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3rd Year Project Interim Report

“Exploring Different Techniques to Improve the Response of a Simple Subwoofer”

**Project Description**

1. Project Aim

The requirements of a loudspeaker as stated by E. R. Hanson [1] are: to 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. These aims are almost never completely realised due to nearly all loudspeakers outside of experimental settings not exhibiting any form of feedback mechanisms. The subwoofer is the worst offender in this category; since such large masses of air must be moved to produce low frequencies, the requirements become even more difficult to meet, and poor performance under the 70Hz range [2] is coupled with non-linear and non-ideal performance in the passband. The aim of this project is to improve the sound quality of a cheap loudspeaker by using open- and closed-loop electronic circuits, in order to present potential buyers with a cheap way to obtain near-reference sound reproduction.

**Background Theory**

A loudspeaker may be modelled as two circuits which interact through a magnetic field. 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 inductance *LM*, capacitance *CM*, and resistance *RM* respectively [3]. As shown in Fig. 1 [4], 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. A full system block diagram for a loudspeaker is shown by Fig. 2 [5,6]. For an input voltage *Vin(s),* the electrical impedance produces an output current *I(s)* as described by the transfer function

(1)

where *R*, *L* are the resistance, inductance of the voice coil respectively. The coupling effect of the back-emf/force constant transfers *I(s)* to the equivalent mechanical impedance as an equivalent force. The velocity of the cone *v(s)* as a result of this force *F(s)* is described by the transfer function

(2)

where *k*, *m*, *b* are the stiffness, mass, and damping coefficient of the loudspeaker respectively.

The existence of two systems, each with different measurable parameters, means that a closed-loop compensator that

1. State variable feedback

As can been seen from Fig. 2, the loudspeaker is a single-input single-output (SISO) system. However, there are other potential system outputs that would be valid signals to feed back to the control circuit, such as the current in the voice coil, and some states that cannot be measured directly and thus require the measurement of other parameters to obtain, such as the cone velocity. Thus, the technique of state variable feedback [7] becomes useful for this project. State variable feedback allows different feedback signals to be collected and mixed together, which increases the accuracy of control of the loudspeaker, since there are both electrical and mechanical effects to consider.

1. Obtaining Feedback Signals

The system block diagram shown in Fig. 2 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 [5]; 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 [8], the raw displacement measurement is obtained, and a differentiator converts this into the velocity of cone.

The work in [9] 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 [5] – 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.

1. Enclosure Design

Manufacturers of loudspeakers do not quote the equivalent electromechanical circuit parameters shown above and in Fig. 1 because it is difficult to measure them directly. Instead, some parameters that describe the low-frequency performance of the loudspeaker are provided; these are known as the Thiele-Small parameters [10]. When designing the enclosure for a loudspeaker, it is vital to know its Thiele-Small parameters to ensure that the full range of electrical and mechanical effects are considered and accounted for, such that sound performance is as optimal as possible given the requirements for the enclosure. The work conducted by S. Linkwitz as summarised in [11] demonstrates the process of designing an enclosure that is sufficiently small for a reasonable output. This process is necessary to ensure that the introduction of any control system does not unnecessarily increase the size of otherwise cheap and compact loudspeakers. The size of the enclosure defines the loudspeaker’s maximum excursion, so when designed properly, the loudspeaker cannot ever distort by travelling too far, so it is important that the mechanical building stages are afforded as much care and attention as the electrical design and build stages.

Manufacturers of loudspeakers describe the equivalent circuit parameters of their drivers through Thiele/Small parameters [10]. These parameters can be used to design an enclosure for a loudspeaker that imposes in a predictable manner a desired response onto the loudspeaker’s frequency response. It also reduces the cost of owning a system of similar sound quality, which, given that high-end audio is a premium market, may be worth the time and effort required to design and build the enclosure.

**Project Specification**

* Theorise, predict, and simulate open-loop loudspeaker behaviour and frequency responses, based on actual subwoofer device parameters.
* Explore and choose from different topologies of open-loop circuits one that presents the best improvement to low-frequency performance of a subwoofer system.

**Project Schedule**

Fig. 3 is a Gantt chart that showcases the general outline for work for this project. The task names corresponding to the numbers given in Fig. 3 can be found in Fig. 4.

|  |  |  |
| --- | --- | --- |
| **Tasks** | | **Description** |
|  | **Sub-tasks** |  |
| *1* |  | *Project Initialisation Document* |
|  | 1.1 | Initial research |
|  | 1.2 | Write-up |
|  | 1.3 | Hand-in  Fig. 1 Loudspeaker electrical and equivalent mechanical circuit |
| *2* |  | *Interim Report* |
|  | 2.1 | Simulation and build of open-loop system plus Linkwitz filter |
|  | 2.2 | Simulations of closed-loop system |
|  | 2.3 | Design and build of different closed-loop circuits |
|  | 2.4 | Report writing |
|  | 2.5 | Hand-in |
| *3* |  | *Second marker viva* |
|  | 3.1 | Collation of understanding and milestones |
|  | 3.2 | Slide preparation |
|  | 3.3 | Practice and refinement |
|  | 3.4 | Presentation |
| *4* |  | *Public engagement video* |
|  | 4.1 | Choosing a target audience |
|  | 4.2 | Storyboarding |
|  | 4.3 | Filming / animating and editing |
|  | 4.4 | Hand-in |
| *5* |  | *Symposium* |
|  | 5.1 | Adaptation and updating of viva slides |
|  | 5.2 | Practice and refinement |
|  | 5.3 | Presentations |
| *6* |  | *IEEE Article* |
|  | 6.1 | Design and build different types of control circuits using real parameters |
|  | 6.2 | Combine several control circuits together |
|  | 6.3 | Troubleshooting, testing, validating |
|  | 6.4 | Report writing |
|  | 6.5 | Hand-in |

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Fig. 2 Loudspeaker system diagram with coil current as the output

**Methodology**

An overly zealous respect to iterative design was demonstrated throughout the project to this stage. Most of the work I conducted was deriving an equivalent circuit for the loudspeaker and trying to design two different types of open-loop compensation circuits that adequately boosted the low frequency response of the loudspeaker. The problem I faced was that I took simulation results far too seriously, and as actual representations of the real world, rather than treating them as design indicators. Even though a simulation of an electrical circuit is usually fairly accurate, this circuit represents both electrical and mechanical systems, as seen in the system block diagram. This means that that real-life measurements of frequency responses are necessary in order to build an adequate compensation circuit. Failing to realise this, I spent copious amounts of project work time going over covered ground, tweaking circuit values for the chosen open-loop compensation topology, and trying to complete the project in the simulation domain instead of working with something that actually exists. As a result, project time has now been lost, and the aim and Gantt chart of the project have been edited to reflect this.

The iterations of design that I underwent are as follows: from the given driver Thiele-Small parameters, I calculated missing parameters, derived a simplified equivalent circuit, then experimented with adding extra equivalent compliance and mechanical damping (representing the addition of a box) to find a frequency response that would be easiest to linearise with the addition of an open-loop compensator. Towards the latter stages of this stage of the project, my supervisor reminded me of the futility of this repetition, and I then finally moved forward with proceedings and actually designed and built a real enclosure for a subwoofer driver.

Upon further reflection, I can also admit that I misinterpreted the aim of the project. Most literature that I explored prior to beginning the project spoke in great detail about closed-loop compensation improving the performance of a loudspeaker. None of this literature at any point describes an open-loop compensator that can achieve anything close to the same results. Most of my work and experimentation was trying to find a perfect simulated (bearing in mind the problems with simulations of a loudspeaker system discussed above) response. I therefore cannot claim to have fully understood the methodology and aims of the project until now.

If I were conducting the project anew from the beginning, I would spend at most two weeks on the process of understanding and simulating the equivalent circuit. I would then choose a box size that only slightly alters the frequency response of the loudspeaker – admittedly this would be an unacademic choice, but there is unfortunately no optimum size for any driver, nor is there any easy, clear way to derive such a size. I believe that my current methodology accounts well for this ambiguity – the program I wrote gives users the flexibility to choose exactly how the mounted subwoofer system would perform – if the size isn’t wieldy, then a new size can be given to the program and the estimated performance based on this size is given. Having then derived a box size, I would update the equivalent circuit model and then design an open-loop compensator. If the box size requires changing to allow for an adequate compensator topology, I would change it to achieve this, but this process of iteration would only occur once or twice. I would then carefully manufacture the subwoofer system, and then derive new impedance responses for it and measure its real-life frequency response. Then I would implement the open-loop compensator on breadboard, then stripboard. With the saved time and reduced complexity of this design process, I could work on understanding different closed-loop compensators, design these compensators and simulate them.

**Risk Register**

Risk factor = severity x likelihood. 0-5 = no further action needed, 5-10 = caution required when conducting activity, 10-15 = change to activity ideal, 15-25 = mandatory STOP and improve activity.

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| --- | --- | --- | --- | --- | --- | --- | --- |
| **Risk** | **Scoring** | | | **Reducing the risk** | **New scoring** | | |
| **Severity** | **Likelihood** | **Risk Factor** | **New Severity** | **New Likelihood** | **New Risk Factor** |
| Losing all project files due to computer hardware failure or carelessness with removable storage. | 5 | 4 | 20 | Version control using git, keep local copies of legacy repositories on home computer / laptop / university computer. | 3 | 1 | 3 |
| Running out of time | 3 | 3 | 9 | Strict adherence to Gantt chart (external factors allowing) should keep progress on-track at all times. | 3 | 2 | 6 |
| Over-spending | 3 | 4 | 12 | Purchasing through approved project budget acts as a deterrent against bad purchases but does not stop it completely. Purchase double of all required circuit board materials in case of damage to a prototype board. | 2 | 2 | 4 |
| Workshop injuries | 4 | 2 | 8 | Read, view, and absorb all health and safety related material delivered to undergraduates. Conduct health and safety training. | 4 | 1 | 4 |
| ‘Office’ injuries e.g. eye strain, carpal tunnel, posture issues | 5 | 2 | 10 | Wear glasses, consciously improve posture, take regular breaks | 3 | 1 | 3 |
| Software / hardware limitations or failure | 4 | 3 | 12 | Set the standard for weekly meetings and regular email communication early on in the project. Report to Kean Boon Lee if necessary. Individual nature of project allows for some complete autonomy if necessary. | 2 | 1 | 2 |
| Illness and/or injury | 3 | 2 | 6 | Limit risky activities close to crucial project deadlines and maximise project work whilst in a good physical and mental condition to mitigate losses when not, however some illnesses and injuries are unavoidable and unpredictable. | 2 | 2 | 4 |

**Bibliography**

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. M. Golnaraghi and B. Kuo, *Automatic Control Systems,* Tenth Edition, 10th ed. New York: McGraw-Hill Education, 2017.
8. P. Horowitz and W. Hill, *The Art of Electronics,* 3rd ed. New York: Cambridge University Press, 2015.
9. 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.
10. N. Thiele, “Loudspeakers in Vented Boxes, Part I,” in *Journal of the Audio Engineering Society,* vol. 19 no. 5*,* Audio Engineering Society, 1971.
11. S. Linkwitz, "Subwoofer estimates", linkwitzlab.com. [Online]. Available: https://www.linkwitzlab.com/thor-estim.htm. [Accessed: 22- Oct- 2019].