Loudspeaker operation: The superiority of current drive over voltage drive

Esa Merilainen - October 22, 2013

This is an overview of the destructive effects that voltage drive has on the performance of electrodynamic loudspeakers. A more comprehensive treatment of the subject can be found in the book *Current-Driving of Loudspeakers: Eliminating Major Distortion and Interference Effects by the Physically Correct Operation Method* by Esa Meriläinen.

Today, practically all available audio amplifier and loudspeaker equipment works on the voltage drive principle without significant exceptions. This means that the power amplifier acts as a voltage source exhibiting low output impedance and thus strives to force the voltage across the load terminals to follow the applied signal without any regard to what the current through the load will be.

However, both technical aspects and listening experiences equally indicate that voltage drive is a poor choice if sound quality is to be given any worth. The fundamental reason is that the vague electromotive forces (EMF) that are generated by both the motion of the voice coil and its inductance seriously impair the critical voltage-to-current conversion, which in the voltage drive principle is left as the job of the loudspeaker.

The driving force ($\boldsymbol{F}$), that sets the diaphragm in motion, is proportional to the current ($\boldsymbol{I}$) flowing through the voice coil according to the well known formula $\boldsymbol{F} = \boldsymbol{BlI}$ where the product $\boldsymbol{Bl}$ is called force factor ($\boldsymbol{B}$ = magnetic flux density; $\boldsymbol{l}$ = wire length in the magnetic field). $\boldsymbol{B}$ is the flux density that exists when the current is zero. (The current always induces its own magnetic field, which may react with adjacent iron, but the effect is not related to this equation.)

This force, then, determines the acceleration ($\boldsymbol{A}$) of the diaphragm, which in the main operation area (the mass-controlled region) is got from the Newtonian law $\boldsymbol{F} = \boldsymbol{mA}$. The radiated pressure, in turn, follows the instantaneous acceleration and not the instantaneous displacement, as many mistakenly imagine.

The most remarkable thing here regarding loudspeakers is that the voltage between the ends of the wire does not appear anywhere in these equations. That is, the speaker driver in the end obeys only current, not caring what the voltage across the terminals happens to be.

There cannot be found any scientifically valid reasons that justify the adoption of voltage as the control quantity - it is only due to the historical legacy originated almost a century ago, most likely by cheapness and simplicity; the quality and physical soundness of operation have not been considerations in this choice. Engineers are also more accustomed to identifying electrical signals as voltages rather than currents.

At least the hi-fi community should be interested and able to better see through this discrepancy. But they too have taken the state of affairs as a given, being largely conditioned to the wishful thinking that tightly held voltage somehow "controls cone motion," even up to middle and high frequencies. Such a notion doesn't have real scientific grounds, and it can be clearly shown by basic analysis and modeling that any damping effects that voltage drive can have on driver operation are strictly limited to the bass resonance region.

The components of impedance

The electrical equivalent circuit of a moving-coil drive unit can be depicted as the series connection of a resistor and two voltage sources, as shown in Figure 1. $\boldsymbol{R_c}$ represents the voice coil DC resistance; voltage source $\boldsymbol{E_m}$ represents the motional EMF (so-called back-EMF) of the driver and is calculated by $\boldsymbol{E_m} = \boldsymbol{BlV}$ ($\boldsymbol{V}$ = voice coil velocity); and voltage source $\boldsymbol{E_i}$ represents the inductance EMF that is generated by the lossy inductance of the voice coil. This is the proper end essential representation of the electrical system for examining the amplifier-speaker interface. Any wiring resistances and possible output resistance of the voltage amplifier simply add to $\boldsymbol{R_c}$ and thus don't need any specific attention.

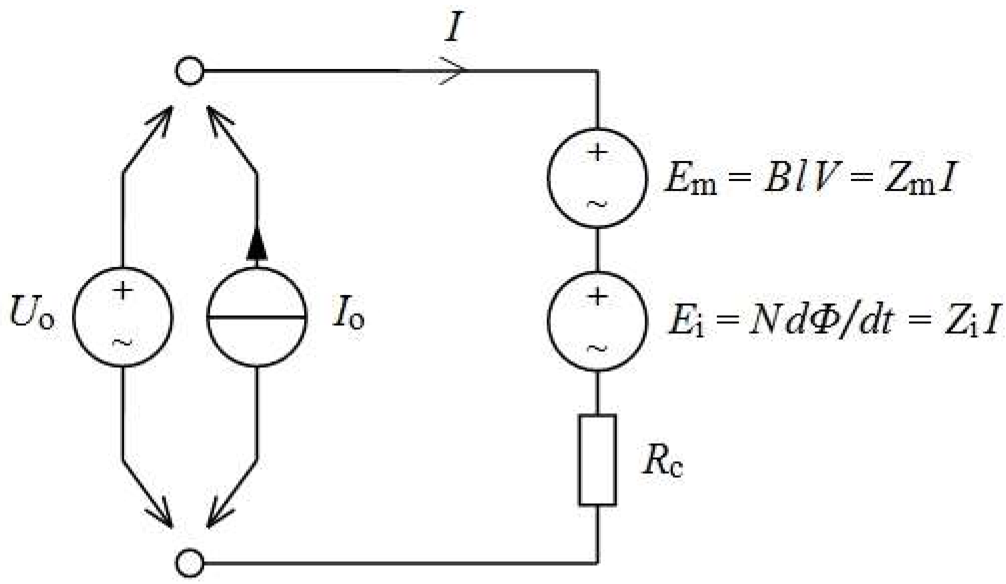

Figure 1: The electrical equivalent circuit of a moving-coil transducer with two kinds of feeding sources.

Both $\boldsymbol{E_m}$ and $\boldsymbol{E_i}$ are subject to a multitude of disturbances that corrupt the flow of current when the circuit is fed by a voltage source ($\boldsymbol{U_o}$). Thus the magnitudes of these two are of utmost interest. When the feed comes from the current source ($\boldsymbol{I_o}$), $\boldsymbol{E_m}$ and $\boldsymbol{E_i}$ only appear as additional voltages in the amplifier output, having no influence on the current.

In the impedance modulus curve of a typical moving-coil driver ($|\boldsymbol{Z_{tot}}|$ in Figure 2), $\boldsymbol{E_m}$ manifests itself as the high peak at the resonant frequency, while $\boldsymbol{E_i}$ is responsible for the gradual rise typically starting in the whereabouts of 300 Hz. When looking at such a curve, one can easily be mistaken to assume that $\boldsymbol{E_m}$ is significant only near the fundamental resonant frequency or that $\boldsymbol{E_i}$ is significant only at the highest operating frequencies. In reality, however, these two components are of almost opposite phase in the midrange and therefore largely mask each other near the impedance minimum.

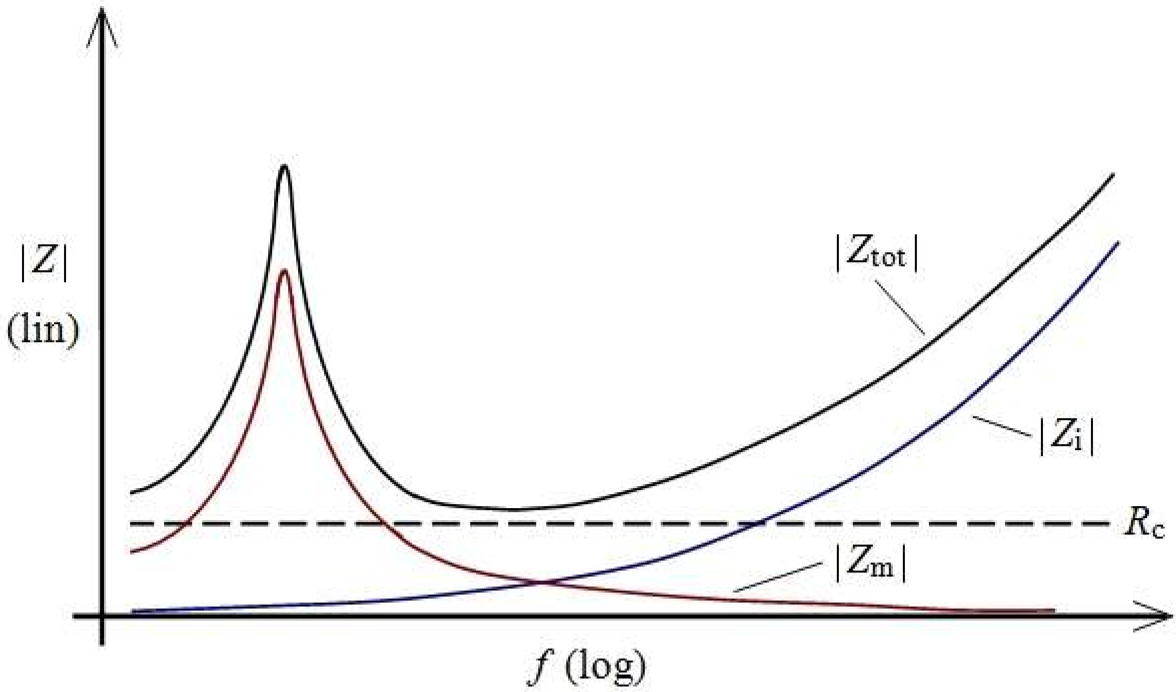

Figure 2: Composition of the impedance magnitude curve of a typical cone driver. Both the motional impedance Z_m and the inductance impedance Z_i have considerable magnitude throughout the main operation area.

Figure 2 thus also shows the actual and typical magnitudes of the impedance components separately, which are also measurable by special techniques. It is seen that the sum of $|Z_m|$ and $|Z_i|$ is in fact in the whole operation band at least of the same order of magnitude than R_c. Increasing driver efficiency also increases both $|Z_m|$ and $|Z_i|$.

Basic low-frequency operation

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The moving-coil driver in free air or closed enclosure essentially constitutes a 2nd-order system that has three mechanical parameters: the moving mass ***m***, the spring constant ***k*** and the damping constant ***b*** (also known as the mechanical resistance). When a driving force ***F* = *BlI*** is applied to the system, the force divides into three components:

F* = *BlI* = *mA* + *kX* + *bV

where ***mA*** is the force accelerating the mass, ***kX*** is the force stretching the spring (***X*** = displacement), and ***bV*** is the force moving the (virtual) damper. ***mA*** forms the dominant force in most of the drivers operating band (i.e. above the resonance), ***kX*** forms the dominant force below the resonance, and ***bV*** is dominant at the resonance, where the two other components are equal but opposite phase and hence cancel each other out. On voltage drive, the current ***I*** is not constant but exhibits a notch in the resonance region.

The shape of any 2nd-order low-pass, high-pass or band-pass response can be determined by just two parameters: the resonant frequency f_0, which denotes the roll-off corner frequency, and the ***Q*** value that tells the relative gain at that frequency. Starting from the above equation and the fact that ***V*** is the derivative of ***X***, and ***A*** is the second derivative of ***X***, the system transfer functions can be derived (omitted here) and the resonance parameters determined.

The resonant frequency is independent of the driving mode and given by

$$f_0 = \frac{1}{2\pi}\sqrt{\frac{k}{m}}$$

The effective ***Q*** value, instead, is very different in the two modes. On current-drive, the ***Q*** factor is determined solely by the mechanical parameters:

$$Q_c = \frac{\sqrt{km}}{b}$$

This is also called the mechanical ***Q*** of the driver. On voltage drive, the effective ***Q*** is always lower due to electrical damping and is given by

$$Q_v = \frac{\sqrt{km}}{b + (Bl)^2 / R_c}$$

Now we have a second term in the denominator that consists of electrical parameters and, in practice, dominates over the mechanical damping constant ***b***.

A closer look to the motional EMF

The motional impedance, $\boldsymbol{Z_m}$, follows a 2nd-order band-pass response that has the same $\boldsymbol{f_0}$ and the same ***Q*** value as the current-driven speaker. The ***s***-domain expression for the motional impedance can be written as

$$Z_m = \frac{(Bl)^2}{m} \cdot \frac{s}{s^2 + \frac{b}{m}s + \frac{k}{m}}$$

If we plot the locus of $\boldsymbol{Z_m}$ in the complex plane with frequency as the parameter (Nyquist plot), we get a circle with diameter $(\boldsymbol{Bl})^2/\boldsymbol{b}$. Thus, the total impedance behaves like illustrated in Figure 3. Only the inductive impedance $\boldsymbol{Z_i}$ deflects the locus from the pure circle. In Figure 3c we see in particular how the total impedance comes close to $\boldsymbol{R_c}$, although both $\boldsymbol{Z_m}$ and $\boldsymbol{Z_i}$ are rather significant.

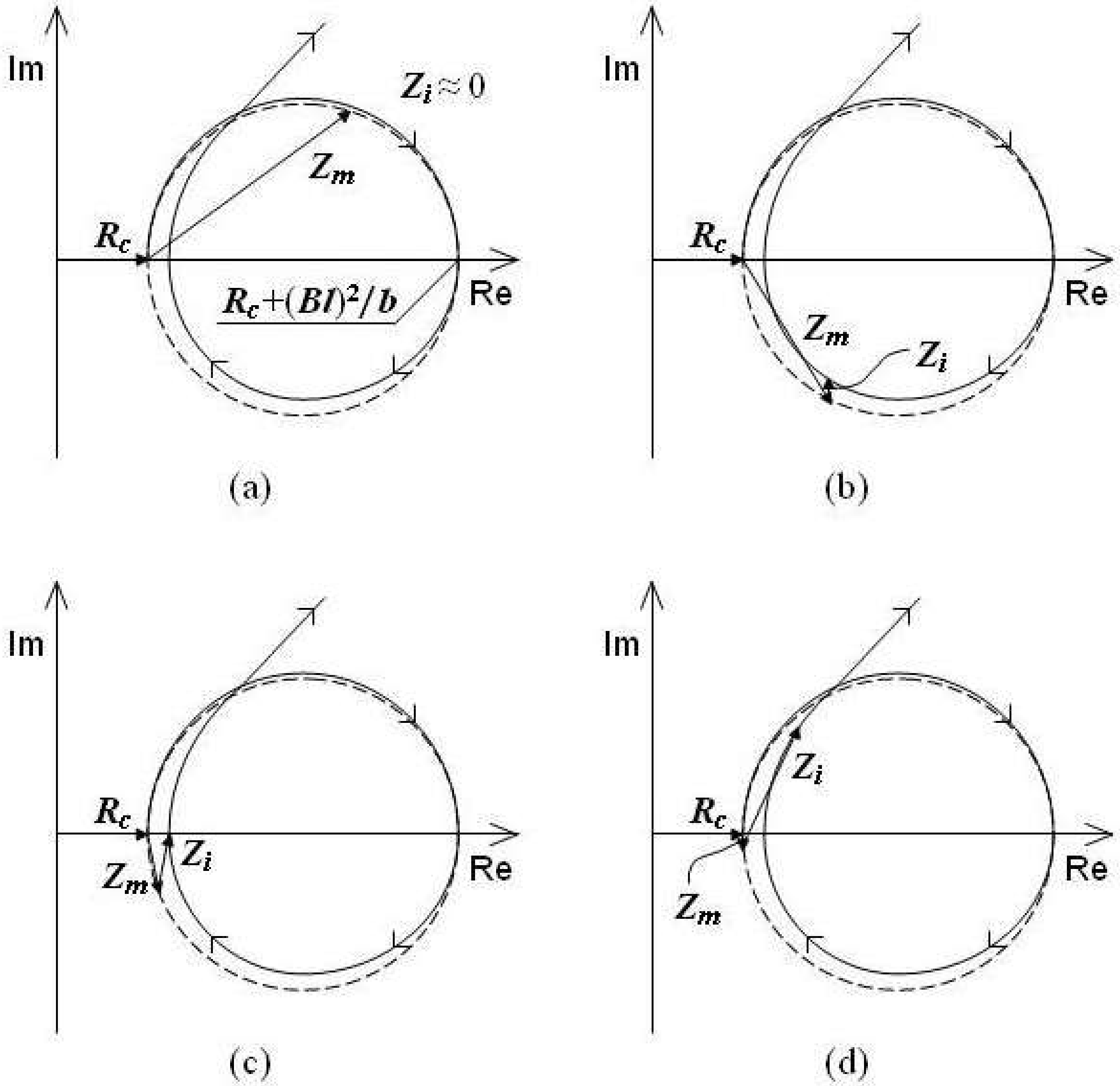

Figure 3: Impedance behavior of a driver in the complex plane. The diameter of the circle (dashed line) is $(Bl)^2/b$, where b is the damping constant. The composition of impedance is shown below the resonant frequency (a), somewhat above the resonant frequency (b), at the point of minimum impedance (c), and in the highest part of the operation band (d).

Above the resonance region, the $\boldsymbol{s}^2$ term dominates the denominator; and with $\boldsymbol{s} = \boldsymbol{j}2\pi\boldsymbol{f}$, the expression reduces to

$$Z_m \approx \frac{(Bl)^2}{j2\pi fm} \;;\; f >> f_0$$

Thus, in most of the driver's operation band, $\boldsymbol{Z}_\mathrm{m}$ is practically capacitive and hence perpendicular to the resistive part, $\boldsymbol{R}_\mathrm{c}$. In Figure 2, we can see $|\boldsymbol{Z}_\mathrm{m}|$ declining smoothly in about inverse proportion to frequency, as inferred above. In real-world drivers, however, the decline is far from smooth and exhibits spurious anomalies and resonances that often also show up in the total impedance.

The assumed control of cone motion

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Suppose that in a voltage-driven speaker some unwanted mechanical disturbance force strives to exert the cone just at the resonant frequency. Here, the mass and spring forces (mA and kX) cancel each other out, and thus all of the force first ends up to move the (mechanical) damper. Thus, the disturbance force translates into the velocity of the cone ($F = bV$). This velocity now generates an EMF that is in phase with the velocity and hence also in phase with the disturbance force. This in-phase EMF in turn introduces an in-phase current through R_c, which in turn effects a force that counteracts the original disturbance force. Thus, the disturbance-induced velocity becomes greatly reduced by the velocity-induced counterforce.

Suppose now that a similar mechanical disturbance force strives to exert the cone at some frequency well above the resonance region. Now, the force ends up accelerating the mass and thus translates into cone acceleration ($F = mA$). The consequent velocity comes, by definition, 90° behind the acceleration and hence also behind the disturbance force.

Ignoring inductance, the EMF generated and hence also the resulting current and force are now perpendicular to the original force and therefore do not in any way counteract it.Thus, throughout the whole mid-frequency region, the motional EMF no longer damps or controls anything but merely acts as an uncontrolled interference source, wreaking havoc on the vulnerable V/I conversion performed by the voltage-driven speaker. (The so-called back-EMF is thus a back-EMF only near the fundamental resonance; elsewhere it is a perpendicular EMF.)

If the voice coil inductance is taken into account (and it should be), the action gets even worse. The inductance namely introduces yet an extra phase lag in the current caused by the EMF, meaning that the phase of the supposed damping force lags considerably more than 90°, and thus the whole mechanism actually turns to enhance the original disturbance instead of damping or suppressing it.

The supposed justification for the status quo of voltage drive lies mostly, if not entirely, in the widely shared belief and refrain that voltage "controls cone motion" as if by some miraculous iron grip that is the result of high "damping factor." In light of any valid engineering analysis, however, the belief amounts to total nonsense, at least for most of the operation band; and we shall yet take a look on the low end.

What does the motional EMF, or electrical damping, precisely speaking do in a voltage-operated driver? Figure 1 provides the answer. For simplicity, let us assume E_i to be negligible. Without E_m, the current would be simply U_o/R_c. E_m is, however, a direct measure of the velocity V and reaches its maximum at the resonant frequency, as does Z_m. According to the superposition principle, the current (component) caused by E_m is $E_m/R_c = BlV/R_c$. This current then brings about a mechanical force that is given by

$$F_{ED} = (Bl)^2 V/R_c$$

This simple formula tells what electrical damping is all about. It is a dull force always directly proportional to the velocity and indifferent to whether the velocity results from the wanted signal or an unwanted disturbance. Thus, it is questionable to call it "control" even in the resonance region since the net result of the whole thing is only an increased opposition to all velocity; in other words an increase in one system parameter, the effective damping coefficient, and a respective decrease in the effective Q value.

Just the same kind of action is also established by mechanical damping, where the velocity-proportional force is simply given by $F_{MD} = bV$. By increasing the system's mechanical resistance b to a suitable value, we can provide a current-driven speaker with just the same damping force as any voltage-driven speaker has. (Though as a voltage-driven speaker has both $\boldsymbol{F}_{ED}$ and $\boldsymbol{F}_{MD}$, it never happens in the same driver.) Thus, there is nothing indispensable in electrical damping; and in principle, there cannot be a difference in the driver's resonance behavior, either in the frequency or time domains, whether the damping is accomplished by a low-impedance amplifier or mechanically.

The value of $\boldsymbol{b}$ is best affected by the suspension materials and enclosure filling. Where low enough $\boldsymbol{Q}$ values are not achieved, a passive series-RCL network connected across the driver and tuned close to $\boldsymbol{f}_0$ will help in the adjustment with only minor compromise to the overall driving impedance.

The delusion of "damping factor"
According to a rampant myth, a high "damping factor" (ratio of nominal load impedance to amplifier output impedance) is needed to deal with the back-EMF, to prevent who knows what errors from happening in the amplifier or the feedback loop, and of course, to control cone motion. (The quotation marks have been used because it is an artificial metric created for marketing purposes and not deriving from any relevant operational equations.) It is not recognized that the $\boldsymbol{R}_c$ is already there, often about 6 Ω, so making any minor increments or decrements to its value doesn't determine anything.

There are also not any distortion mechanisms involved in $\boldsymbol{R}_c$, and adding a bit more linear resistance to the circuit does not alter the distortion scheme either. The amplifier always sees the motional EMF as **nothing else** than an additional (complex-valued) impedance ($\boldsymbol{Z}_m$) that appears on top of the DC resistance. From the amplifier's standpoint, dealing with this peaking in impedance does not differ in any way from dealing with any other peaks that there may occur along the impedance curve.

Even normal temperature variations in the voice coil make empty any efforts to gain any benefit from a high DF. As the temperature coefficient of copper resistance is 0.4%/°C, resistance increases of roughly 50% are possible within rated operation. Thus, even if there would be an infinite DF determined for a room temperature speaker, on continued high-level passages there can be some 3 Ω of additional resistance, which drops the effective DF down to 8/3 = 2.7. Not something to tout.

Coming up in Part 2: Microphone action of the voice coil.

More about Esa Meriläinen.