Measurement of Loudspeaker Parameters with a Raspberry Pi

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Introduction

Over the past two decades, technological advancements have led to nearly universal access to small, cost-efficient computing devices, with more and more alternative platforms emerging, still. This surge has empowered makers and do-it-yourself spirits worldwide to realize small-scale projects in many different areas of life, art, and research, from home automation to environmental science.

The Raspberry Pi is an example of such an easily available computing device. It is widely used in academia, e.g., in student projects. With its various modules it can serve as a sensor and actuator platform, a means of interacting with its environment. As such, it is well-suited for the implementation of measurement systems, and its performance allows for its use in audio applications.

This article proposes a system that uses a Raspberry Pi with some audio-specific peripherals, e.g., the HiFi Berry, to measure electroacoustic parameters of electrodynamic loudspeakers, including the Thiele-Small parameters (TSPs). To that effect, the paper is structured as follows: After some fundamentals related to loudspeakers and the TSPs, the practical implementation of the measurement system with a Raspberry Pi device is presented. The following section evaluates the capabilities of the Raspberry Pi setup regarding impedance measurement and parameter estimation, using appropriate reference devices. At the end of the article, a conclusion and a short summary are given before a final outlook on future work.

Fundamentals

This section introduces some necessary fundamentals about electrodynamic loudspeakers and their small-signal model before going on to explain the TSPs.

Electrodynamic transducer

The measurement system is intended for loudspeakers using electrodynamic drives. A schematic of such a transducer is shown in Figure 1.

Very simply put, the chassis consists of a membrane connected to a voice coil that is surrounded by a permanent magnet. The input electrical signal is applied to the voice coil, resulting in a moving electrical charge and, ultimately, the Lorentz force that displaces the membrane. Counteracting this Lorentz force is the restoring force of the membrane suspension [1].

Small signal parameters

In this way, the loudspeaker chassis can be described as a damped spring-mass oscillator. As such, it can be modelled using electromechanical analogies, leading to the well-known, classic equivalent circuit shown in Figure 2. The circuit includes three physical domains: electrical, mechanical, and acoustical. All the parameters are described by either resistances, inductances, and capacitances or two-port elements. This equivalent circuit is valid at low frequencies, where the membrane movement is piston-like, and for small input signals for which the transducer behaves linearly, i.e., its output is proportional to its input [3].

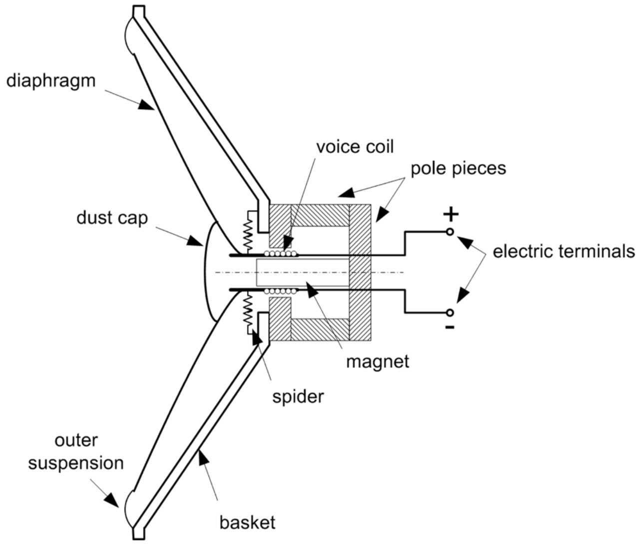

Figure 1: Schematic representation of the electromechanical assembly of an electrodynamic transducer [2].

Now, the commonly used electromechanical small signal parameters of a loudspeaker, as shown in Figure 2, are presented [1][3].

S_{d}: equivalent piston area of the transducer diaphragm, in m²

M_{ms}: mass of the transducer diaphragm and voice-coil assembly, including acoustic load, in kg

M_{md}: mass of the transducer diaphragm and voice-coil assembly, in kg

C_{ms}: compliance of the driver's suspension, in m/N (the reciprocal of its stiffness)

R_{ms}: the mechanical resistance of the driver's suspension in $\mathrm{Ns/m}$

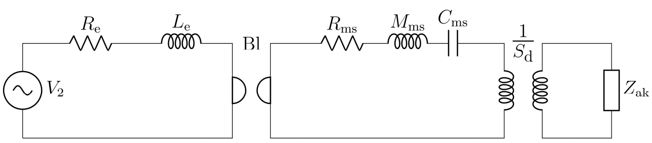

Figure 2: Small signal equivalent circuit of an electrodynamic loudspeaker.

L_e: voice coil inductance, in H (typically measured at 1 kHz for woofers)

R_e: DC resistance of the voice coil, in Ω

Bl: the product of magnetic flux density in the voice-coil and the length of wire in the magnetic field, in Tm

Thiele-Small parameters (TSPs)

The small signal parameters of an electrodynamic transducer are not the most straight-forward resource when designing loudspeakers. Instead, it is recommended to use the TSPs [1][3] that can be calculated based on the previously described small signal parameters.

Some relevant TSPs are defined in (1–5). More information about their measurement and calculation can be found in [1].

f_s: transducer resonance frequency, defined in (1):

$$f_s = \frac{1}{2\pi\sqrt{C_{ms} \cdot M_{ms}}} \quad (1)$$

Q_{es}: transducer Q at f_s considering electrical resistance R_e only, defined in (2):

$$Q_{es} = \frac{2\pi \cdot M_{ms} \cdot R_e}{(Bl)^2} = \frac{R_e}{(Bl)^2}\sqrt{\frac{M_{ms}}{C_{ms}}} \quad (2)$$

Q_{ms}: transducer Q at f_s considering driver nonelectrical losses only, defined (3):

$$Q_{ms} = \frac{2\pi \cdot f_s \cdot M_{ms}}{R_{ms}} = \frac{1}{R_{ms}}\sqrt{\frac{M_{ms}}{C_{ms}}} \quad (3)$$

Q_{ts}: total driver Q at f_s resulting from all driver resistances, given in (4):

$$Q_{ts} = \frac{Q_{ms} \cdot Q_{es}}{Q_{ms} + Q_{es}} \quad (4)$$

V_{as}: volume of air having the same acoustic compliance as the driver suspension, resulting in (5):

$$V_{as} = \rho \cdot c^2 \cdot S_d^2 \cdot C_{ms} \cdot 1000 \text{ litres}, \quad (5)$$

where ρ is the density of air 1.184 $\frac{\text{kg}}{\text{m}^3}$ at 25 °C, and c is the speed of sound 343 $\frac{\text{m}}{\text{s}}$ at 25 °C.

Practical Implementation

With the fundamentals presented in the preceding section, the measurement system for the acquisition of the TSPs can be presented. The measurement is performed with a Raspberry Pi 4 model B device, using the HiFi Berry and an amplifier PM40C as audio-specific peripherals.

Figure 3 illustrates the impedance measurement circuit. The Raspberry Pi generates a chirp signal which is amplified by the audio amplifier PM40C and results in a voltage V_g. This voltage is applied to the whole circuit consisting of a shunt resistance R_1 (exemplary value: 3.9 Ω) and a loudspeaker in series. Its value is chosen to fulfil the small signal condition, e.g., about 0.1 V. The voltages V_g and V_1 are measured, then the voltage V_2 over the loudspeaker can be calculated as $V_2 = V_g - V_1$, while the current flowing through the shunt and the loudspeaker can be calculated as $I = V_1/R_1$. The impedance is then $Z = I/V_2$.

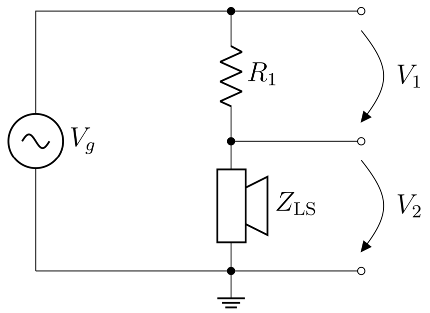

Figure 3: Circuit configuration for the electrical impedance measurement (based on [4]).

For good signal-to-noise ratios in both the voltage and current measurements, ceramic shunts with resistance values close to the loudspeaker resistive impedance were used. Moreover, it was necessary to take parasitic elements into account, due to the wires within the circuit. The additional wire impedance had a value of 0.3 Ω.

For the measurement and the subsequent calculation of the TSPs, the method that was implemented involves an additional mass on the membrane, which is a way to determine Bl and the mechanical parameters. It is generally known as the 'added mass' or 'perturbation' method [5].

Figure 4 shows a graphical user interface (GUI) for controlling the measurement hardware and software, which was developed using the Python language. To this end, the packages numpy, matplotlib, and scipy were used to process and visualize the data, as well as the package tkinter to develop the interface, and audioop which permits the reproduction of the audio signal by the Raspberry Pi. From the GUI, in the buttons section, the first buttons 'Measure' and 'Continue' allow to perform two measurements. The first one is performed without an added mass on the membrane, whilst the second one is performed with an added mass, whose value can be entered via the GUI in the second section 'Variables' below 'Mass (g)'. Membrane diameter and shunt resistance value are other variables that the user should enter manually in the options 'Shunt (Ohm)' and 'Diameter (cm)' since the measurement device cannot determine them on its own. The 'Plot' button permits to plot the impedance curves from the measurements with and without added mass. An 'End' button can be pressed to terminate the measurement.

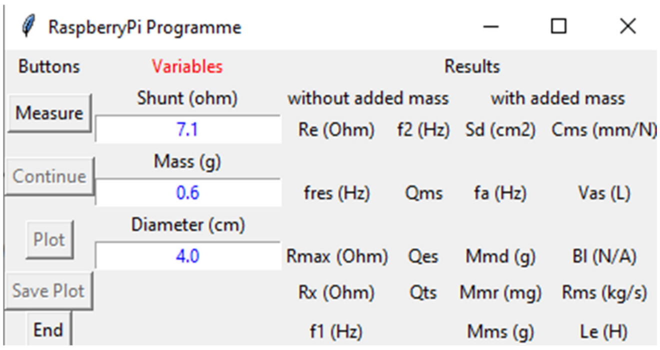

Figure 4: GUI for the measurement of the TSPs, with the control buttons (left), user-definable parameters related to the loudspeaker and the measurement setup (centre), and TSPs (right).

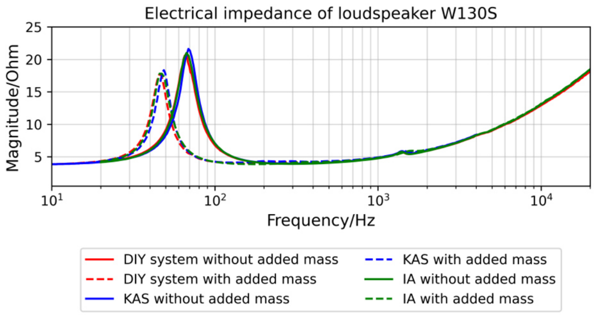

Figure 5: Loudspeaker W130S electrical impedance without (solid lines) and with an added mass (dashed lines), measured using the proposed Raspberry Pi system (red), a Klippel Analyser System (blue), and a Keysight E4990A Impedance Analyser (green).

Evaluation

The DIY Raspberry Pi measurement system was evaluated by comparing its measurement results to those obtained with reference devices. A Keysight E4990A impedance analyser (IA) and a Klippel Analyser System RnD (KAS) with a Distortion Analyser 2 hardware platform served as references in this case.

The IA measurements were compensated for additional impedances that occur through leads or contact resistances. With the Klippel system, four-terminal sensing was used.

Comparison of Impedance Measurements

Figures 5 and 6 show electrical impedance measurements for two different loudspeakers obtained with all three measurement systems. Only the impedance magnitude is considered.

Figure 5 shows the results for a Visaton W130S woofer. The measurement results of all three systems agree. Using the Raspberry Pi system, the f_s of the loudspeaker is 68.6 Hz in the measurement without an added mass, whilst in the measurement made with the added mass of 7.8 g, there is a clear drop to 47.2 Hz. There is also a drop in electrical impedance magnitude from 20.6 Ω to 17.7 Ω respectively. This behaviour is expected.

The results with a Visaton FRS 5 X miniature woofer (added mass 0.6 g), presented in Figure 6, speak a similar language:

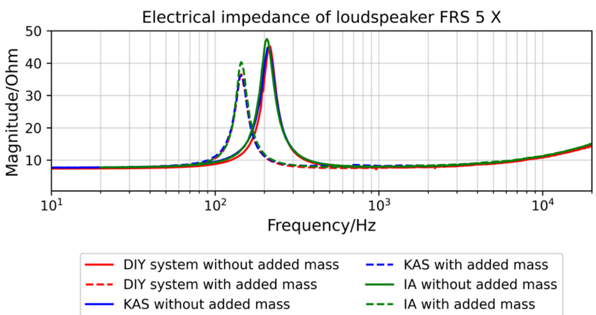

Figure 6: Loudspeaker FRS 5 X electrical impedance without (solid lines) and with an added mass (dashed lines), measured using the proposed Raspberry Pi system (red), a Klippel Analyser System (blue), and a Keysight E4990A Impedance Analyser (green).

Table 1: TSPs of the loudspeaker W130S using the Raspberry Pi measuring device and the Klippel Analyser System.

Variants	Raspberry Pi	Klippel	Unit	Error
	Value	Value		%
Electrical Parameters				
Re	3.69	3.75	Ω	1.55
Le	0.15	0.18	H	14.77
fs	68.60	69.20	Hz	0.87
Qms	4.24	4.24		-0.02
Qes	0.91	0.89		-2.02
Qts	0.75	0.74		-1.63
Mechanical Parameters				
Mms	7.40	7.03	g	-5.23
Mmd	7.00	6.25	g	-12.07
Rms	0.753	0.72	kg/s	-4.29
Cms (Cas)	0.727	0.753	mm/N	3.45
Vas	6.469	6.57	L	1.56
Bl	3.598	3.59	N/A	0.31

All three measurement devices deliver comparable impedance curves, with only a slight deviation in the results obtained with the IA. There, the resonance has a higher magnitude, i.e., a higher Q. Other than that, the results are in close agreement. Regarding the added mass method, the loudspeaker behaves as expected.

Comparison of TSP Measurements

By using the laser measurement technology developed by Klippel, the TSPs can be directly measured in one go, without the need to use the added mass method [5].

The TSP measurement results for the W130S obtained with the KAS and the Raspberry Pi device are displayed in Table 1, whilst Table 2 shows the results for the FRS 5 X.

Table 2: TSPs of the loudspeaker FRS 5 X using the Raspberry Pi measuring device and the Klippel Analyser

Variants	Raspberry Pi	Klippel	Unit	Error
	Value	Value		%
Electrical parameters				
Re	7.25	7.72	Ω	6.10
Le	0.11	0.10	H	-1.94
fs	216.91	211.00	Hz	-2.80
Qms	5.97	5.41		-10.49
Qes	1.14	1.11		-2.98
Qts	0.96	0.92		-4.13
Mechanical parameters				
Mms	0.51	0.54	g	6.30
Mmd	0.48	0.49	g	2.04
Rms	0.12	0.13	kg/s	13.53
Cms (Cas)	1.06	1.06	mm/N	-0.19
Vas	0.23	0.24	L	0.94
Bl	2.09	2.23	N/A	6.31

Once more, the results of the two measurement systems are in good agreement. The relative errors in the measurement results of the Raspberry Pi device in reference to the Klippel system are below 10% for the most part, with only four values exhibiting slightly larger errors.

Discussion and Conclusion

The evaluation of the Raspberry Pi measurement system led to several insights. The most important one being, that to draw a valid comparison between its measurement results and those obtained with other systems, the measurement conditions should be kept identical.

In practice, this implies that the same measurement voltage must be applied (e.g., 0.1 V at the loudspeaker terminals), the same measurement leads, or cables should be used, the loudspeaker's spatial orientation should not be altered, and ideally, even the same audio amplifier is used. Excessive input voltages may occur at lower levels than anticipated, resulting in unexpected, sometimes baffling nonlinear behaviour of the chassis being characterised.

Based on the comparison between the three measurement systems, the DIY Raspberry Pi device seems to be able to deliver adequate impedance measurement results, which are the basis for the TSP estimation. In the TSP estimates, there is a mean absolute error percentage between Raspberry Pi and KAS of 4.4%, while the largest error percentage is 14.8%. In addition to minor measurement errors, these differences may be explained by different small signal loudspeaker models used in the Raspberry Pi software and the KAS.

This article shows that overall, a DIY Raspberry Pi measuring device can estimate TSPs within a sufficiently low margin of error compared to professional reference systems, at least when considering the application area of homemade loudspeaker design projects. The system should work with a wide range of electrodynamic loudspeakers.

Summary

This article serves as a rough tutorial on the implementation of a DIY loudspeaker measurement device. The proposed system uses a Raspberry Pi with some audio-specific peripherals, e.g., the HiFi Berry, to measure the loudspeaker electrical impedance and to estimate its electromechanical parameters, including the Thiele-Small parameters. The measurement results achieved with the developed system were compared to results obtained with two different professional measurement systems to evaluate its reliability and accuracy. It was shown that it can estimate TSPs within a sufficiently low margin of error.

Future Work

Since the measurement system was only implemented as a rough laboratory setup over the course of a student project, an obvious next step will be to integrate all hardware components into one clean assembly. Furthermore, a smartphone app for controlling the measurement system could be developed to improve the user experience. Finally, the parameter estimation could be extended to nonlinear loudspeaker parameters.

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