# Damping control

## Damping of a 2nd order system and how to implement a feedback loop for electronic damping control

## 1 Speaker as second order system

Some key elements that characterize a speaker are the mass of the moving parts and the stiffness of the suspension, together these form a resonant 2nd order system. If the cone is excited at resonant frequencies the oscillation tends to have a behavior like in FIGURE 1 (y = 1 is the steady position of the system).

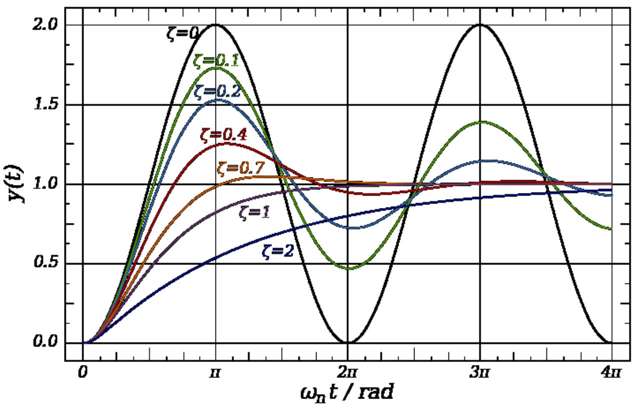


*FIGURE 1: Second order system, various damping behaviors*

- Over-damped ($\zeta > 1$): The system returns (exponentially decays) to equilibrium without oscillating. Larger values of the damping ratio $\zeta$ slower this process.
- Critically damped ($\zeta = 1$): The system returns to equilibrium as quickly as possible without oscillating. This is often desired for the damping of systems such as doors.
- Under-damped ($\zeta < 1$): The system oscillates (with a slightly different frequency than the undamped case) with the amplitude gradually decreasing to zero.

$\zeta$ (zeta) is the damping ratio, defined as:

$$\zeta = \frac{c}{2\sqrt{mk}}.$$

- k: stiffness.
- m: mass.
- c: viscous damping coefficient.

In the real world some mechanical damping is always present, but such a slight amount that the system can be considered highly under-damped. In this case $\zeta = 0$ the resonant angular frequency is:

$$\omega_0 = \sqrt{\frac{k}{m}}$$

The under-damped ($0 < \zeta < 1$) angular frequency depends from the damping case with the following relationship:

$$\omega_1 = \omega_0\sqrt{1-\zeta^2}.$$

This formulas means that if the cone is displaced and then released (with hands or with an electrical signal), it oscillates across the resting position for several cycles at its natural resonant frequency; this oscillation will decrease in amplitude and finally reach a state of rest due to the small amount of damping.

If this under-damped speaker is driven by hands or driven by a voltage source having a very high internal impedance (to maintain the under-damped condition), the cone will vibrate at a greater amplitude at frequencies close to its natural resonance. This action is similar to pushing a swing or pendulum "in time" with its natural period so as to obtain large amplitudes. The frequency-response curve of the speaker under these conditions will show a peaked output near the cone resonance, usually between 30 and 100 cycles per second.

This kind of oscillation is all distortion, since the cone does not follow the applied square waveform (or impulse) of depressing and releasing it.

The result is not only distortion but another effect is to reduce the SPL produced by the diaphragm of the loudspeaker because of its own inertia after the end of the stimulus. The frequency of the sound produced with this movement is the resonant frequency of the moving system.

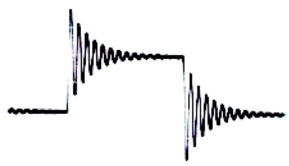

*FIGURE 2: Under-damped response example*

A common term for this phenomenon is "overhang". In severe cases this can translate into a "one note bass" behavior.

## 2 Modelling the Loudspeaker as a Lumped System

Loudspeaker systems are more complex than a typical second order system, a driver with a voice coil is also a current generator, since it has a coil attached to the cone and suspension, and that coil is immersed in a magnetic field.

A handy way to simulate the damping control is to represent the loudspeaker as a lumped electrical equivalent circuit, composed by three parts:

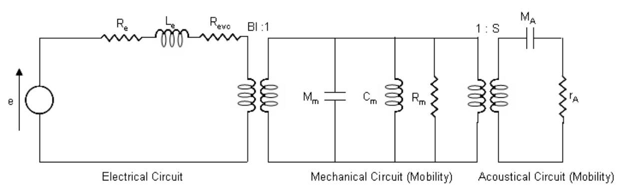


*FIGURE 3: Equivalent Speaker Circuit*

- Equivalent electrical circuit: $R_e$ is the resistance of the output stage of the amplifier and the connection cables; $L_e$ is the imaginary part of the voice coil inductance; $R_{evc}$ is the real part of the voice coil inductance.

- Equivalent mechanical circuit: modelled with an electrical equivalent representing the mechanical parameters of the loudspeaker. $M_m$, is the electrical capacitance due to the moving mass; $C_m$ is the electrical inductance due to the compliance (the inverse of the stiffness) of the moving mass and $R_m$ is the electrical resistance due to the suspension system.

- Equivalent acoustical circuit: modelled with an electrical equivalent representing different acoustics parameters of the loudspeaker. $M_A$ models the air mass and $r_A$ models the radiation impedance.

This equivalent circuit is an insight about what parameters modify the characteristics of the loudspeaker, in FIGURE 4 it is represented the electrical input impedance as a function of frequency, developed using the equivalent circuit of the loudspeaker.

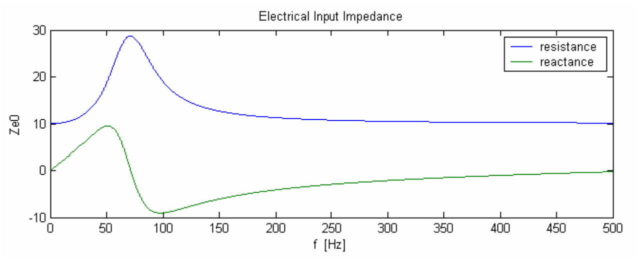


*FIGURE 4: Example of frequency response of a typical Speaker Circuit*

Without going too much in details we can observe a very important fact: every time a voltage is applied to the coil, it starts to move in the magnetic field, along with the attached cone. If the cone is mechanically moved, the motion of the coil in the magnetic field generates a voltage in the coil called Back-EMF. This force will be seen by any electrically attached equipment, such as an amplifier. In fact, the amp's output circuitry will be the main electrical load on the "voice coil current generator". Two important factors need to be considered:

- Larger diaphragm excursion brings to a higher Back-EMF. This is obviously more critical at low frequencies where diaphragm movement is large and results in a large current draw. A poor damping brings to a compressed and ill-defined bass reproduction.

- A lesser output impedance of the amplifier results in a less negative influence of the Back-EMF on the amplifier's circuit. If that load has lower resistance, the current will be larger and the voice coil will be strongly forced to decelerate.

For a given speaker, the amount of damping can be varied by changing the value of the external resistance (amplifier plus cables/connector) and consequently the value of the braking current. Remember that the output impedance consists of the amplifier plus the cable/connector and it's the impedance of the entire interface that defines the damping of the diaphragm.

There is a damping value at which the cone returns to the rest position in the quickest possible time without further oscillations This condition is called the critically damped state. Transient distortion is greatly reduced and the low-frequency response is more consistent.

As we will see later the trick is to regulate the voltage and current at the resonance points, changing the resistance seen by the coil on the amplifier.

## 3 The damping factor

In audio system terminology, the damping factor is the ratio of the nominal impedance of the loudspeaker to the source impedance and describes the ability of the amplifier to control undesirable movement of the speaker cone near the resonant frequency of the speaker system. It is usually found in the context of low-frequency driver behavior, because LF drivers and subwoofers have the most problems regarding damping. Their moving mass is quite high and their suspensions are comparatively weak compared to this mass. Because of this such drivers have a relatively poor mechanical damping and therefore electrical damping is important. High frequency drivers have less mass and stiff suspensions compared to that mass. As a result electrical damping is negligible.

To define the damping factor only the resistive parts of source, cable and coil are considered. This simplification is taken because the worst situation is around the resonance of the speaker, where the impedance is pure resistive.

Load impedance $Z_{load}$ (input impedance) and source impedance $Z_{source}$ (output impedance) are shown in FIGURE 5. The source impedance (seen by the loudspeaker) includes the connecting cable impedance.

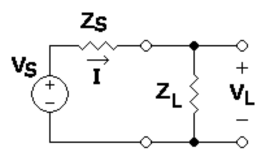


*FIGURE 5: Definition of electric damping factor*

The damping factor (DF) is defined as:

$$DF = \frac{Z_{\text{load}}}{Z_{\text{source}}}$$

A high damping factor (which requires low output impedance at the amplifier output) rapidly damps unwanted cone movements induced by the mechanical resonance of the speaker, acting as the equivalent of a "brake" on the voice coil motion (just as a short circuit across the terminals of a rotary electrical generator will make it very hard to turn). It is generally thought that tighter control of voice coil motion is desirable, as it is believed to contribute to a better-quality sound.

The damping factor varies with frequency, since driver's voice coils, as seen above, are complex impedances changing with frequency. In addition, the electrical characteristics of every voice coil will change with temperature; high power levels will increase coil temperature and thus resistance. Finally, passive crossovers (made of relatively large inductors, capacitors, and resistors) that can be found between the amplifier and speaker drivers also affect the damping factor, again in a way that varies with frequency.

As a rule of thumb, for audio power amplifiers, this source impedance Zsource (output impedance) is generally smaller than 0.1 Ω and from the point of view of the driver voice coil, is a near a short-circuit.

## 4 Cable effect

If the problem lies only with the impedance of the amplifier output stage and a manufacturer could design the ideal output stage with an output impedance of zero ohm, the consequence would be a critical damped system (what we ideally want). This ideal amplifier becomes an ideal voltage controlled generator. Generally the actual amplifiers are very near to be perfect voltage generator (there's always a huge damping factor in the amps specs), but let's consider the contribution of cables.

The resistance of a wire increases with the length, decreases with increased conductor cross-sectional area and it's frequency independent (in the audio bandwidth). As the resistance of the wire increases, the current flowing in the circuit reduces; this leads immediately to a line loss problem resulting in a drop of the sound level.

This partitive effect can be compensated with the good design rule of the 5%: use wire with a resistance less than the 5% of the nominal speaker impedance (for a 4 Ω speaker it's recommended a cable with less than 0.02 Ω resistance).

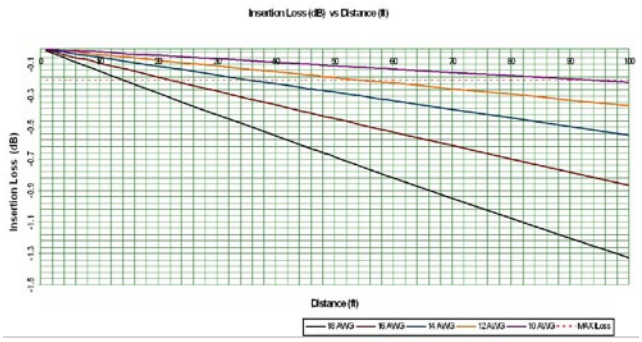


FIGURE 6: Insertion Loss (dB), best if <0.2db

Anyway we must remember that higher the resistance, lower the braking effect, so cables will lead to a non-zero impedance inside the output stage of the (near to be) perfect voltage generator.

But how much a poor damped system brings to a loose sound? In literature it's possible to define a DF limit from 50 to a minimum of 20, below those values the overhang bass effect start to be unacceptable.

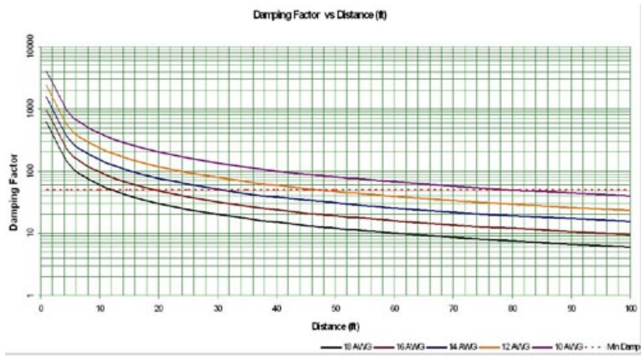


FIGURE 7: Damping factor vs Distance, best if >50

As already told the actual amplifiers has typically a very low output impedance, this means a high DF, or better, the effect of the amplifier is very little (negligible) in reducing the damping factor.

*Other to the cable loss, another important effect of damping variation is the temperature variation of the coil, causing a change in the impedance curve (see the tech note regarding limiters).*

## 5 Compensate the Damping: Active Damping control

A solution to the variable DF mentioned above could be to add a negative and adjustable "emulated" resistor, in series with the output of the amp. In that way It would be possible to compensate the parasitic impedance of the cable and/or hot voice coil effect, in order to maintain the correct damping factor.

But how to implement this negative resistor? The DSP board acquires the output voltage and current signals, with a very low latency. A fraction of the output current signal is added to the signal output by the KDSP.

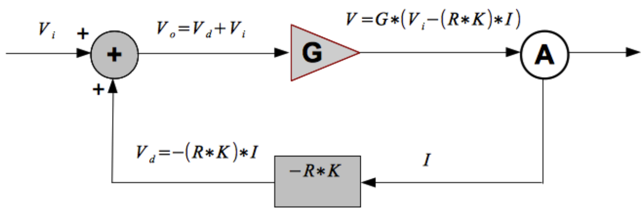


FIGURE 8: Feedback loop for damping control with negative virtual resistance

Where:

- $V_i$: input voltage (taken after the processing).
- $V_d$: damping voltage controlled by the current.
- V: output voltage, applied on the speaker.
- I: output current.
- R: virtual resistance.
- K: a constant, for feedback stability control.
- G: (linear) gain of the amplifier.

For example, suppose we add a –2 Ω virtual resistance, we add a contribution of 2 times the actual current (–R*K = 2 assuming K=1) to the output voltage. With no load and a 0 V input, we will obtain a 0 V output. If we now sink a 1 A current from the output, we will see that the output voltage will raise up to 2 V, thanks to the I contribution. We have built a generator which output voltage is dependent from the output current, with a positive resistance, voltage drops with current, while with a negative resistance, voltage increases with current.

As any feedback loop stability problems could arise, for example if we change the factor from 2 to another value, let's say 4, with a load of 2 ohm the result would be a –2 ohm output impedance amplifier with a 2 ohm load.

Other issues may arise with latency, the DSP is a piece of digital hardware and as any discrete system there are problem in timing and interaction with analog quantity. Most of the implementation effort was taken to guarantee the stability of the system despite of ADC / DAC and DSP latencies and to manage situations where user settings could cause and unstable behavior, avoiding the creation of any destructive oscillation...

## 6 Possible applications of the DF control

- Cable loss compensation.
- Voice coil increase in resistance due to heating compensation, even dynamically adjusted with the estimated voice coil temperature.
- Damping factor "creative" adjustment, to create a dry and damped or a "boomy" bass response (i.e.: DSP4).
- Active loudspeakers with reduced loading volume: a negative resistance has the effect of reducing the Qes of the driver, allowing for smaller enclosures for the same driver.
- Introducing negative feedback in amplification chain.

## 7 Bibliography


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