A craft-project loudspeaker to serve as an educational demonstration

Scott P. Porter,[a)] Daniel J. Domme, and Alexander W. Sell
The Graduate Program in Acoustics, The Pennsylvania State University, 201 Applied Science Building, University Park, Pennsylvania 16802

Jeffrey S. Whalen
Department of Mechanical and Nuclear Engineering, The Pennsylvania State University, Reber Building, University Park, Pennsylvania 16802

(Received 30 November 2010; revised 11 April 2011; accepted 10 May 2011)

Moving-coil loudspeakers typify the interdisciplinary nature of acoustics: in order to reproduce sound, these devices employ principles of electricity, magnetism, mechanics, and acoustics. The widespread use of loudspeakers has made them a familiar and valuable opportunity to introduce students to acoustics. A low-cost loudspeaker project/demonstration is presented here that is built from scratch using common household items and craft supplies. A variety of educational topics may be illustrated with this device, making it appropriate for a wide range of academic levels.
 [DOI: 10.1121/1.3676734]

PACS number(s): 43.10.Sv, 43.38.Ja [TDR] Pages: 2431–2434

I. INTRODUCTION

Electrodynamic moving-coil loudspeakers represent a unique opportunity to engage students in the exploration of acoustics. With 85 years of refinement,[1] the loudspeaker represents a technically rich problem that is well-understood by the scientific community. However, many students do not know how a loudspeaker works, even though most have an appreciation for its role in entertainment systems. In general, the construction of commercial loudspeakers makes it difficult to observe the inner-workings. To overcome this, the present paper details a craft-project loudspeaker that is intended to serve as an educational demonstration and that is assembled *by the students themselves*. Such an exercise presents opportunities for hands-on learning at a number of different academic levels.

The motivation for this project is to create an educational demonstration that may be distributed in kit form and that is appropriate for the society's *Project Listen Up* initiative. As such, the authors set out to design a loudspeaker with a target cost of $5 for purchased materials. Also, because students are supposed to assemble this demonstration themselves, the construction should not be difficult and should avoid the use of specialized tools. Finally, the assembled device should be capable of reasonable audio reproduction. The metrics for success are therefore low cost, ease of construction, and audio quality.

Previous efforts have demonstrated simplified moving-coil mechanisms for educational purposes.[2–5] The design presented here is distinguished by its integrated enclosure, deliberate magnetic circuit, and separable assembly (which allows for easy inspection of the internal components). These features help relate the structure of the craft-project loudspeaker to its commercially available counterparts.

Although there is a vast body of literature on moving-coil loudspeakers, a few key developments are reviewed here. Werner von Siemens invented the moving-coil motor in 1877 but he did not anticipate that the device would be used for sound reproduction; he envisioned the moving-coil motor being used to ring a bell in telegraphy.[6] The modern hornless moving-coil loudspeaker design came from the seminal work of Rice and Kellogg in 1925.[1] In 1954, Edgar Villchur pioneered the use of smaller loudspeaker enclosures to provide an acoustic suspension.[7] Thiele and Small published a series of papers in the 1960 s and 1970 s describing how to synthesize the response of a loudspeaker-enclosure system.[8–15]

Over the decades, countless improvements have been studied and suggested for the moving-coil loudspeaker. In spite of this, the basic form remains essentially unchanged. Therefore, the components of the moving-coil loudspeaker will not be reviewed in this paper although the standard component terminology is used. Loudspeaker schematics that label the various components are widely available from a variety of sources; one such resource is Fig. 2.2 in Ref. 16.

II. THEORY

While loudspeakers are hardly new technology, it is valuable to review some of the fundamental concepts that they demonstrate. The reason this project is well-suited for educational purposes is that it displays a wide range of physical principles, from basic concepts like the Lorentz force, simple harmonic motion, and resonance, to more advanced topics such as magnetic circuits and radiation resistance.

The physical phenomenon that moving-coil loudspeakers are based on is the Lorentz force, which describes the scenario of a current-carrying wire in the presence of a magnetic field:

$$\mathbf{F} = (\mathbf{i} \times \mathbf{B})\ell. \quad (1)$$

[a)]Author to whom correspondence should be addressed. Electronic mail: s.p.porter@me.com

Here **i** is a current vector oriented along the wire axis, **B** is the magnetic induction, ℓ is the length of wire in the magnetic field, and **F** is the resulting force. For many students, this equation describes a remarkable concept: electricity and magnetism being combined to create a mechanical force.

Next, the mechanics of the loudspeaker are well-modeled as a simple harmonic oscillator that is driven by the Lorentz force of Eq. (1). The linear differential equation of motion is

$$m\frac{dv(t)}{dt} + R_m v(t) + k_m \int v(t)dt = F(t), \tag{2}$$

where $v(t)$ is the velocity of the voicecoil, m is the moving mass, R_m is the mechanical resistance, and k_m is the effective mechanical stiffness. For the lightly damped case, mechanical resonance—a key concept of dynamic systems—occurs at the angular frequency $\omega_0 = \sqrt{k_m/m}$.

One reason for the longstanding popularity of the moving-coil loudspeaker is that it exhibits a region of flat frequency response above resonance. The radiated acoustic power, $\Pi_{\rm rad}$, is defined as

$$\Pi_{\rm rad} = \frac{1}{2}R_{\rm rad}(\omega)v^2, \tag{3}$$

where v^2 is the diaphragm velocity squared and $R_{\rm rad}$ is the radiation resistance. In the above-resonance region, the frequency dependence of these two terms cancel out, making the radiated acoustic power frequency-independent. This is illustrated using the results of a simple lumped-element model[17] of a commercial loudspeaker in Fig. 1. The radiated power is relatively flat above resonance before rolling off around 1.2 kHz. The high-frequency limit of this region is caused by the radiation resistance deviating from quadratic behavior.

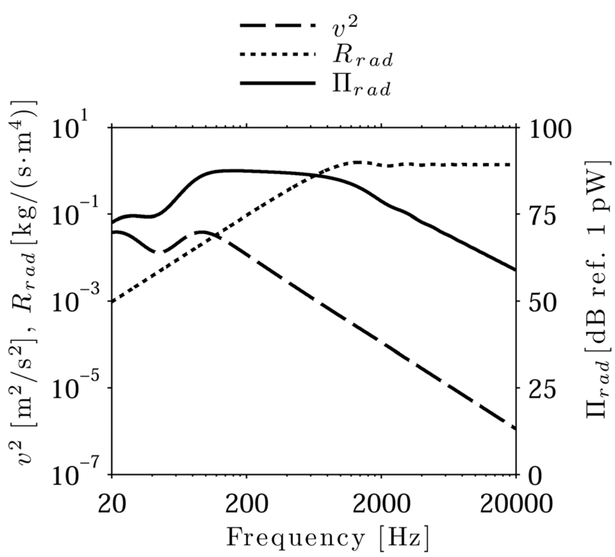

FIG. 1. A plot of diaphragm velocity squared and the radiation resistance of a circular baffled piston, showing how multiplying these quantities results in a region of relatively flat power response.

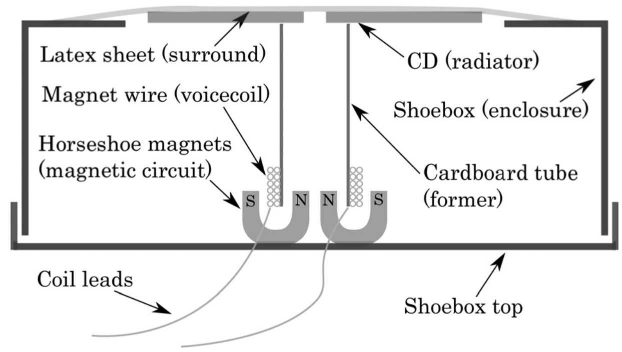

FIG. 2. Simplified shoebox speaker design.

III. CONSTRUCTION

In this section two designs are presented: a simplified demonstration design and a more sophisticated revision. To achieve low-cost and easy-to-build devices, household items were incorporated into the designs and craft supplies were used to assemble these demonstrations.

A. Simplified design

The intent of the simplified speaker design was to prove that a working moving-coil loudspeaker could be achieved using primarily household supplies. To do this, the authors employed a shoebox to serve as the loudspeaker enclosure, a compact disc (CD) for the acoustic radiator, and a cardboard tube as the voicecoil former. These items were supplemented with a handful of purchased components: a pair of Alnico horseshoe magnets for the magnetic circuit, magnet wire for the voicecoil, and a latex sheet for the surround. A schematic of the speaker is shown in Fig. 2 and a photograph of the completed project is shown in Fig. 3. Notice from Fig. 3 that the entire assembly may be opened up to reveal the motor mechanism. This ability may also be used to demonstrate to students that if a signal-carrying voicecoil is removed from the gap of the magnetic circuit during operation, sound reproduction will cease.

FIG. 3. Construction of the simplified shoebox speaker, showing how the assembly may be opened up to inspect the internal components.

TABLE I. Estimated cost for the authors' simplified shoebox speaker design.

Item	Cost
Horseshoe magnets (2×)	\$4.50
Latex sheet (1.5 ft^2)	\$0.98
Magnet wire ($n = 100$)	\$0.56
Total	**\$6.04**[a]

[a]Total cost varies from previously stated values (Ref. 18) because the better price estimates are available here.

Construction of this speaker was accomplished using common craft tools: scissors, a hot-glue gun, and tape. The full details of the construction and assembly are recorded elsewhere.[18]

As a teaching demonstration, the performance of this device was adequate. The shoebox speaker reproduced audio content surprisingly well considering the crudeness of its construction. This claim is supported by the fact that it has been successfully used as an educational demonstration on several occasions. The main drawback of this simplified design was that the poor magnetic circuit necessitated the use of a 90 watts-per-channel (WPC) amplifier to produce acceptable output levels.

Estimated costs for the original shoebox speaker design are given in Table I. This breakdown assumes that the student will provide their own shoebox, cardboard tube, and CD.

B. Revised design

Having demonstrated the feasibility of a loudspeaker made from household supplies, the authors turned their attention to revising the design and improving its performance. Two important changes were made.

The magnetic circuit was the focus of the first change. Although Alnico magnets have a greater magnetic permeability than most high-strength magnets, their energy product is much smaller. Therefore, neodymium (NdFeB) magnets were used instead with small steel C-clamps forming high-permeability flux paths. This improves the magnetic circuit in three ways: the magnets are stronger, the flux paths have a higher magnetic permeability, and the air gap can be minimized by adjusting the clamp. With a Hall probe sensor, the authors quantified the magnetic induction in this scheme to be approximately six times greater than for the Alnico horseshoe magnet arrangement. This increase in **B** allows good output levels with a portable and inexpensive 15 WPC switching amplifier.

The second change in the revised design concerns the acoustic radiator. Instead of a CD, a styrofoam bowl is used in this version. The bowl is lighter and more closely resembles a paper cone. Most importantly, the bowl is inexpensive. A schematic diagram of this more sophisticated design is shown in Fig. 4.

It is important to note that these changes did not add cost to the project, as seen in the cost breakdown presented in Table II.

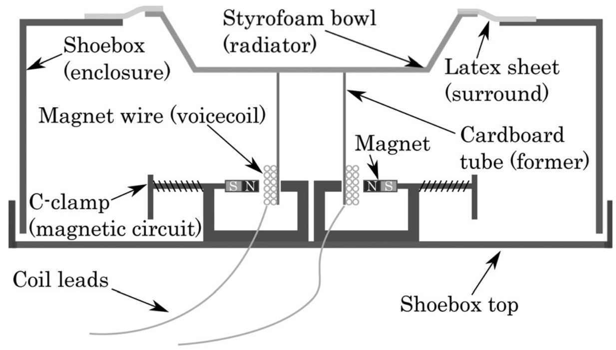

FIG. 4. Revised shoebox speaker design.

IV. OPTIMIZATION

One useful feature of the shoebox speaker is the ease with which it may be modified. Thanks to the relative crudeness of its construction, adjustments to individual components in the system can be made without requiring a complete rebuild, which presents an opportunity for learning through experimentation and discovery. Equation (1) provides guidance for improving the moving-coil motor: to get more force for a given current, the design must be changed to either increase **B** or ℓ. Increases in the **B** field can be accomplished by using better permanent magnet material, by adding more magnets (as long as the magnetic circuit does not saturate), or by narrowing the air gap through which the coils pass (the gap must not be made so small that it causes the voicecoil/former assembly to rub or buzz against the magnets). In this design, ℓ may be increased in two ways: by winding more turns on the voicecoil or by adding more C-clamp structures to increase the length of wire immersed in the magnetic field. As students endeavor to optimize their shoebox speaker projects, a useful metric for quantifying the performance is the electroacoustic sensitivity, which is discussed in the next section.

V. PERFORMANCE

Although the shoebox loudspeaker is no competition for even entry-level commercial loudspeakers, it performs well enough to clearly reproduce music and voice. The relatively low dc resistance of the speaker—1.5 and 1.8 Ω for the first and second iteration, respectively—presents a matching issue with most amplifiers. However, for the revised design the authors were able to achieve more than 1 watt input power with a 15 WPC amplifier.

In keeping with the low-budget theme, performance may be examined using a simple sound level meter (SLM), multimeter, and frequency generator (a computer sound card

TABLE II. Estimated cost for the authors' refined shoebox speaker design.

Item	Cost
C-clamps (2×)	\$2.62
Latex sheet (1.5 ft^2)	\$0.98
Magnet wire ($n = 100$)	\$0.56
NdFeB magnets	\$1.80
Styrofoam bowl	\$0.06
Total	**\$6.02**

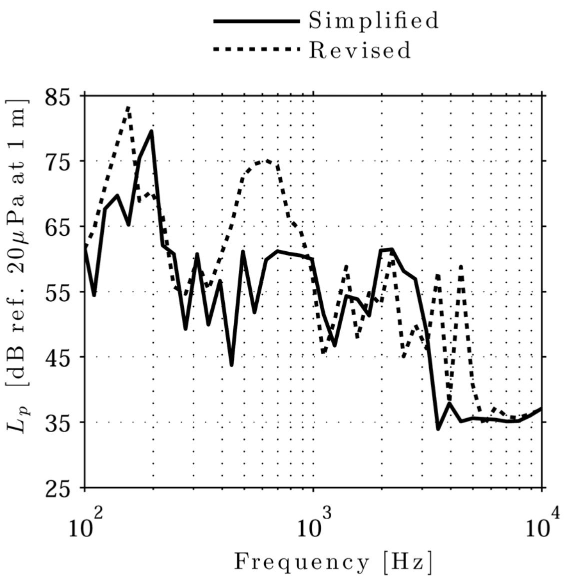

FIG. 5. SLM estimate of frequency response for both shoebox speaker designs.

will work). Measures for efficiency and ability to faithfully reproduce sound can be taken using this equipment.

A common measure of efficiency in the loudspeaker industry is sensitivity, the ratio of the sound pressure level at 1 m referenced to 20 μPa, L_p, to the input electrical power supplied to the loudspeaker, P_e. The standard unit of sensitivity is dB/watt and the measurement can be performed using white noise as input. To make this measurement using the equipment listed above, one must first determine the resistance of the loudspeaker. A multimeter's dc resistance function is sufficient for this as the frequency dependence of the voice-coil resistance may be neglected over the useful range of the shoebox loudspeaker. Following the resistance measurement, the speaker is connected to an amplifier driven by white noise. By measuring the voltage across the outputs of the amplifier, one can determine the input power for the speaker using

$$P_e = \frac{V^2}{R_e}, \tag{4}$$

where V is the rms voltage across the amplifier outputs, and R_e is the dc resistance of the loudspeaker. Once the amplifier gain is properly adjusted to produce 1 watt through the speaker, an SPL measurement may be taken by placing the SLM 1 meter away from the speaker.

Using this method, the authors achieved a sensitivity of 46 dB ref. 20 μPa at 1 m for the original design and 53 dB ref. 20 μPa at 1 m for the revised design. Considering most commercial loudspeakers fall between 85 and 95 dB sensitivity, the shoebox speaker is no match, but the performance using the 15 WPC amplifier is comparable to speakers for the average notebook computer.

It is also possible to use the above setup to estimate frequency response by driving the system with a single tone, sweeping it through the audible frequency range of the speaker, and measuring the acoustic output with an SLM. Frequency response results for each of the shoebox loudspeakers discussed in this paper are shown in Fig. 5. Both curves were measured with linear weighting as the input power was maintained at one watt. Despite a jagged response due to resonances, an overall flat trend can be seen before the response rolls off between 3 and 4 kHz. This kind of uneven frequency response is not ideal, but acceptable as an educational tool. In Fig. 5, it is clearly seen that the second iteration of the speaker has an improved operating range and output level, compared to the first. Ambient noise during this measurement was 35 dB ref. 20 μPa at 1 m.

VI. CONCLUSIONS

A craft-project loudspeaker for scientific demonstration has been presented. From a kit perspective, the design is successful because it is easy to build, inexpensive, and capable of adequate audio reproduction. As an educational demonstration, the shoebox speaker exhibits the moving-coil mechanism and is an engaging demonstration of electroacoustics. Although the cost to prototype these designs slightly exceeded the $5 target in both cases, the authors anticipate that bulk purchase of the components will significantly lower the effective cost per kit. By having students construct a device from scratch that is capable of reproducing recorded audio, the authors believe this demonstration can be used to inspire students to investigate the science of sound.

ACKNOWLEDGMENTS

The authors wish to acknowledge several insightful conversations with Dr. Steven Garrett.

[1]C. W. Rice and E. W. Kellogg, "Notes on the development of a new type of hornless loudspeaker," Trans. Am. Inst. Electrical Eng. **44**, 982–991 (1925) [reprinted in J. Audio Eng. Soc. **30**(7/8), 512–521 (1982)].

[2]A. Keeney and B. Hershey, "Making your own dynamic loudspeaker," Phys. Teach. **35**(5), 297–299 (1997).

[3]M. Johnson and V. Stonick, "Sound science—A simple and robust hands-on loudspeaker activity," Phys. Teach. **37**, 350–351 (1999).

[4]R. Herman, "As simple as possible," Phys. Teach. **40**(21), 182–183 (2002).

[5]C. Galeriu, "Magnetostatics analysis, design, and construction of a loudspeaker," Phys. Teach. **48**(8), 537–540 (2010).

[6]F. V. Hunt, *Electroacoustics: The Analysis of Transduction and Its Historical Background* (AIP, New York, 1982), pp. 57–59.

[7]E. M. Villchur, "Revolutionary loudspeaker and enclosure," Audio **38**(10), 25–28 (1954).

[8]A. N. Thiele, "Loudspeakers in vented boxes: Part I," J. Audio Eng. Soc. **19**(5), 382–392 (1971).

[9]A. N. Thiele, "Loudspeakers in vented boxes: Part II," J. Audio Eng. Soc. **19**(6), 471–483 (1971).

[10]R. H. Small, "Direct-Radiator loudspeaker system analysis," J. Audio Eng. Soc. **20**(5), 383–395 (1972).

[11]R. H. Small, "Closed loudspeaker systems, Part I: Analysis," J. Audio Eng. Soc. **20**(10), 798–808 (1972).

[12]R. H. Small, "Closed loudspeaker systems, Part II: Synthesis," J. Audio Eng. Soc. **21**(1), 11–18 (1973).

[13]R. H. Small, "Vented loudspeaker systems, Part I: Small signal analysis," J. Audio Eng. Soc. **21**(5), 363–372 (1973).

[14]R. H. Small, "Vented loudspeaker systems, Part II: Large signal analysis," J. Audio Eng. Soc. **21**(6), 438–444 (1973).

[15]R. H. Small, "Vented loudspeaker systems, Part III: Synthesis," J. Audio Eng. Soc. **21**(7), 549–554 (1973).

[16]J. Borwick, *Loudspeaker and Headphone Handbook*, 3rd. ed. (Focal, Boston, 2001).

[17]L. L. Beranek, *Acoustics* (Acoustical Society of America, Woodbury, NY, 1954).

[18]S. P. Porter, D. J. Domme, and J. S. Whalen, "The singing shoebox: A $5 loudspeaker project," *Proceedings of Meetings on Acoustics Online*, 2010, Vol. 9, p. 1.