*[Intro slide] ~ 8 secs*

Welcome to this presentation where I will discuss my 3rd year project, entitled “Motional Control of Loudspeakers.”

*[Loudspeaker diagram] ~ 18 secs*

To begin with, I shall make reference to this labelled loudspeaker diagram. I will be referring to the terms in this diagram throughout the presentation so please familiarise yourself with them. Of particular note are the following terms: voice coil, cone, and spider – which shall henceforth be referred to as the cone suspension.

*[Background 1] ~ 46 secs*

Loudspeakers should be small, efficient, and reproduce sound linearly, but in practice can only either be small/efficient OR linear. Linearity is hard to achieve, which leads to manufacturers overengineering loudspeakers, leaving the best sound unattainable except to those willing to spend large amounts of money (the large speakers pictured cost over £12,000), and deal with an impractically sized device. The worst-performing loudspeaker is the subwoofer, which performs worse than tweeters and midrange drivers because of the increased effect of non-linearity at low frequencies. A mathematical treatment may prove this, as seen in “Adaptive Linearisation of a Loudspeaker”; it states that because more air needs to be moved to generate low frequency sounds, larger cone excursions increase the margin for error.

*[Background 2] ~ 40 secs*

Since it is clear that no amount of mechanical trickery will ever make a loudspeaker perform perfectly, electronic controllers are the key to better sound quality and smaller loudspeakers. Electronics are much cheaper and lighter than mechanical bulk, so more consumers have access to cheaper, smaller, and better sounding loudspeakers. Two types of controllers will be investigated in this project: open-loop (or, feedforward) controllers, which are already used by audio enthusiasts (for example: in EQ filters), and feedback controllers, which have only been used with loudspeakers experimentally. Different controllers will be compared against each other to determine which improves a subwoofer’s response the most.

*[Aims] ~ 10 secs*

These are the project’s aims – these will be referred to after presentation of the results to assess whether the methodology was able to achieve them.

*[Theory 1] ~ 46 secs*

Fundamental loudspeaker theory shows that loudspeakers can be modelled as equivalent electrical circuits. The electrical and mechanical circuits can be thought of as the primary and secondary of a transformer with turns ratio equivalent to the force-current constant Bl because an input voltage is transformed into an output velocity through Bl. Bl is derived from the well-known electromechanical coupling equation F=Bl I. Whilst these equivalent circuit parameters are easy to create simulations with, they are difficult to determine a loudspeaker’s performance at a glance, and are difficult to measure directly so are not quoted by manufacturers on datasheets. Instead, a set of parameters known as Thiele-Small parameters (TSPs) are used instead.

*[Theory 2] ~ 24 secs*

Thiele-Small Parameters (TSPs) are used as intermediaries between the equivalent circuit and an actual loudspeaker. They are easier to measure and understand than circuit parameters – you get a better picture of the loudspeaker’s performance. Inter-dependence means only a couple are needed to calculate the rest. The three highlighted parameters – fs, Bl, and Xmax, are the most important and will be used the most in the project.

*[Theory 3] ~ 47 secs*

Open-loop controllers only work for the configuration they are designed for. Whilst this is also true for simple closed-loop controllers, state observers, disturbance observers, and estimators can all be used in a state-space controller to predict how the subwoofer’s physical properties change over time and try to eliminate noise from affecting its output. State observers can obtain values for normally unmeasurable equivalent circuit parameters, disturbance observers can measure disturbances that affect system performance such that they can be eliminated, and estimators can predict how certain loudspeaker parameters change over time. As such, an ideal result would show that a closed-loop controller can outperform an open-loop controller, such that the described techniques can be implemented.

*[Methodology 1] ~ 5 secs*

The first step of the methodology is to choose a subwoofer to work with.

*[Methodology 2] ~ 13 secs*

The Pyle PLPW6D was chosen as the candidate subwoofer due to its cheapness, small size, and dual voice coils which could be used for novel driving-and-sensing setups.

*[Methodology 3] ~ 25 secs*

The second step is to obtain impedance measurements for the unmounted PLPW6D. Datasheet values cannot be trusted for such large devices, so it’s crucial to measure them again. The Bode 100 Impedance Analyzer was used to re-plot an impedance characteristic. From this, new TSPs were calculated and an equivalent circuit re-made for simulation purposes.

*[Methodology 4] ~ 15 secs*

The measurements show that the datasheet resonant frequency is around 20 Hz less than the real-world values. The discrepancy in peak impedance values can be attributed to the nature of the voice coil inductance not being constant across every subwoofer.

*[Methodology 5] ~ 21 secs*

The third step is to design an appropriate enclosure for the subwoofer. Adding an enclosure has the effect of stiffening the loudspeaker – more power is needed to get the same sound pressure and the resonant frequency is raised. There is no optimum value for the size of a loudspeaker’s enclosure – you must balance between size, sound quality, and power requirement.

*[Methodology 6] ~ 44 secs*

The easiest way to design an enclosure is to choose a new, higher target resonant frequency, then calculate the peak current requirement to excurse the cone to *XMAX* at this frequency using the first equation. Then, use this peak current value in the second equation to ascertain the volume of enclosure that lets the cone excurse to *XMAX* at low frequencies, given the force on the cone delivered by that peak current value. *XMAX* is used as the limit for the subwoofer’s performance because the cone’s suspension is not linear past it. A MATLAB script was used to implement these equations, whilst also maintaining a modest power requirement. A 6-litre box was found to be most appropriate, coupled with a 30 W power amplifier. The design and construction of the power amplifier was planned, but never came to fruition due to the impact of the ongoing coronavirus pandemic. Therefore, it won’t be discussed further.

*[Methodology 7] ~ 3 secs*

The fourth step is to construct the enclosure.

*[Methodology 8] ~ 40 secs*

12 mm MDF was chosen as the material of choice due to its strength – pressures inside the enclosure during operation will be substantial and thin woods may buckle under them. A Fusion 360 model was created to assist construction. A laser cutter was used to cut all panels. Each panel was secured to the others initially with wood glue, then with 3mm diameter screws. More complicated joints were not used to minimize the length over which air could possibly escape from the enclosure. All joints were sealed with bathroom silicone before the final panel and driver were mounted. Banana ports were mounted on the rear of the enclosure.

*[Methodology 9] ~ 21 secs*

The fifth step is to re-obtain impedance measurements for the mounted PLPW6D. Measuring the impedance of the completed system is crucial because the TSPs will have changed, and it’s with the new TSPs that the controllers are tuned. COVID-19 prevented this from actually happening.

The sixth step is to choose an open-loop compensator.

*[Methodology 10] ~ 41 secs*

The Linkwitz Transform is a high-pass filter that replaces existing poles of the loudspeaker system with zeroes and reintroduces a new pair of poles lower down the frequency spectrum. If used with the PLPW6D, the system would exhibit better bass response and better group delay – the speaker would take less time to reach an input nominal value and would distort less. The transform has several resources available freely to tune it in accordance with standard resistor and capacitor values, making it attractive from an ease of design perspective. The diagram shows the transform tuned for the PLPW6D, moving the resonant frequency down to 19 Hz with a Q-factor of 0.19.

*[Methodology 11] ~ 30 secs*

The next step is to choose closed-loop controllers. The most easily observable system states are: coil current (measured by an ammeter or shunt resistor), and cone displacement and its derivatives with time (somewhat easily measured with accelerometers and integrators). The output voltage of the system is observable but requires a voltage bridge setup – potentially only feasible in a lab. For the purposes of the project, voltage, current, and displacement controllers will be used and investigated.

*[Methodology 12] ~ 11 secs*

All controllers are then simulated in Simulink, and the data collected is compared against the uncontrolled subwoofer’s data. Analyses may then be made to determine if the project aims have been met.

*[Methodology 13] ~ 23 secs*

The methodology described consists solely of simulation work. This is due to the impact of COVID-19 on the normal duration of the project – ideally, real analog circuits would have been built to implement the controllers in real life. As such, the results must be considered as guidelines for the presented methodology, to be used as validation in the case where this project is undertaken again.

*[Methodology 14] ~ 20 secs*

This first Simulink model interfaces with a script which automatically runs simulations at desired frequencies and determines the magnitude response, phase response, and group delay of each subwoofer system configuration seen. This is analogous to performing a .ac simulation in LTspice. Data collection is very straightforward.

*[Methodology 15] ~ 12 secs*

These models are more user-friendly and examine the loudspeaker at a much more granular level. Simulink’s sandbox nature makes these models very easy to create and work with, but data collection is more cumbersome and repetitive.

*[Results 1] ~ 15 secs*

The results show that the voltage controller makes the system perform perfectly. The Linkwitz Transform exhibits boosted and linear performance to around 70 Hz. The current controller boosts, but does not linearize, system performance.

*[Results 2] ~ 11 secs*

The Linkwitz Transform and current controller exhibit the best and second-best group delays. The voltage controller exhibits exceptionally poor group delay at extremely low frequencies.

*[Results 3] ~ 19 secs*

The voltage controller has unacceptable coil current and cone excursion – subwoofer would blow up! The LT and current controller both have large coil current and cone excursions at low frequencies but rapidly return to acceptable levels – recorded sound rarely has power in the frequency bands less than 20 Hz so this is okay.

*[Conclusion] ~ 58 secs*

Due to the infeasibility of implementing the voltage controller, two choices exist: for more accurate, linear bass, use the Linkwitz Transform. For the largest increase to bass irrespective of accuracy, use the current controller. As discussed earlier, these results are only simulations and do not properly reflect real-life, so are best used as guidelines for further work. It is important to note that the results may only be confidently applied to similarly smaller subwoofers – concert or cinema-sized subs require further investigation with the same control techniques. The price of current system plus electronics that went unused came to around £75 – much cheaper than overdesigned open-loop speaker systems. Including the impact of COVID-19, the project was overall partly successful, and met some of the aims outlined. Future work that has been suggested based on this progress has been included to assist those who may come across this project in the future.