Interim Technical Report

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**Project Description**

**Project Aim**

E.R. Hanson stated in [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 is such 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.

**Project Specification**

* Theorise, simulate, and implement open-loop loudspeaker behaviour.
* Choose an open-loop compensation circuit suitable for a cheap subwoofer setup.
* Build a simple subwoofer setup and measure response before and after applying open-loop compensator.
* Design, simulate, and implement closed-loop compensators, comparing the subwoofer’s behaviour before and after adding them (time permitting).
* Final quantitative and qualitative assessment of compensated subwoofer performance versus an existing high-performance uncompensated system.

The specification has changed slightly from that introduced in the Project Initialisation Document – this is to reflect the slower-than-expected progress in the project. This is indicated by the ‘time permitting’ statement next to the closed-loop compensation specification point; after a discussion with my supervisor, it was suggested to refocus the project to at least prove that an open-loop compensation circuit provides better measurable results to a subwoofer’s performance, such that, if the worst case scenario of minimal progress were to occur, that there would at least be some results to present at the end of the project.

**Background Theory and Methodology**

**Loudspeaker Equivalent Circuit**

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. The work in [4] introduces a simple equivalent circuit model (Fig. 1).

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Fig. 1 Simple loudspeaker electrical and equivalent mechanical circuit

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. Both improvements are shown in Fig. 2.

Fig. 2 Improved loudspeaker electrical and equivalent mechanical 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 effectively stiffens the cone suspension, which is represented as an additional equivalent inductance *CB*. This represents the final additions to the equivalent electromechanical circuit that are actually relevant from a design perspective – any other additions would increase the accuracy of the model but only marginally, so it’s easier to just ignore these. Fig. 3 shows the final equivalent circuit used for the project.

Fig. 3 Final loudspeaker electrical and equivalent mechanical circuit

A full system block diagram for a loudspeaker is shown by Fig. 4 [5,6]. 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.

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Fig. 4 Loudspeaker system diagram with coil current as the output

**Enclosure Design**

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), first explicitly 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 their variation and a change in the driver’s performance is not easily obvious.

Common TSPs stated by manufacturers are [7]:

* *fs* – the driver’s unmounted resonant frequency
* *RE* – voice coil DC resistance
* *QM* – driver mechanical circuit Q-factor
* *QE* – driver electrical circuit Q-factor
* *QT* – driver total Q-factor
* *VAS* – driver compliance equivalent volume (a volume of air having equal compliance as the driver’s suspension)
* *Bl* – back-emf/force constant
* *Sd* – cone surface area
* *Xmax* – maximum cone excursion from equilibrium
* *D* – cone diameter

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.

**Control Circuits**

The system block diagram shown in Fig. 4 shows that the cone’s velocity is fed back into a controller, but velocity is not a directly measurable property. The electromechanical parameters described earlier must be measured and velocity mathematically derived, or the control loop mathematics adjusted to accept a different parameter as feedback. Some methods of doing so are presented in [8]; the author designs and implements a method using a varactor (variable capacitor) as a displacement sensor. The varactor, as part of a Clapp oscillator, is placed onto the loudspeaker’s cone, and varies in capacitance with the excursion of the cone, generating a frequency-modulated value for displacement of the cone. This varies the frequency of oscillation of the Clapp oscillator, therefore, when, the Clapp oscillator’s output is compared with that of a phase-locked loop circuit [9], the raw displacement measurement is obtained, and a differentiator converts this into the velocity of cone.

The work in [10] describes an accelerometer attached to the cone measuring acceleration, specifically, the details of the effect of the accelerometer on the loudspeaker’s performance. The effect of the varactor on the loudspeaker’s performance was not evaluated in [8] – for any control system that will be implemented, its effect on performance must be evaluated, in order to ensure that all work against non-linearity isn’t being undone by the same equipment that is being used.

The work in [6] describes a method of controlling the loudspeaker current by using a disturbance observer estimator. Disturbance is random, therefore cannot be calculated and must be estimated; the generated estimated error signal is fed forward and subtracted from the output to ensure that any noise or unwanted external signals are removed from the output of the loudspeaker. It would be wise to implement uncertainty estimation along with disturbance estimation, since the mechanical properties of the loudspeaker will change over time. This allows linearity to be achieved not just in ideal laboratory conditions, but in real-world conditions with real-world usage.

**Methodology**

The methodology that was undertaken in the project thus far shall now be described.

1. Firstly, a driver was selected. For this project, the Pyle PLPW6D was chosen partly for its cheapness, but also because it features two voice coils. This dual voice-coil (DVC) setup could be used for a driving/sensing setup, where one voice coil drives the cone, and another provides the control circuitry discussed above with a reference signal. Therefore, the act of sensing would not impede upon the act of driving. The TSPs supplied in its datasheet [11] are given in the Appendix. On the datasheet can also be found the manufacturer’s impedance plot for the driver, which shall be referred to henceforth as the **datasheet plot.**
2. As the arrival of the drivers from the supplier was awaited, background research and initial simulations of electrical circuits occurred. As can be seen from the PLPW6D’s TSPs, some calculations were necessary to find *Bl* and *CMS, MMS, RMS*. These equations, laid out in [7], along with common circuit analysis techniques, were used to derive the equivalent circuit:
   1. It was initially assumed that the amplifier’s output impedance was a necessary component in the equivalent circuit. Whilst it is true that amplifiers feature non-linearity and distortion, these effects are orders of magnitude lower than those for the loudspeaker, and so the amplifier could be ignored.
   2. The voice coil’s inductance was initially erroneously derived from the resonant peak of the datasheet plot. After the error was identified, it was then estimated from the impedance at 20kHz of the datasheet plot – at high frequencies for an RL low-pass filter, only the inductor will define circuit behaviour.
   3. The most important TSP that required calculation was *Bl*, as all equivalent circuit parameters are dependent on it. However, *CMS* can be calculated first as it only depends on *VAS*, which was given:

(1)

* 1. *Bl* could then be calculated using:

(2)

* 1. At the driver’s resonant frequency, only the equivalent mechanical capacitance and inductance would define the circuit. Therefore:

(3)

* 1. *RMS* could then be derived from the mechanical circuit and its Q-factor:

(4)

* 1. From the relationships seen in Figs. 2 and 3, the electrical equivalent values were derived:

The circuit was simulated to gauge the predicted frequency response of the loudspeaker.

It should be noted that the methodology from this point onwards is flawed – this will be discussed after the results section of this document.

1. The Linkwitz Transform [12,13] was chosen as the best open-loop compensator for the subwoofer system. This is because it not only extends the bass response for a subwoofer, but also reduces the group delay of the system, meaning that the driver responds faster to an input signal, reducing potential lag between different parts of the audio reproduction signal chain. Traditional equalisation methods revolve around introducing electronically a pair of zeros to cancel out undesirable poles in the frequency response to try and flatten it. There are two methods of designing a Linkwitz Transform for a system:
   1. Using the original formulas laid out by the transform’s late designer [12].
   2. Using resources available from the late designer’s website [13] that automate the process of designing and optimising the circuit for a system.
2. Many hours were spent on optimising the Linkwitz Transform for the simulated circuit. Many different values were given to the design tools available to try and ascertain a perfectly flat response that still gave a reduction in group delay. Eventually, one circuit topology was chosen.
3. A design for a box commenced. Putting a driver into a reasonably sized box is guaranteed to increase its resonant frequency, because the air behind the driver is sealed in the box and therefore has a compliance. The air can be thought of as a spring, stiffening the driver’s suspension – below resonance, adequate power is required to overcome this spring.
   1. It is best to choose a new resonant frequency for the driver-box system and ascertain the power requirements for the system at that point.
   2. Ensuring that it is a reasonable power, the peak current can be derived from this power, and converted into a peak force requirement through *Bl*.
   3. It is known that the driver can only excurse to *Xmax­* given that peak force, which is equivalent as saying that the box has a certain compliance – a certain amount of excursion per Newton. Thus, a new box compliance is derived.
   4. This compliance can be converted through *Bl* into an equivalent circuit parameter, and into an equivalent volume of air through (1). This volume is the volume of the inside of the box.

The box resistance is large enough such that when combined in parallel with *RMS*, it barely alters *RMS*. Therefore, it may be ignored if sufficiently large.

* 1. Some further simple arithmetic can be conducted to form the dimensions of the exterior of the box, given a material thickness. This whole process was automated using MATLAB, the code for which is given in the Appendix.
  2. The box was modelled in Autodesk Fusion 360 to ensure visually that the driver would fit inside it, and that the dimensions seemed reasonable.

1. A Simulink model was created to ensure that *Xmax* would not be disobeyed, given a certain size of box. This validated the theory and code described in part 5 of this section.
2. The enclosure for the subwoofer was then manufactured. The chosen material for the enclosure was 12mm thick medium density fibreboard (MDF) – this was chosen due to its strength and density, necessary as pressures inside the box during subwoofer operation are similar to those that push the required amount of air to generate bass sounds. The walls of the enclosure were laser cut from the dimensions in its 3D design, with an extra circular hole cut out of the front panel to accommodate the driver. Smaller holes were cut on the back to mount banana plugs to the enclosure.
   1. Assembly involved gluing all the sides together bar one (to allow access to the inside of the box) using PVA, then securing the joints with screws.
   2. A pillar drill was used to cut any screw pilot holes, and a hand drill used to drive the screws into the holes.
   3. In this manner, holes were drilled to allow the driver to be screwed onto the front panel.
   4. Then, all the inside joints were sealed with silicone sealant, wires soldered to the spade terminals and affixed to the mounted banana plugs.
   5. Then the final panel was glued and screwed on.

All of these steps ensure that the box can withstand the pressures generated by the driver, and that there are no air gaps which would cause irritating whistling noises and disturb all electronic compensation theory up to this point.

**Results**

**LTSpice Simulations**

Fig. 5 shows the LTSpice simulation of the Pyle PLPW6D equivalent electromechanical circuit. Fig. 6 shows the same circuit but with the addition of a tuned Linkwitz Transform. Fig. 7 compares the magnitudes of the unmounted, mounted, and mounted-transformed frequency responses of the Pyle PLPW6D.

**References**

1. E. R. Hanson, “A motional feedback loudspeaker system,” in *Audio Engineering Society Convention 46,* Audio Engineering Society, 1973.
2. F. Rumsey and R. McCormick, *Sound and Recording,* 5th ed. 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," *[Proceedings] ICASSP 91: 1991 International Conference on Acoustics, Speech, and Signal Processing,* Toronto, Ontario, Canada, 1991, pp. 3589-3592 vol.5.
5. J. Catrysse, “On the Design of Some Feedback Circuits for Loudspeakers,” in *Audio Engineering Society*, vol. 33, Audio Engineering Society, June 1985.
6. Yaoyu Li and G. T. Chiu, "Control of Loudspeakers Using Disturbance-Observer-Type Velocity Estimation," in *IEEE/ASME Transactions on Mechatronics*, vol. 10, no. 1, Feb. 2005.
7. smalls\_closed\_box\_article\_2\_OCR
8. J. Catrysse, “On the Design of Some Feedback Circuits for Loudspeakers,” in Audio Engineering Society, vol. 33, Audio Engineering Society, June 1985.
9. P. Horowitz and W. Hill, The Art of Electronics, 3rd ed. New York: Cambridge University Press, 2015.
10. H. Schneider, E. Pranjic, F. Agerkvist, A. Knott, M. A. E. Anderson, “Design and Evaluation of Accelerometer based Motional Feedback,” in Audio Engineering Society Convention 138, Audio Engineering Society, May 2015.
11. <https://www.pyleaudio.com/sku/PLPW6D/65-600-Watt-Dual-Voice-Coil-4-Ohm-Subwoofer>
12. Speaker Builder 1/86
13. Linkwitzlab

**Appendices**

**Appendix A**

Pyle spec

**Appendix B**

MATALB code