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Distortion Improvement in the Current Coil of Loudspeakers

Gaël Pillonnet¹, Eric Sturtzer¹, Timothé Rossignol², Pascal Tournier², and Guy Lemarquand³

¹ University of Lyon, CPE Lyon, INL, UMR CNRS 5270 - France
gael.pillonnet@cpe.fr

² ONSemiconductor Toulouse - France
pascal.tournier@onsemi.com

³ University of Maine, LAUM, UMR CNRS 6613 - France
guy.lemarquand@univ-lemans.fr

ABSTRACT

This paper deals with the comparison of voltage and current driving units in an active audio system. The effect of the audio amplifier control on the current coil of an electrodynamic loudspeaker is presented. In voltage control topology, the electromagnetic force linked to coil current is controlled through the load impedance. Thus, the electromechanical conversion linearity is decreased by the impedance variation, which implies a reduction of the overall audio quality. A current driving method could reduce the effect of the non-linear impedance by controlling the coil current directly, thereby the acceleration. Large signal impedance modeling is given in this paper to underline the non-linear effects of electrodynamic loudspeaker parameters on the coupling. As a result, the practical comparison of voltage and current driven methods proves that the current control reduces the voice coil current distortions in the three different loudspeakers under test.

1. INTRODUCTION

An active audio system composed of an electrodynamic loudspeaker and its associated electronics is now widely used in a large range of electrical equipment, such as mobile phones, tablets and automotive [1]. The objective of the audio reproduction chain is to convert the electrical signal into sound waves by a few

conversion steps as shown in Figure 1. The first step consists in delivering the required electrical power to the loudspeaker coil. Then, the coil current interacts with the magnetic field to generate a mechanical force. Thirdly, this force moves the membrane to create a sound wave. Lastly, the sound wave, after interacting with the environment, is received and construed by the ears.

To have the required audio reproduction quality, each transformation would/should be optimized separately and together. Compared to a high performance audio amplifier, the mechanical conversion still suffers from the highly nonlinear behavior of the inner loudspeaker structure, i.e. the suspension, magnetic field, and membrane stiffness [2]. The improvement of the mechanical part could be done but might be too expensive for many mass market applications, such as cars or tablets. The link between electrical and mechanical parts also has an effect on both electrical and mechanical conversion steps. The improvement of the coupling could be relevant for the overall audio quality and could be less expensive by changing the audio amplifier circuit only. Unfortunately, there is a lack of published work which studies the coupling on the overall audio quality [3–6]. This leads to an unclear response concerning the best coupling methods and electrical amplifier specification. For example, a key question has persisted in audio engineering for a few decades: which is the better way to control the electrodynamic loudspeaker / loudspeaker electro-dynamics by the audio amplifier, voltage or current driving method?

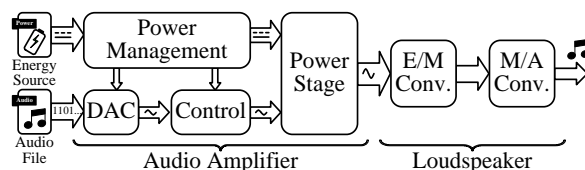


Figure 1 Audio reproduction chain

This paper tries to partially answer this question by studying the effect of both methods on the linearity of the loudspeaker coil current, which produces the mechanical force directly to the membrane by Faraday's law. Firstly, the paper presents the potential benefit of different feedback methods including current and voltage drives. Then, a loudspeaker model, including some nonlinear effects, has been developed to study the driving methods in the current voice coil and in the overall audio quality. Lastly, practical measurements validate the results obtained by the model.

2. AMPLIFIER AND LOUSPEAKER CONNECTIONS

The voltage mode amplifier is widely used in a large range of applications, from automotive to tablets. Unfortunately, only a few published papers [3–6] try to

compare the benefit of driving the speaker in different ways. It seems to be more a subjective point of view [6]. Today, “Could the amplifier designer do more to induce the maximum performance from any speaker?” is still an open question. In this section, the authors try to give the reasons for using driving methods different from the existing published work. There are four/three main techniques to control the electrical energy flow to the speaker: voltage [7], current [8–12], velocity [13–14] feedback as shown in Figure 2. The common objective is essentially to be independent of operating voltages, gain, and non-linearities of the electrical part [15].

The motional feedback controls the cone velocity by sensing the induced current in a secondary coil. It provides a useful enhancement but it is limited to low frequency [16]. The direct control of the velocity through the cancellation of the voice coil impedance has also been discussed [14]. There are few/is little commercial exploitation of this technique due to the need of a great/significant integration level between the loudspeaker and the amplifier.

To clearly understand the difference between voltage and current controls, electromechanical conversion has to be discussed. The loudspeaker is composed of an electrical part (DC resistance and voice coil) coupled to a mechanical system by an electrodynamic motor. The mechanical force applied to the mobile part is equal to the product of the force factor, Bl , and the coil current, I_s , according to Faraday's law. Thus, the coil current studied in this paper is the key parameter in obtaining a mechanical force proportional to the electrical input signal, V_e . If the loudspeaker impedance, Z_{hp} , is constant ($V_s = Z_{hp} \times I_s$), the current, I_s , is proportional to the voltage at the (*added*) terminal of the loudspeaker, V_s . In this case, the loudspeaker can be controlled by a voltage feedback which maintains a constant relation between I_s and V_s .

However, it is well-known [17–18] that the impedance, Z_{hp} , is not purely resistive. Figure 3 shows the impedance modulus, $|Z_{hp}|$, and phase angle, φ , over frequency. The reaction to the voice coil motion and the reactive electrical element induce these variations. If voltage feedback (especially with a high damping factor [19]) is used rather than a current drive unit, the coil current is modulated by the impedance variation. Near the impedance peak induced by the mechanical resonance, the voltage control reduces the coil current reducing the coil motion. By reducing the system quality factor, this effect generally contributes to a better quality sound.

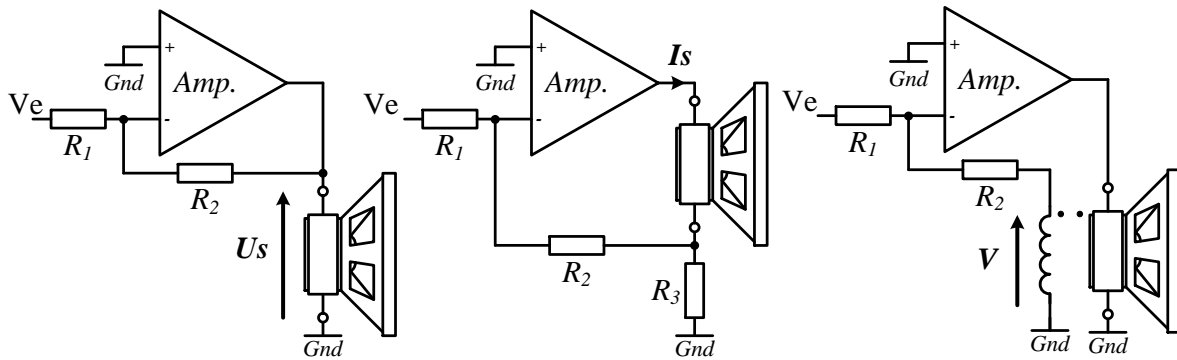


Figure 2 Voltage, current, and velocity drive methods

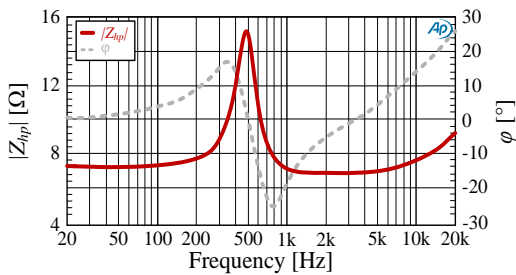


Figure 3 Typical loudspeaker impedance over the audio band

The loudspeaker impedance is also temperature dependent due to the voice-coil resistance. Thus the current drive reduces the thermal dependence of the drive-unit on the loudspeaker. The temperature modulates the applied mechanical force and the damping if voltage drive unit is used.

The interconnection elements and the output impedance of the amplifier (modulated by the amplifier feedback) also change the current in the voice coil and could create unwanted distortion.

Lastly, the impedance is also largely nonlinear due to loudspeaker structure, such as the spring stiffness and magnetic field variations over the cone displacement [2]. [3,11] claim that voltage drive is more susceptible to main sources of nonlinearities, such as the coil inductive distortion effects at high frequency.

To conclude, the current drive seems to be a better candidate to directly interface the loudspeaker. Even if it changes the frequency response near the resonant frequency, the acoustic transfer function could be realigned by using an open-loop compensation, a

motional feedback [3] or mixed feedback control [11]. In the next section, the authors describe an electromechanical model to analyze the nonlinear interaction as a function of the coupling.

3. NON-LINEAR LOUDSPEAKER MODEL

To clearly understand the amplifier and loudspeaker coupling, a large signal loudspeaker model has been developed in Matlab environment based on published work [5].

3.1. Small signal model

Figure 4 represents the well-known linear model of the loudspeaker developed by Thiele & Small in the early 1960's [17].

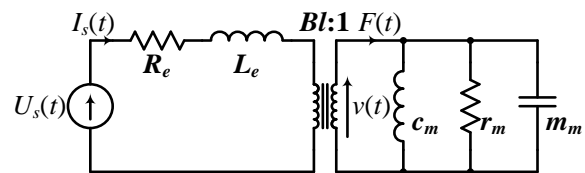


Figure 4 Small signal model of a loudspeaker

The electrical part is modeled by an inductor, L_e , and an equivalent series resistor, R_e . The mechanical part is represented by a second-order system composed of the moving mass, m_m , the velocity loose/loss, r_m , and the suspension compliance, c_m . The coupling between electrical and mechanical systems is the Faraday force, $Bl \times i$, and the back electromotive force due to the Lorentz law, $Bl \times v$. $U_s(t)$ and $I_s(t)$ are the loudspeaker

input voltage and current, $F(t)$ the force applied to the diaphragm and $v(t)$ the diaphragm velocity. In the small signal model, all parameters are linear and the loudspeaker does not introduce any distortion. Moreover, the acoustic pressure is proportional to acceleration if the membrane is considered without resonance mode (i.e. rigid body, piston mode). Analysis of this model gives the transfer function in the Laplace domain between the acceleration and the output voltage $TF_{a/v}$ or the current $TF_{a/i}$ amplifier:

$$TF_{a/u}(s) = \frac{\frac{c_m Bl}{Z_e + R_e} s^2}{1 + \left(\frac{c_m Bl^2}{Z_e + R_e}\right) s + c_m m_m s^2} \quad (1)$$

$$TF_{a/i}(s) = \frac{c_m Bl s^2}{1 + r_m m_m s + c_m m_m s^2} \quad (2)$$

In comparison, the current-driven case has a simpler form, independent of the terms Z_e and R_e . Thus, the current mode is less dependent of the coil impedance and Bl variations.

3.2. Large signal model

The small signal model fails to model the large signal behavior because the parameters listed in section 3.1 become nonlinear. In the proposed model, the three main displacement dependent nonlinearities have been taken into account: force factor, Bl , compliance, c_m , and voice coil, L_e . Figure 5 shows an example of the variation of the Bl parameter as a function of the membrane displacement, x [20]. These measurements could be obtained by using the procedure described in [2]. The authors notice/observed that the eddy current and hysteresis effect have also been included in the model.

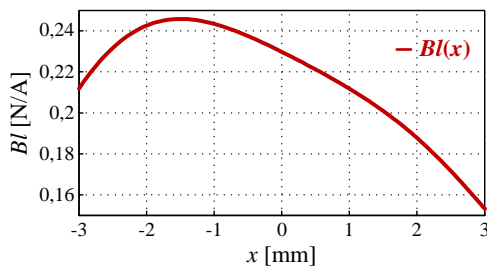


Figure 5 Force factor Bl vs displacement

The authors include all these previous parameters in their model based on a Matlab Simulink environment. The block diagram is given in Figure 6 for the loudspeaker controlled by voltage. The model allows us to find the current coil, displacement and acceleration for any stimuli by solving the nonlinear differential equations formed by/from the electromechanical system.

3.3. Current/Voltage Comparison

Based on a complete characterization of the model parameters for a particular loudspeaker, Figure 7 gives the equivalent electrical impedance variation when a large signal is applied in voltage mode. As a result, a 30 % load variation is measured at the resonant frequency 300 Hz where the amplitude is the largest. Thus, the current is nonlinear as the impedance varies as a function of the voltage signal. The mechanical force induced by the coil current is also nonlinear. Thus, the voltage mode is not the optimal coupling to directly drive the mechanical force. Similar results are obtained when the membrane acceleration is compared in the current and voltage driving methods as shown in Figure 8. The current drive unit seems to be more appropriate as it reduces the harmonic distortion induced by the nonlinear parameters (THD = -45 dB in voltage mode and THD = -50 dB in current control).

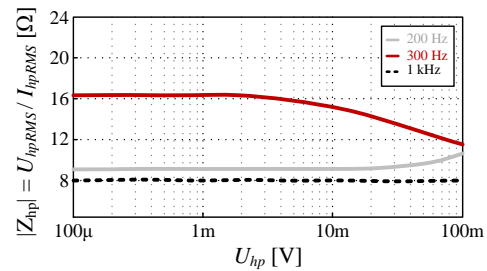


Figure 7 Impedance variation v. applied voltage

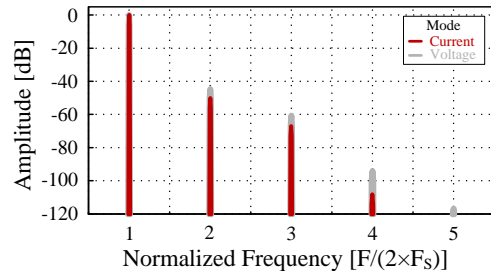


Figure 8 Acceleration spectra for both couplings

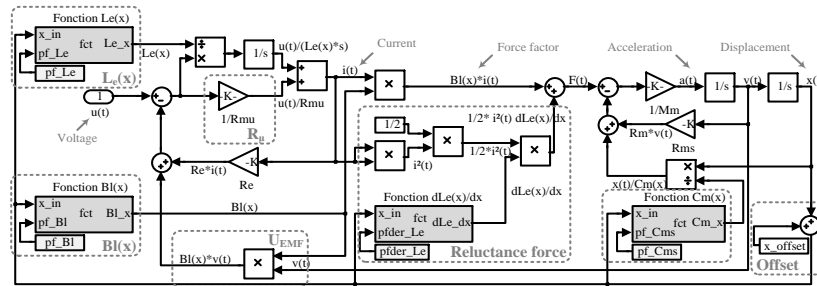


Figure 6 Diagram of a voltage-controlled loudspeaker

4. PRACTICAL VALIDATION

4.1. Loudspeaker under test

The authors chose three speakers to cover a large range of applications. The impedance of each loudspeaker shown in Figure 9 has been characterized for different amplifier output power. The impedance variation is induced by the nonlinear behavior of the loudspeaker.

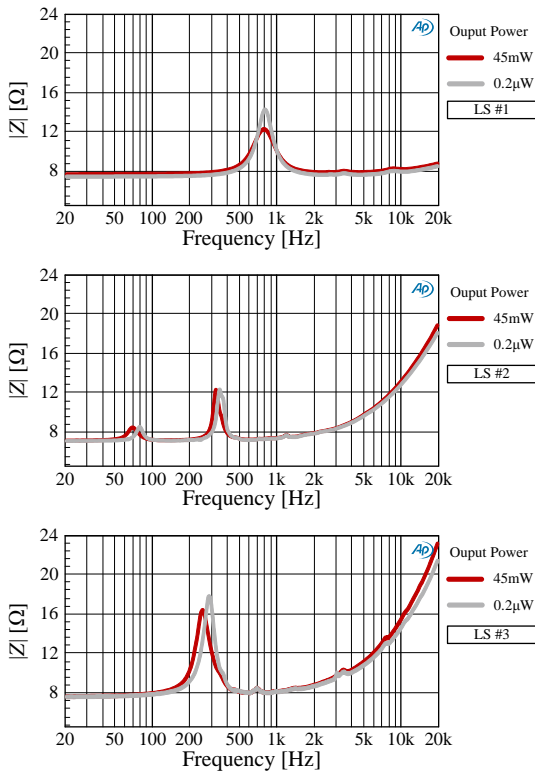


Figure 9 Loudspeaker impedances under test

4.2. Current and voltage amplifier

To validate the theoretical analysis, two audio amplifiers with current and voltage control have been developed based on the same architecture as in Figure 2. The amplifier reference is NCP2990 and the 1 Ω sense resistor is non-inductive. The amplifier open-loop gain maintains a low and high output impedance for the voltage and current mode, respectively. The current feedback is a voltage-controlled current source. The final test board is shown in Figure 10. The audio performances are similar (in terms of linearity and noise) with a pure resistive output load. The following comparisons are therefore equivalent.



Figure 10 Test board with current and voltage feedback

4.3. Current in the voice coil

Figure 11 shows the spectral difference of the current coil between the current and voltage drive units when double tones at 100 mVrms amplitude are applied in/to the loudspeaker #1 (used for TV application). As the amplifier is non-ideal, the current drive has some distortions, but less than its voltage counterpart. The harmonics and the intermodulation products in the current voice coil have been reduced up to 20 dB in the current driving method as expected in section 3.3.

The other loudspeakers confirm a substantial reduction of around 10 dB for all harmonics. Figure 11 show the current spectrum in loudspeaker #2 (used for large range applications) and #3 (micro speaker for mobile phones) when the input signal is a double tone at 500 mVrms amplitude. The current drive unit shows better results again.

We then made a comparison of the intermodulation distortion levels of the coil currents driven by the two audio feedback principles. In the voltage feedback mode, low distorted voltage across the load provides a higher distorted coil current due to the impedance nonlinearities. In the current mode, the current is directly controlled by the feedback loop without impedance transformation unlike the voltage mode as also shown in equation (1). The current drive is completely free from voice coil variation or back electromotive force. Therefore, it provides a less distorted coil current than the voltage driving method for all loudspeakers under test. As the mechanical force applied to the mobile part is proportional to the coil current ($F = Bl \times I_s$), the current mode provides a better linearity to transform the electrical signal to a force. In this way, the global electro-acoustic transformation by the loudspeaker is more linear.

The interconnection between amplifier and loudspeaker is also reduced by the current drive unit. It could be particularly useful in mobile phones when a low cost output filter in the switching amplifier is used [21].

Finally, a subjective acoustic comparison, with a sample of listeners confirms this analysis. The sound seems to be clearer in the current mode than in the voltage mode.

5. CONCLUSION

To conclude, the assumption that the pure voltage source amplifier is ideal for audio applications has been discussed. The paper presents a model to understand the root cause of non-linearity, as well as a practical comparison between the current and voltage methods using three different loudspeakers. As the force to the voice coil is directly proportional to current, the current driving principle appears to be more appropriate to couple the amplifier to a loudspeaker. Thereby, it reduces the dependence to the load variation in large signals and over the temperature and interconnection variations. However, some design considerations have to be taken into account, such as the mechanical resonance or the impedance variations versus frequency.

Finally, the two principles of control have been tested and deliver more linear force/acceleration results for the current control driving unit.

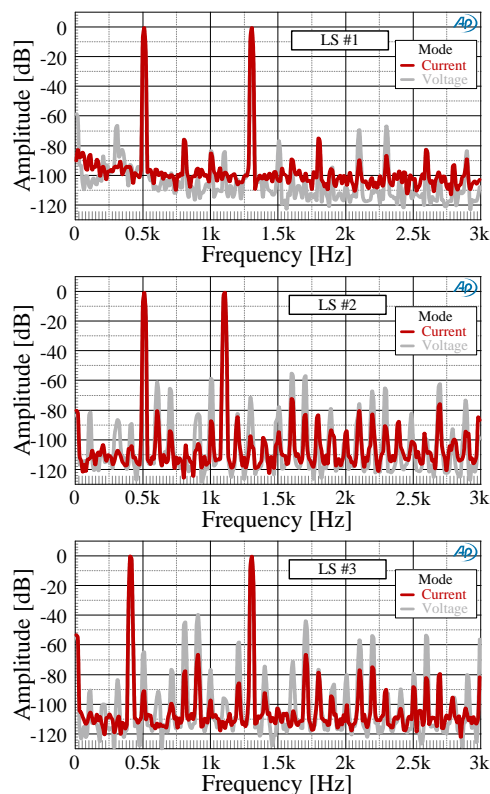


Figure 11 Current coil spectra in loudspeakers under test in current (red) and voltage (grey) modes

6. ACKNOWLEDGEMENTS

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