Motional Control of Loudspeakers

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*Abstract*—Loudspeakers are electromechanical systems; therefore, they exhibit many non-linearities and unwanted responses to an input signal. Manufacturers favour spending huge amounts of money perfecting the balance between the mechanical and electrical parts of the loudspeaker system such that the input signal is reproduced accurately as a sound wave, instead of using feedback techniques, in order to drive up the price of higher fidelity sound systems. Here, a repeatable and easy to understand methodology for simulating a subwoofer driver with feedback and feed-forward techniques is presented. It is predicted that the performance of a cheap subwoofer driver paired with relevant control circuitry rivals that of an expensive system.

Index terms— Feed-forward Control, Linkwitz Transform, Loudspeaker, LTSPICE, Motional Feedback, Simulink, Subwoofer, Thiele-Small Parameters.

# Introduction

E.R. Hanson stated [1] that loudspeakers should be as small as possible, respond as linearly and across as much of the frequency spectrum as possible, to distort minimally, and to consume and emit power efficiently. The practical nature of conventional loudspeaker designs means that this aim is difficult to achieve across the entire audible frequency spectrum. Hi-fi audio setups will therefore make use of multiple speakers, each responding adequately in a particular part of the audible frequency spectrum, to achieve a fairly linear response overall. The added complexity of multiple speakers and their associated crossover and filter electronics will vastly increase the price of such systems, relegating most consumers to inferior quality, single-speaker setups.

The worst-offending loudspeaker in the available range is the subwoofer – since it must move much larger amounts of air than woofers or tweeters, they are often much larger, more expensive, and more prone to distortions. In the sub-70Hz “sub-bass” range, performance is considered unreliable [2].

This project combines these two problems; the aim is to take a cheap subwoofer driver and explore open- and closed-loop compensation electronics improvements to its response, focusing on the sub-bass frequencies. The cost of such electronic solutions in combination with a cheap subwoofer system should be significantly cheaper than the price of a similarly performing, non-compensated existing system. Thus, the audio-conscious consumer would have a cheaper way of achieving better audio reproduction, companies could earn more profit from existing systems, and the compensation techniques could be applied to any system exhibiting similar physical properties as a loudspeaker.

# Economic, Legal, Social, Ethical and Environmental Context

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# Loudspeaker Theory

## Equivalent Circuit Diagram

A loudspeaker may be modelled as two circuits which interact through a magnetic field. From a design perspective, this is a very powerful tool – a full electrical simulation for a subwoofer in a box can also be combined with compensation circuit simulations, which saves time and makes the design process much easier. The electrical circuit is the voice coil resistance *RE* and inductance *LE*. The mechanical circuit represents the mass of the cone and air, the spring property of the suspension, and the total mechanical damping effects as an equivalent capacitance *MMs*, inductance *CMs*, and resistance *RMs* respectively [3]. These two circuits are linked by a transformer that represents the back-emf/force constant, *Bl*, which represents the constant of proportionality between force on the cone and current through the coil. In accordance with the introduced force-current proportionality, and with the intuition that, since all the mechanical parts of the loudspeaker are attached, they must share the same velocity, the simple circuit can be improved. Using standard techniques to refer values on the secondary of a transformer to its primary, the equivalent mechanical circuit parameters can be placed in parallel with the electrical circuit parameters, and the coupling effect may be removed from the circuit.

An enclosure represents an additional mechanical resistance *RB*, since the loudspeaker is now affixed to a non-moving mounting face, which impedes more subtle movements than in the unmounted case. The compression of air behind the speaker that the box stiffens the cone suspension, thereby decreasing compliance, which is represented as an additional equivalent inductance *CB*. This represents the final additions to the equivalent electromechanical circuit that are relevant from a design perspective. Fig. 1 [4] shows the final equivalent circuit used for the project.

## System Diagram and Classification

The electrical system forms a low-pass filter, whose cut-off frequency will lie above the frequency of operation. The mechanical system forms a band-pass filter – below its resonant frequency, for a subwoofer, the cone will be moving slowly but pushing a large volume of air, which requires large forces, and therefore large currents. Above resonance, less air is being moved but the cone moves faster; as the cone’s acceleration increases, the force and therefore the current required increases. To achieve this project’s aim, it is more important to satisfy below-resonance requirements as opposed to those above resonance. Of note in [4] is that, assuming that the force on the cone is non-linear, it can be shown that the effects of a non-linear cone suspension are stronger than at higher frequencies, legitimising further the choice of using a subwoofer as part of this project.

A full system block diagram for a loudspeaker is shown by Fig. 2 [5] [6].

## Thiele-Small Parameters

The Loudspeaker driver manufacturers do not directly quote values for MM, CM, RM etc. because it is difficult to measure these values directly. Instead, a set of values known as Thiele-Small parameters (TSPs), described in [7]. These values are easier for loudspeaker driver manufacturers to measure and can be converted into an equivalent circuit by the user if necessary. They also give a viewer a more intuitive view of the driver’s performance – whilst the equivalent circuit parameters describe individually each aspect of the mechanical parts of the driver, the correlation between n their variation and a change in the driver’s performance is not easily obvious. With TSPs, the equivalent circuit for a loudspeaker can be derived, and a box’s compliance and mechanical resistance can be added into it.

It can be the case that an actual driver’s TSPs will vary from the nominal ones given on a data sheet; it therefore may be advisable to measure all TSPs manually for each driver.

## Power Amplifier Requirements

The current *I* through a loudspeaker’s coil at any time is defined as:

*m* = mass of cone and air, *a* = cone acceleration, *Bl* = force-current constant. At low frequencies

# Methodology

The general methodology of the project will now be described. A more complete description of all the steps taken, and initial mistakes made, may be found in the Interim Report for this project [11].

The project’s innovative steps of designing and building open- and closed-loop compensators depend upon the existence of a constructed subwoofer. It is much easier to measure physical properties of the subwoofer driver and its enclosure if each is separated from the other; this is necessary in order to derive equivalent electromechanical circuit parameters. Therefore, the first part of this project revolves around constructing a complete subwoofer unit from scratch. This methodology is advantageous as it can be easily replicated by someone that only has access to a driver’s datasheet.

## Driver Selection

The aim of this project is to fulfil the fundamental aims of loudspeakers introduced in section I. The chosen driver, the Pyle PLPW6D, reflects these aims, with its small form factor and low cost [8]. It also features two voice-coils, which introduces the possibility for novel simultaneous driving/sensing setups.

## Enclosure Design

The given TSPs for the PLPW6D can be used to calculate the volume of an enclosure. The easiest way to go about this is to choose a new resonant frequency for the system. As discussed in section III, an enclosure stiffens the driver’s cone suspension, which means that adding any form of enclosure raises the resonant frequency of the system. Once a new frequency is chosen, the volume of the box required to achieve that frequency is calculated using the driver’s TSPs. The result of this calculation can also be used to derive the power requirements for the system at low frequencies

# Results

## SPICE Simulations

Fig. 6 compares the magnitudes of the unmounted, mounted, and mounted-transformed frequency responses of the Pyle PLPW6D. The addition of an equivalent enclosure increases the resonant frequency of the system according to the value given to the MATLAB box designer script. The Linkwitz Transform extends the response of the system well into the sub-bass frequencies, with a flat response from 100Hz down to 10Hz with a gentle roll-off. Figs. 7 and 8 show the comparisons of phase responses and group delays respectively. The group delay gives an insight into the delay of an input signal’s propagation through each system in the critical 10-100Hz region of operation.

## Bode 100 Impedance Analyses

The impedance plots for each voice coil of each speaker followed the shape of the datasheet plot. The resonant frequencies lay at around 70Hz for each, which would slightly alter the calculated value of Bl. The speaker out of the three that were purchased that will be mounted into an enclosure is henceforth referred to as ‘Speaker 3’, and its impedance analyses plots are shown in Figs. 9 and 10.

## Simulink Simulations

Fig. 11 shows the results of the Simulink simulation of this mounted and Linkwitz-Transformed system given the peak voltage input into the system based on the power amplifier rating calculated using (6), at 20Hz.

# Discussion

## Discussion

The results of the impedance analyses show that the design for the box is too small for the original poweramp requirement, as the magnet cannot actually generate enough force to overcome the decreased compliance of the box. However, this is easily rectified by simply increasing the power delivered to the speaker, which is acceptable since the original power requirement was so modest.

Measuring across separate voice coils lead to a massive impedance measurement, implying the existence of a dielectric, thereby confirming that the voice coils were independent from one another. The perceived error in impedances and phase responses between the two for the selected subwoofer is small enough such that no correction circuitry is required, so the driving-sensing setup discussed earlier can be undertaken with confidence.

The results of the SPICE simulations prove that the Linkwitz Transform not only increases the magnitude of response at sub-bass frequencies, but also improves the group delay of the subwoofer system in the range of operation. This means that adding the transform would enable the subwoofer to produce more bass, more linearly, and with less of a lag from when an input voltage is applied to it. The latter analysis shows that this subwoofer system would be appropriate to transplant into a full sound system instead of existing as a stand-alone research item.

The current Linkwitz Transform circuit is not optimised well for a real-world subwoofer. Under 20Hz, massive current and cone excursion requirements render accurate sound reproduction difficult, with risk to the physical integrity of the system high.

The Simulink simulation may be considered a ‘worst-case’ scenario for the system’s operation – at low frequencies the cone must move the furthest to move the required volume of air to reproduce the driving frequency. Nevertheless, it is clear that the cone excursion does not exceed 4mm from equilibrium in either direction of its travel once the system is stable. This Simulink model could be used further into the project to test the validity of closed-loop circuits.

Frequencies lower than 20Hz were not considered worth simulating given that most recordings do not contain sound data below 20Hz. The action of one closed-loop controller will be to limit the cone’s excursion to X¬max to avoid damage to the system and distortion to reproduced sound.

## Evaluation

All results currently exist as simulation data. This can be considered as a shortcoming of the progress thus far, as physical systems and results will always differ from experimental results. Too much time has been spent simulating the systems instead of actually building and measuring the systems. Although it is not clear to find one easy way to build the perfect enclosure, a decision should have been made much earlier into the project, in order to have a system to work with to create novel electronic solutions. What should have been a precursor activity to the bulk of electronic work has now taken over the project as the bulk of the work. This puts into jeopardy the possibility of finding and implementing closed-loop control circuits. A better methodology for the project up to this point shall be briefly detailed:

1. Create loudspeaker equivalent circuit from datasheet values whilst waiting for subwoofers to arrive.
2. Conduct impedance analyses on subwoofers and edit equivalent circuit to reflect real-world values.
3. Derive box dimensions using equivalent circuit theory.
4. Build box and mount subwoofer.
5. Measure frequency response of system in anechoic chamber and take new impedance measurements.
6. Use measured frequency response to design and tune Linkwitz Transform circuit.
7. Measure new frequency response of subwoofer with Linkwitz Transform.

The progress thus far has nonetheless solidified a clear build plan for a well-performing subwoofer, with extra steps taken to automate and validate the process as much as possible. The principles of iterative design, and of verification and validation, were displayed.

The project was not conducted with enough respect to the original Gantt chart, which lead to constant intervention and guidance from the supervisor being necessary to stay on track. The learning from these mistakes should, however, bolster the progress in the next stage of the project. Fig. 12 shows an improved Gantt chart for the rest of the project’s duration, along with the key.

# Bibliography

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| [1] | E. R. Hanson, "A motional feedback loudspeaker system," in *Audio Engineering Society Convention 46*, 1973. |
| [2] | F. Rumsey and R. McCormick, Sound and Recording, Oxford: Focal Press, 2006. |
| [3] | H. F. Olson, Elements of Acoustical Engineering, New York: D. Van Nostrand Company, Inc, 1940. |
| [4] | F. X. Y. Gao and W. M. Snelgrove, "Adaptive linearization of a loudspeaker," in *1991 International Conference on Acoustics, Speech, and Signal Processing*, Toronto, 1991. |
| [5] | J. Catrysse, "On the Design of Some Feedback Circuits for Loudspeakers," *Audio Engineering Society,* vol. 33, June 1985. |
| [6] | L. Yayou and G. T. Chiu, "Control of Loudspeakers Using Disturbance-Observer-Type Velocity Estimation," *IEEE / ASME Transactions on Mechatronics,* vol. 10, no. 1, Feb 2005. |
| [7] | R. H. Small, "Direct-Radiator Loudspeaker System Analysis," *Audio Engineering Society,* vol. 20, no. 5, June 1972. |
| [8] | Pyle Audio, "pyleaudio.com," [Online]. Available: https://www.pyleaudio.com/sku/PLPW6D/65-600-Watt-Dual-Voice-Coil-4-Ohm-Subwoofer. [Accessed April 2020]. |
| [9] | S. Linkwitz, "A Three-Enclosure Loudspeaker System Part III," *Speaker Builder,* no. 4, p. 16, 1980. |
| [10] | S. Linkwitz, "12 dB/oct highpass equalization ("Linkwitz Transform", Biquad)," [Online]. Available: https://www.linkwitzlab.com/filters.htm#10. [Accessed April 2020]. |
| [11] | S. Malde, "Interim Technical Report," 20 January 2020. [Online]. Available: https://github.com/spez1998/3rd-year-project/blob/master/Deliverables/InterimReport/INT\_ela17sm.pdf. [Accessed April 2020]. |

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