 3 - Effect Of Two Time Constants In Input Circuit

Using a 1µF cap for C1 gives a perfect response, with just the smallest overshoot and no low frequency boost where you really don't need it. Unfortunately, the servo makes the input capacitor value critical for proper circuit behaviour, something that isn't usually a problem. We've come to expect that altering the low frequency response is simply a matter of changing the input capacitor, but once a DC servo of the form shown is in place, the capacitor value becomes a critical part of the circuit. In particular, the response of the red trace is not simply undesirable, it's potentially dangerous! There's more on that further below.

While they are used sometimes, inverting DC servos are the least desirable way to achieve the goals expected. An input capacitor should be considered *mandatory* to prevent possibly serious interactions with the source impedance/ resistance. The capacitor value has to be selected with care, and extensive tests are needed to ensure that the circuit is absolutely stable. A damped oscillation or premature rolloff will result if the cap is too large or too small (respectively). Consider that many sources (e.g. preamps) have an output capacitor, and that may interact very badly with the power amplifier/ servo combination.

---

3 - Non-Inverting DC Servo

If the DC servo is non-inverting so its output is at the same polarity as the amp's output, the correction signal can be applied to the negative feedback point of the main amplifier to correct any error. This overcomes the problem of the input capacitor, because it's no longer part of the DC feedback loop. The value can be changed at will (or even left out if you are particularly brave) without affecting the response of the DC servo. Note that if there is *any* DC potential at the amp's input, that can cause issues, and the servo may not have sufficient range to change that.

The resistance of the DC feedback resistor now becomes part of the main amp's feedback circuit, so it has to be high enough as to not adversely affect the desired gain. With the values shown below, the gain is affected very marginally, but it won't normally be a problem. You need to be aware that when used like this, the opamp's output noise (and any distortion that may be created) will be injected into the amplifier's feedback loop, so that needs to be considered in circuits designed for very low noise. The opamp's output is also part of the feedback loop, and by extension is also part of the signal chain.

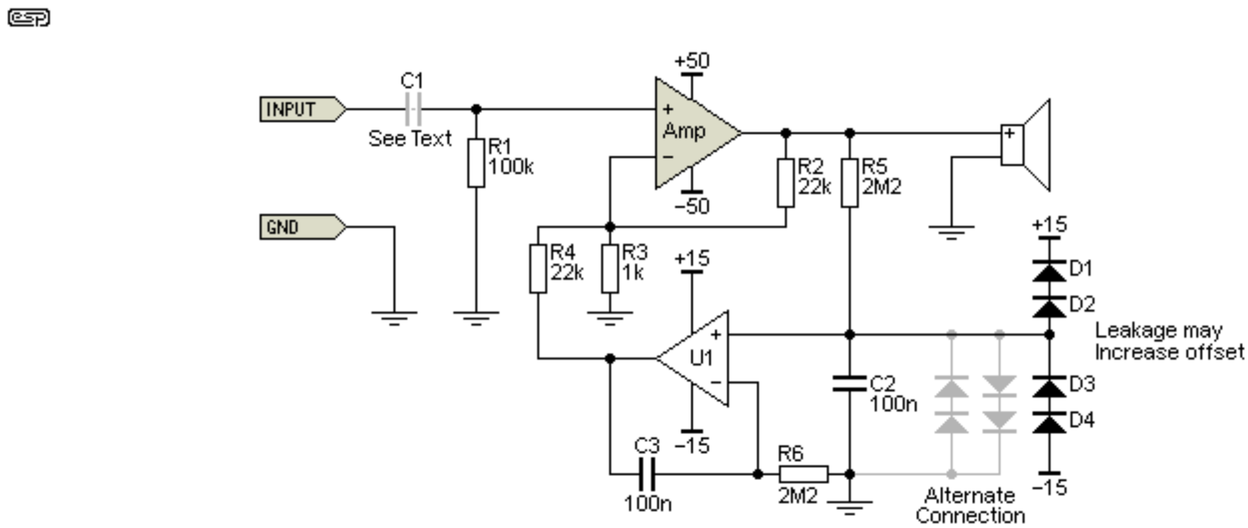

Figure 4 - Non-Inverting DC Servo Connections

The input to the DC servo opamp must be constrained so that it's within the opamp's input voltage range. If the amp has supply voltages of ±50V, you can't apply that to an opamp's input because it will die. Now, we can either add an attenuator (which will badly affect performance) or get clever (the preferred choice whenever possible). If a passive integrator is used we can ensure that nothing below 1Hz can cause a problem, and the opamp's input can be protected easily because of the high impedance. An interesting point about this circuit is that the rolloff is 6dB/ octave, and *not* 12dB/ octave as you might expect. This is fortunate, because it means that only one time constant is involved (2.2MΩ and 100nF). The benefit of the circuit shown is that it has far greater gain at DC (and below 1Hz).

The diodes protect the opamp's input from fault voltages. Note that when diodes are connected in the 'preferred' position, leakage can cause the servo to adjust the output voltage to a few millivolts (rather than less than 1mV). This is minimised by using lower value resistors and higher value caps. For the circuit shown, 100k resistors and 2.2µF caps minimise any offset created by diode leakage. An alternative is to use two (or even three) diodes in series at each location.

Despite the capacitor from the servo opamp's output to input, this is not an integrator. The cap allows the opamp to run at maximum gain for DC voltages, but doesn't add any usable AC filtering. In theory it can use lower (or higher) values, but it's more sensible to maintain C2 and C3 at the same value. This ensures that the circuit is unconditionally stable and has no very low frequency response aberrations which will occur if the values are different. Likewise, R5 and R6 should also be the same value, both to maintain a stable circuit and minimise opamp input DC offset.

If the servo is configured any other way, it will reduce the available gain of the DC servo, and that affects the ability of the circuit to remove DC. With the arrangement as shown above, the servo can pull the offset back to well under -25µV (as simulated). No-one actually *needs* offset to be that low, but nor does it hurt anything. This is obviously a far better option, as it means that you can use any value of input capacitor you like (including no cap at all), but beware if part of the DC offset problem is actually caused by the input stage of the power amp. That will cause a pot to become noisy, and will also 'upset' the delicate balance achieved by the DC servo when the level is changed. It will correct for any change, but it's not instant (it will take up to 1.5 seconds to re-settle with the values shown).

The servo's settling time is an important consideration, and it should be *at least* twice the periodic time of the lowest frequency of interest. If you expect the amp to be flat to 10Hz, that's a period of 100ms, and the integrator requires a time constant of at least 200ms (2.2MΩ and 100nF gives 220ms). In a simulation, response was still flat to 2Hz with the circuit shown. Making the servo slower will allow lower frequencies, but there's no point because 2Hz is already well below any audible (or reproducible) frequency. The calculated (and simulated) -3dB integrator frequency for the values shown is ...

$$f = 1 / (2\pi \times R \times C)$$
$$f = 1 / (2\pi \times 2.2M \times 100n) = 0.72Hz$$

It may be unexpected, but the integrator's -3dB frequency does not necessarily correspond to the *amplifier's* -3dB frequency. The value of the DC servo output resistor not only changes the amplifier's gain, but also the low frequency -3dB point. With R4 being 22k as shown, the amp has a -3dB frequency of 0.72Hz, as expected. If the value of R4 is increased, the -3dB frequency is reduced and vice versa. For example, if R4 is 100k, the -3dB frequency is 0.16Hz. Provided the integrator's frequency is low enough (aim for less than 1Hz), you don't need to worry too much about it. If you choose to worry anyway, the amp's -3dB frequency is inversely proportional to the value of R4. Double R4 to 44k, and the -3dB frequency is halved, to 0.36Hz. Below the integrator frequency, the amp's response falls at 6dB/ octave.

Note the connections for the two diodes. These are sometimes placed in reverse-parallel with C2 (shown as 'alternate connection', in light grey), but this is basically a very bad idea. The reason is distortion, and this is covered in the following section. It appears that many people seem not to have noticed that this can create measurable distortion with high-level, low-frequency amplifier output signals. The method shown (with diodes in black) is a far better option, provided the integrator frequency is low enough. No audio signal should ever be able to drive the opamp's input outside its linear range.

In general, the non-inverting DC servo is to be preferred in almost all cases. It's inherently stable and has no 'bad habits'. There may well be cases where it's not appropriate, but these are likely to be few and far between. It's essential that you know about both possibilities, because one never knows where a particular electronic building block will be used, and the idea is to pick the topology that works best in the final circuit.

---

4 - Inverting Power Amplifiers

In some cases people operate power amplifiers wired as an inverting amplifier. This isn't especially common, but it may be done for one amp in BTL (bridge-tied-load) configuration. A DC servo doesn't really care very much is the amplifier is inverting or non-inverting, provided the DC feedback applied is negative. It's easy to inadvertently connect the servo's output to provide *positive* feedback, which will result in the amplifier developing a very high DC output voltage (usually close to one or the other supply rail). It's obvious that this would not be good.

If the power amp is inverting, it may be tempting to use an inverting servo, supplying the necessary DC offset compensation to the unused non-inverting amplifier input. The signal to the non-inverting input will typically be bypassed so that it's at earth (ground) potential for AC, as is usually required to ensure proper amplifier function. This approach can produce some rather alarming (and undesirable) results, and it's very hard to recommend. Figure 5 shows an example circuit.

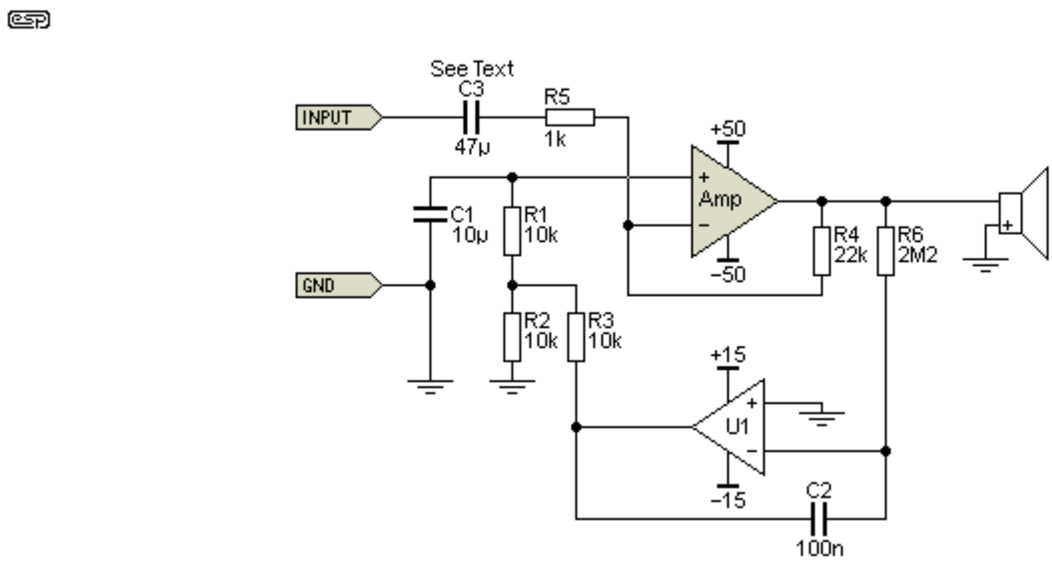

Figure 5 - Inverting Amplifier With DC Servo

This circuit is basically the same as shown in Figure 2, except that the input is now via R5, connected directly to the inverting input of the power amp. The resistors (R1, R2 and R3) have been adjusted to 'sensible' values for this topology. It appears that it should be quite alright, but as discussed with the inverting DC servo, there are some issues that make this approach unstable. The ringing waveform seen in Figure 3 is back in full force, due to the two time-constants (R6, C2, and R1, C1). Not only does this create ripple as the circuit settles, but it creates a resonant boost of 9dB at 3Hz. The only way to prevent both the settling-time ripple and dangerous low frequency boost is to use an input capacitor (C3) in series with R5. The value is critical (again), and with the values shown it has to be 47µF, which ensures complete stability. Alternately, C1 can be reduced to

1µF and C3 bypassed, which also results in stable operation. However, noise from the servo is not attenuated as well.

C3 is optimal at 47µF. Any other value for C3 (and especially no capacitor at all) will provide results that are entirely unacceptable unless C1 is also adjusted. The response with C3 shorted out is shown below, and it should be immediately apparent that this is not a good idea. By way of contrast, if the circuit is used with a non-inverting servo system, it makes no difference if the input capacitor is there or not, and the circuit is much better behaved. Any system that has critical capacitor and/ or resistor values is inherently unstable, and if there is any deviation 'bad things' will happen. By ensuring the servo is unconditionally stable, the potential issues are avoided.

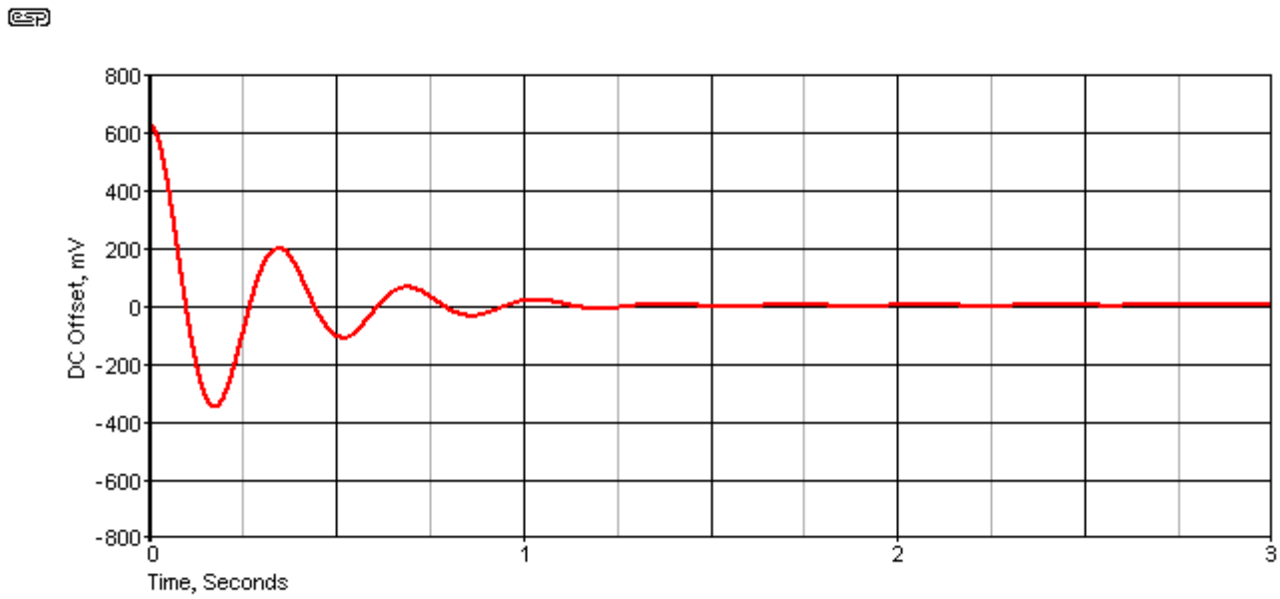

Figure 6 - Inverting Amplifier Settling With DC Servo And C3 Shorted

The initial offset is 600mV as simulated. A damped oscillation such as that shown above is always a sign that something is wrong, and it will occur every time there is a change of impedance at the input. Adding the capacitor provides additional damping that removes the oscillation, but as noted the value is critical. It's also a large value, and the only viable part is an electrolytic capacitor. With the values shown (and *including* C3), the phase shift at 10Hz is 23 degrees. The circuit does behave itself if the input is left open circuit, so at least that's not something you'd need to be concerned about. One advantage of an inverting servo is that you don't need to be so concerned about protective diode leakage.

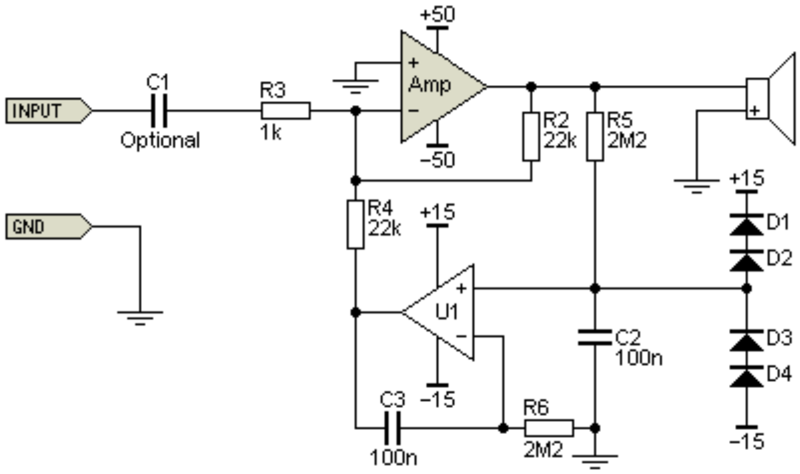

Figure 7 - Inverting Amplifier With Preferred DC Servo

The arrangement shown above is a far better proposition than that shown in Figure 5. It behaves itself without ringing or other misbehaviour regardless of whether you include an input capacitor or not, and is the circuit I'd recommend. A power amplifier is no place for any circuitry that's potentially unstable, because you can never know the exact specification of the preamp driving it, unless the driver circuit is within the same chassis. No performance graphs are shown simply because there's no need for them.

This circuit will increase the amplifier's noise floor very slightly, both because it's an inverting amplifier which has an inherently higher noise that a non-inverting circuit anyway, and also due to the opamp's output injecting opamp output noise into the summing point (the junction of R2, R3 and R4). R1 is not used in this arrangement.

---

5 - Phase Response

In the introduction, I stated that a DC servo can (and does) introduce low frequency phase shifts, and that this can be worse than using a capacitor. We need to examine the circuit to see how this is true, because a DC servo may be used by some people in the belief that it eliminates low frequency phase shift. A quick look at Figure 4 shows that there is feedback at DC, but importantly, low frequencies must also be affected. While a DC servo does remove the DC offset, it must pass some AC as well, because it's basically a fairly simple low pass filter. The *only* component that absolutely removes DC is a capacitor, which can be as large as you wish so it doesn't affect anything within the audio range.

Looking at the Figure 4 circuit, you see that there are two integrators, with an effective (combined) turnover frequency of 0.72Hz. The output from U1 is fed back into the inverting input of the amp, and that has two effects. The first is that in increases the gain, not by very much, but it *is* increased because R4 is effectively in parallel with R3, giving an effective value of 990 ohms. Secondly, the output of U1 is only *mostly* DC, but it also passes some low frequency AC back to the inverting input of the amp. That reduces the gain for low frequency AC, and in turn creates a phase shift. It cannot be otherwise!

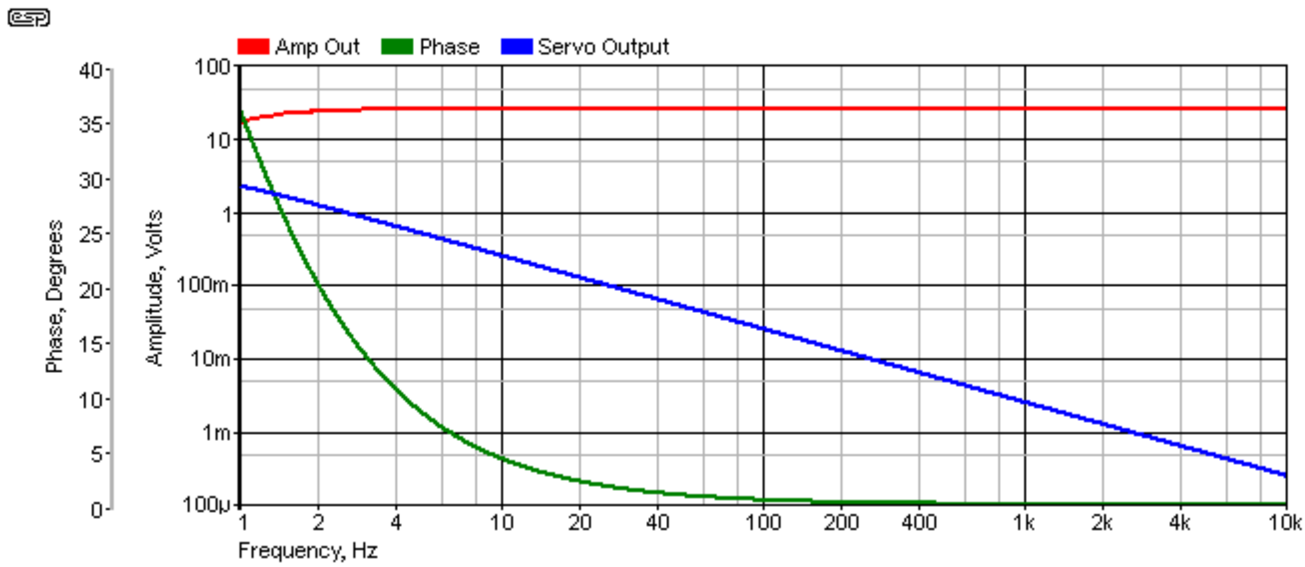

Figure 8 - Amplitude And Phase Of Amp With Servo

The above graph shows amplifier frequency response, DC servo frequency response and amplifier phase, from 1Hz to 10kHz. C1 and C2 are shorted out, and the amplifier and DC servo shown in Figure 4 is used to remove the DC offset. It's quite apparent that the amp's output phase changes as frequency is reduced, and the drop of level below 4Hz is also visible. This graph was taken without an input or feedback blocking capacitor, yet there is still an obvious phase shift and a reduction of the low frequency signal.

You can't tell from the graph, but the frequency response is 1.8dB down at 1Hz. That's nothing to complain about of course, but the phase shift at the same frequency is 36°, rather spoiling the party for those who insist that a servo prevents phase shift. The only difference between the two circuits used is the gain - when the servo is in place, the AC gain is 24 rather than 23 as you'd normally expect, due to the 22k servo resistor (R6) which is in parallel with R3. When used with the servo, the input DC offset was set to 27mV, and DC output was 100µV.

This should be enough to demonstrate that a DC servo *does not* ensure zero phase shift. In fact, if the input cap and a feedback cap are used, it's not difficult to get *less* phase shift than with a DC servo, without the added complexity. You don't get the very low DC offset at the output of course, but there's no good reason to aim of less than 1mV in a real power amplifier. It's generally acceptable to have up to 100mV offset (a power of less than 2mW into an 8 ohm driver).

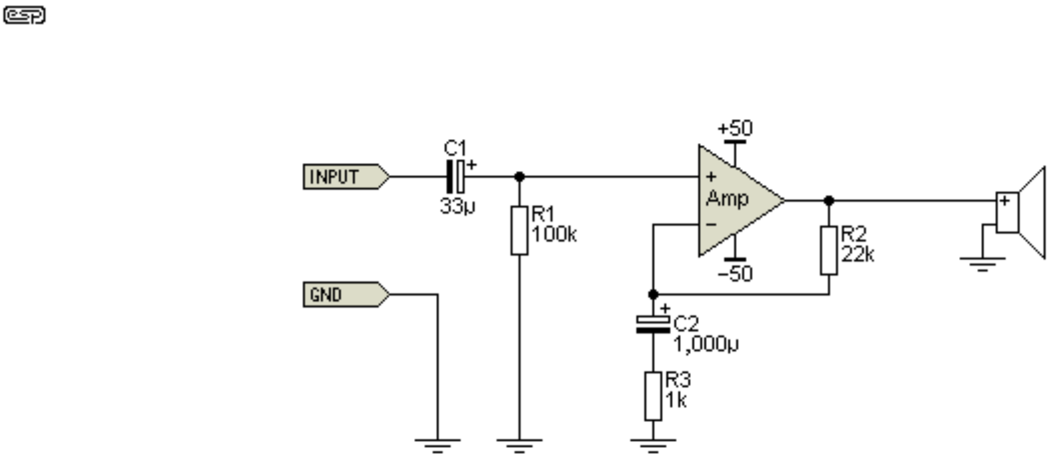

Figure 9 - Amp Circuit Without Servo

This circuit was used to evaluate non-servo amplitude and phase. With the servo disconnected and caps as shown are used, the amp will have an output DC offset of 27mV, but this is well within the acceptable limit for a power amplifier. Most reasonably typical power amps have a DC offset of no more than about 20mV, and in some cases a trimpot is provided to allow it to be removed (almost) completely. Many people don't like trimpots, but they are never a problem if properly sealed multi-turn types are used, rather than cheap open-frame single turn trimmers.

No distortion figures are applicable because the circuit is simulated (including the input DC offset voltage). While the coupling and feedback caps are high values, they are low voltage types because there is almost no voltage across them. It's sometimes thought that electrolytic caps should always have a polarising voltage, but that's not true at all. Countless circuits (DIY and commercial) use electros without any polarising voltage, and they live a long and happy life provided the voltage across them remains below 1V at all times (although I aim for no more than 100mV, AC and/ or DC).

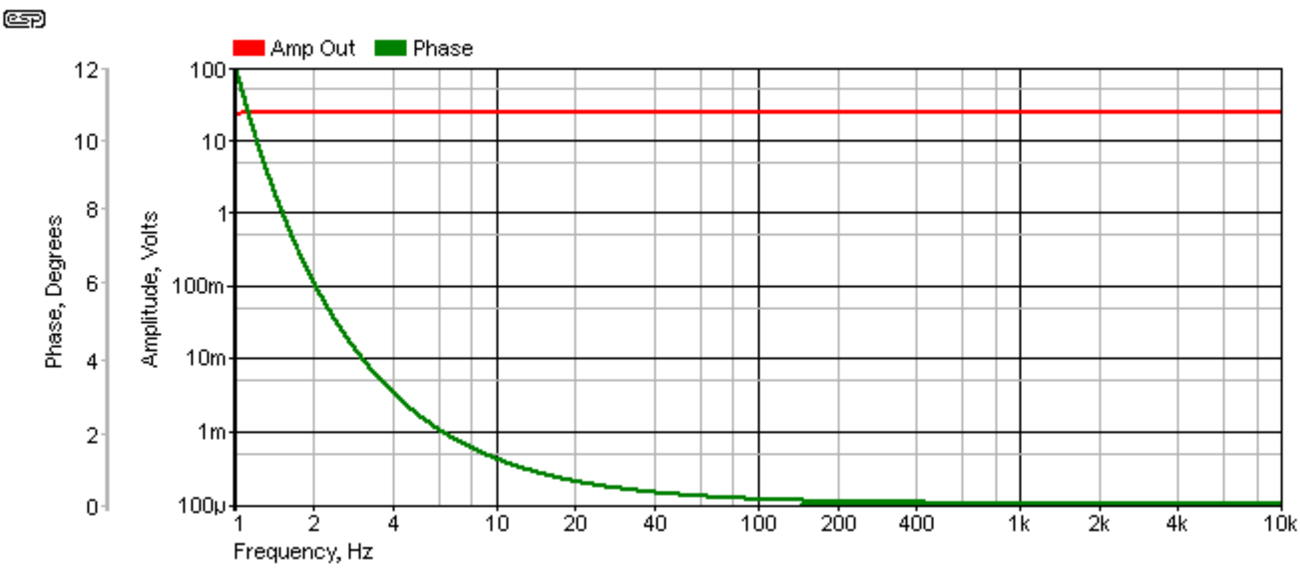

Figure 10 - Amplitude And Phase *Without* Servo

The amplitude is down by 118mdB (0.118dB) at 1Hz, and the worst case phase shift is only 12° at 1Hz (vs. 1.8dB down and over 35° using the DC servo). This was achieved using a 33µF capacitor for C1, and placing a 1,000µF cap in series with R3. The capacitance values are a bit over the top, and I could easily have used lower values and achieved a good result, but it's still quite easy to beat the DC servo with appropriate capacitors, and there is no change to the 'settling time' (this is inevitable of course, because caps have to charge if there's any appreciable offset). With the values shown, steady state DC conditions are achieved in under 2 seconds. This is almost identical to the settling time with the DC servo in place. If R1 is reduced to 22k (which is a more sensible value), the phase shift is still only 21° at 1Hz, and is negligible (< 2°) for any frequency above 10Hz.

Remember, if there's virtually no (AC) voltage across any capacitor, then it can contribute virtually zero distortion, regardless of its 'credentials' or otherwise as discussed *ad nauseam* on internet forum sites. The capacitor values used are much higher than necessary, and it may appear that if the two time constants (C1, R1 and C2, R3) are made the same as those used for the servo (about 220ms) the response and phase should be identical. However, this isn't actually the case at all - they need to be larger. If C1 is 10µF and C2 is 330µF, then the servo and non-servo phase shift is virtually identical, but low frequency attenuation is less (at 1Hz, -1dB without servo, -1.8dB with servo).

It's safe to say that this is probably not what you expected, but before you scoff I recommend that you either run a physical test or a simulation using the values described so you can see it for yourself. The use of a DC servo has long been held as the 'solution' to using input and feedback capacitors in terms of phase response (which is actually inaudible). However, it can easily lead to a system that has turn-on noise, and the phase 'problem' isn't fixed despite the added complexity. The effects of having the opamp's output connected into the feedback path may easily undo any perceived benefit, although again, it's likely to be inaudible in practice if a competent opamp is used.

---

6 - DC Servo Precautions

You have to be careful with any DC servo. If by some misadventure you end up with excessive gain and enough phase shift in the servo loop, it's possible for the entire circuit to oscillate at some very low frequency. It will take a serious error to accomplish this, but it most certainly is possible. I think I can say with some certainty that this is undesirable, so if you intend to use a servo circuit it must be tested thoroughly to ensure that it is stable under all possible operating conditions. The circuit shown in Figure 1 is likely to show a damped oscillation, but only if you try to filter the DC feedback from the amp with a resistor/ capacitor filter. That isn't shown, and for a very good reason - with the wrong combination of input and bypass capacitance, it's may be quite easy to create a low frequency oscillator. Any time you have three time constants in a circuit, you run the risk of creating an unintentional phase shift oscillator, so care is always necessary. Three time-constants is a recipe for disaster! All you need is a 2-stage 'post-servo' filter plus the servo itself, and oscillation is almost a certainly.

The precursor to this peculiar (and most likely unexpected) problem can be seen in Figure 2 (red trace), where there is already a damped oscillation. If a third time constant (i.e. another filter) is added, an oscillator becomes probable. A damped oscillation is bad enough, but one that slowly but surely builds to full power output at a sub-audible frequency has little to commend it. Essentially, adding a third filter creates a phase-shift oscillator, with an unpredictable frequency and amplitude, but the ability to destroy any speaker.

All DC servo systems take time before the servo can correct any gross errors, but small errors are usually dealt with quite quickly. Regardless, it's a good idea to have a muting relay at the amp's output so speakers aren't connected until the system is stable. If this isn't done, there's a good chance that the amp will 'pop' or even 'thump' when turned on, because of the servo's time lag. This problem only becomes critical when a circuit naturally has a high DC offset, because that will be passed through the system until the servo circuit has had enough time to make the necessary correction.

Most of the time, amplifier circuits have a low enough DC offset that a servo isn't necessary. One of the main reasons that servos became popular in the first place was the desire for amplifiers that are flat to DC (or close to it). Claims that phase shift caused by the input (and/ or feedback blocking) capacitor somehow 'ruins' the music are a fantasy, and have no place in engineering. The vast majority of such claims are made based on sighted tests, where the listener/ tester knows which is which. Without the safeguard of a blind (or double blind) test, sighted tests give results based on the 'experimenter expectancy' effect - if you expect something to sound better or worse, then it will. Once the same test is conducted blind, 'obvious differences' vanish in an instant.

The idea that using a DC servo 'eliminates' the need for an input capacitor is true, but it comes at a cost. Not just the extra parts, but like it or not, the servo opamp will have some influence on the amplifier's performance. If done well the influence is minimal, but it's still a consideration for anyone who thinks that eliminating capacitors is a worthy goal. As with all things in life (and electronics) there are compromises. If you want the best performance with a minimum of influence on the amp, then the integrator must be very slow, but that means the amp isn't ready for use until the DC component has been removed. If it has a fast action, the low frequency end of the spectrum is affected, both amplitude and phase.

Something else that may come as a surprise is that at low frequencies, a DC servo may increase distortion. Looking at Figure 4 again, it should be apparent that at some low frequency, the diodes shown in the 'alternate connection' will clip the AC waveform going to U1. Although U1 appears to be configured as an integrator, that's an illusion - it acts as a voltage follower for AC. The capacitor provides AC feedback so the opamp doesn't clip the AC that gets past the 'real' integrator (R5 and C2), and is necessary to ensure very high DC gain so any offset can be cancelled. When the 'grey' diodes are used, they will clip low frequency AC waveforms, and the DC servo couples a distorted signal back into the amplifier's feedback network. This is now part of the amplifier's output. Even with an 'ideal' (completely distortion-free) amplifier, the distortion of the Figure 4 circuit with a

50V peak output signal (full power) is 0.07% at 10Hz, and around 0.05% at 20Hz. The distortion will increase with decreasing frequency, but at higher frequencies it's negligible. With four series-connected diodes as shown, there is no effect at any frequency, and the effects of diode leakage are minimised.

This particular issue can be eliminated by omitting the diodes, but the opamp's input stage may be damaged if an amplifier DC fault develops. While the diode 'alternate arrangement' shown in Figure 4 is common, it's better to use the diodes from the opamp's non-inverting input to each supply rail as shown. To prevent diode leakage from creating offset issues, use ultra-low leakage diodes, or two in series. Provided R5 and C2 are dimensioned properly, no audio signal can exceed the opamp's linear input range. Without proper testing and close attention to every voltage in the system, this potential problem can easily pass un-noticed. An amplifier fault may cause the opamp's input to be forced to just above/ below the supply voltage, but this is allowed for in most opamps. The high value integration resistor limits the current to a safe value.

You also need to select the value of the servo's output resistor carefully. If it's too low, it will affect gain and may inject opamp noise into the amplifier. If it's too high, the servo opamp may not be able to deliver sufficient current into the summing point to remove the offset. The value used in Figure 4 (22k) is reasonable, but it can be increased if desired. However, in combination with the feedback network, this acts as an attenuator, reducing the total DC gain through the circuit. That means there may be a little more DC at the output. If the value is increased too far, the opamp may not have enough output voltage to reach equilibrium. In general, the opamp's output voltage should not exceed ±5V (assuming 15V supplies) once the system has stabilised, to ensure that there is sufficient range to cope with changes over time. The same caveat applies if you use an inverting servo.

---

7 - DC Servo Uses

Despite the comments made above, there are times when the use of a DC servo is either essential or at least highly desirable. For many commercial products, it's essential to ensure that the wrath of 'audiophiles' or reviewers is not incurred, as might be the case if there's any measurable offset. This is a small market, and a perceived 'deficiency' can be damaging in the marketplace, especially for 'high end' products commanding a premium price. Because of the unwarranted bad rap that capacitors have in some circles, it may be seen as desirable to eliminate them from the signal path. No mention shall be made of the electrolytic caps used in the power supply of course, as these are generally ignored, despite the fact that they are most certainly part of the signal path.

A very important application is for instrumentation, where DC offset may be not just troublesome, but may seriously impact the performance of the equipment. Naturally, this isn't easily solved if the measurement system has to include DC, because the servo will (attempt to) remove it. However, the ability to use small metallised film caps instead of bulky electrolytics can deliver an overall improvement, and there's no need for a manual 'set zero' control as might be necessary if there is no DC servo system. The use of film caps and high value resistors can easily extend low frequency response to 0.1Hz or less if needs be, and that would demand very large coupling/ feedback capacitors if extremely low frequency response is needed.

There are many applications for DC servos in test and measurement, scientific equipment and industrial processes, so it would be unwise to dismiss the process. The purposes of this article are to ensure that the user understands that the DC servo is not a panacea, but it is a useful tool when applied sensibly. There are many systems in common use that rely heavily on the ability to remove DC offset, and reduce the remainder to a few microvolts at most. This may not be possible in some systems without the addition of an 'offset null' facility (usually a trimpot), which then demands that the presence of any DC be checked before use, and manually adjusted before the equipment can be used.

Audio doesn't demand ultra-low DC offset in the majority of cases, and where DC is a problem (such as across pots which can make them noisy), a capacitor is always the easiest and cheapest option. If the reader happens to believe that caps somehow 'ruin' the sound, I need only remind him/ her that the music has already passed through *countless* capacitors in the recording and equalisation chain before it even gets onto a disc, so the point is moot.

Conclusions

In short, a DC servo uses the extraordinarily high gain (at DC and very low frequencies) and low input DC offset of an opamp to 'negate' any DC that appears at the amplifier's output. Because the circuit uses filters, there's a limit to the low frequency response, and pretty much by definition an amplifier fitted with a DC servo can't amplify DC. Should the DC input be high enough, the opamp will be forced outside of its linear range, meaning its output will be pushed to one or the other supply rail. The final result will not be a happy one.

Because even a 'pedestrian' opamp will have far greater open-loop DC gain than any power amplifier, it can maintain a much better control of DC offset than the amplifier by itself. While it's certainly possible to include a DC offset trimpot in an amplifier, a servo will usually do a better, more consistent job of removing residual DC. However, it needs to be designed with care, and tested thoroughly to ensure that it doesn't do anything you wouldn't like (such as oscillate!). Ensuring that you have the optimum topology is critical to ensure *unconditional* stability. That means no hint of damped oscillations, at all, with any input device (whether DC coupled or not).

There is a persistent myth that using a DC servo means that there is no phase shift at (very) low frequencies, but this is simply untrue. If input and feedback caps are used, the DC offset from most amplifier designs will be well below 50mV, and if both are made larger than normal, it's easy to keep the phase shift below that you'd normally get with a DC servo. Because the capacitors are large, there is very little voltage dropped across them even at the lowest frequency of interest, and therefore there can be very little distortion contributed by the capacitor(s).

The point that's often missed is that if there is next to zero voltage across *any* component, then it can contribute next to zero distortion. Large value capacitors generally mean that electrolytic caps will be used, but even if the distortion of the cap is (say) 5% and the voltage across the cap is perhaps 1% of the input voltage, the worst case distortion can be 0.05%. I have never measured any (sensible) capacitor with 5% distortion (not even electrolytics with significant AC voltage across them), so the distortion will naturally be lower than the example given.

A DC servo *does* pretty much eliminate any DC offset, but for most power amplifiers it's already low enough so as not to cause any problems. A DC servo is a very good idea if an amplifier is driving a transformer, but that's purely to ensure that there is no DC in the transformer winding. The low frequency content must be carefully tailored to ensure that the transformer doesn't saturate, so a low frequency filter must be considered mandatory. The filter will (of course) use capacitors. This particular topic is covered in detail in the article High Voltage Audio Systems, which discusses amplifiers connected to output transformers.

The preferred connection will use a non-inverting servo, because that minimises interaction with the input circuit (especially the input capacitor if used). Consider that a capacitor may be present without you knowing it, depending on the source, and that *will* create very unwanted interactions if you choose the wrong topology. However, and as noted above, it still comes with caveats, and you need to be aware of the potential interactions. The servo opamp is in effect part of the signal chain, and although its contribution is small, it's not negligible. With care and good design, it can be configured to have minimal effect on the signal while still being able to do its job properly.

The above comments notwithstanding, DC servos are a useful addition where very low DC offset is essential. If you like the idea of close to zero DC output from a power amp, then a DC servo will deliver, but it will *not* eliminate phase shift, and if not done correctly may increase distortion at low frequencies. As noted earlier, it's essential to check that all operating conditions are well within device capabilities, and that nothing 'bad' can happen if the DC servo dies (yes, opamps can, and do, fail).

References

Audio Power Amplifier Design Handbook, Douglas Self - 2012, ISBN 1136123660
Simple DC Servos - Wayne Stegall
Ask the Doctors: Servos - By Dr. Dave Berners (Universal Audio WebZine, Volume 4, Number 9, December 2006)

Interestingly, I received an email from someone who claimed to be the inventor of the DC servo for audio applications, but as it came from a random email address (so my reply bounced) and provided no proof of any kind, I have chosen to ignore the request for attribution. Should the *real* inventor of the idea be prepared to contact me and provide acceptable proof, then I will include this information.

Change Log: Page created and copyright © Rod Elliott, June 2019./ Update: March 2023 - amended protection diode recommendations to account for leakage.