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Further experiments with a loudspeaker

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Abstract

A common moving-coil (dynamic) loudspeaker is a device very suitable for teaching the general features of oscillating systems. As an addition to a previous paper (Kraftmakher 2009), this paper includes the following topics: (i) a new design of the optical sensor for measuring the cone oscillations; (ii) positive feedback and self-excited oscillations; (iii) the determination of the loudspeaker parameters without direct measurements of the cone oscillations; and (iv) the loudspeaker in a vacuum chamber. The measurements are performed without a lock-in amplifier. The tight connection between the mechanical and electrical parameters of a loudspeaker is confirmed. The experiments are well related to the university courses of electricity and magnetism and can be used in undergraduate laboratories.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

A common moving-coil (dynamic) loudspeaker is a device very suitable for teaching the general features of oscillating systems (Rossing 1980, Tan 1982, Diamond *et al* 1990, Keeney and Hershey 1997, Freschi *et al* 2003). In this paper, some experiments with a moving-coil loudspeaker are presented, in addition to those described earlier (Kraftmakher 2009). The new topics presented are the following: (i) a new design of the optical sensor for measuring the cone oscillations; (ii) positive feedback and self-excited oscillations; (iii) the determination of the loudspeaker parameters without direct measurements of the cone oscillations; and (iv) the loudspeaker in a vacuum chamber. The new optical sensor is simpler and more reliable than that used earlier, and the measurements are performed without using a lock-in amplifier. A data-acquisition system serves for processing the data and displaying the results.

1.1. Theoretical background

Oscillations of the loudspeaker cone are described by well-known equations for a harmonic oscillator (e.g. Hecht 1994, Kibble and Berkshire 1996, Thornton and Marion 2004). At sufficiently low frequencies, the cone moves as a whole. Free oscillations of an oscillating system occur every time when the system is displaced from its equilibrium position and then released. If the frictional force is proportional to the oscillation velocity, the oscillations decay exponentially. Free oscillations of the loudspeaker cone follow the common equation

$$mx'' + bx' + \kappa x = 0, \quad (1a)$$

or

$$x'' + 2\gamma x' + \omega_0^2 x = 0, \quad (1b)$$

where m and x are the mass (including the so-called air loading mass) and displacement of the cone, b is the dissipation constant, k is the restoring constant, $\omega_0 = (k/m)^{1/2}$ is the natural angular frequency and $\gamma = b/2m$ is the decay constant. The solution of this equation is

$$x = A \exp(-\gamma t) \cos(\Omega t + \varphi), \quad (1c)$$

where $\Omega = (\omega_0^2 - \gamma^2)^{1/2}$, and A and φ depend on the initial conditions.

Forced oscillations of the cone occur due to the driving force Bli , where B is the magnetic field that is radial and perpendicular to all parts of the wire in the voice coil, l is the total length of this wire and i is the driving current in the voice coil. The real and imaginary parts of the displacement are

$$\text{Re } x = Bli(\omega_0^2 - \omega^2) / [m(\omega_0^2 - \omega^2)^2 + 4m\gamma^2\omega^2], \quad (2a)$$

$$\text{Im } x = -2Bli\omega\gamma / [m(\omega_0^2 - \omega^2)^2 + 4m\gamma^2\omega^2]. \quad (2b)$$

The modulus of the displacement is

$$x_0 = Bli_0 / [m^2(\omega_0^2 - \omega^2)^2 + 4m^2\gamma^2\omega^2]^{1/2}, \quad (3)$$

where x_0 is the amplitude of the displacement of the cone, and i_0 and ω are the amplitude and the frequency of the driving current (e.g. Fishman 1987, Freschi *et al* 2003, Kraftmakher 2009).

The total impedance of the voice coil includes its usual electrical impedance and the so-called motional impedance, which reflects the EMF generated in the oscillating voice coil. According to Faraday's law of induction, this EMF is $e = Blx'$, where x' is the velocity of the cone; the phases of e and x' thus coincide. The real and imaginary parts of the motional impedance Z_{mot} are

$$\text{Re } Z_{\text{mot}} = 2B^2l^2\omega^2\gamma / [m(\omega_0^2 - \omega^2)^2 + 4m\gamma^2\omega^2], \quad (4a)$$

$$\text{Im } Z_{\text{mot}} = B^2l^2\omega(\omega_0^2 - \omega^2) / [m(\omega_0^2 - \omega^2)^2 + 4m\gamma^2\omega^2]. \quad (4b)$$

With a dual-channel lock-in amplifier, it is easy to display continually both parts of the electrical impedance of the voice coil as functions of frequency. Without such a device, we can display continually the modulus of the total impedance, $|Z_{\text{total}}|$, and determine its real and imaginary parts at discrete frequencies (see below). In our case, only the resistance R of the voice coil is significant, so that

$$|Z_{\text{total}}| = [(R + \text{Re } Z_{\text{mot}})^2 + \text{Im } Z_{\text{mot}}^2]^{1/2}. \quad (5)$$

Our foremost aim is to demonstrate that the mechanical and electrical parameters of a loudspeaker are tightly connected, and the mechanical parameters are available through the measurements of the frequency dependence of $|Z_{\text{total}}|$.

2. Experimental details

2.1. The loudspeaker

The basic parameters of a loudspeaker are the mass of the cone m , the natural angular frequency ω_0 , the decay constant γ and the quantity Bl . They can be found from different experiments, but the most reliable values are those obtained with a simplest and direct measurement. Earlier, the parameters of the loudspeaker were found to be $m = 1.15$ g, $\omega_0 = 1560$ s⁻¹, $\gamma = 70$ s⁻¹ and $Bl = 1.1$ T m (Kraftmakher 2009). To determine m , ω_0 and γ , there is no need to know the absolute displacements of the cone. Moreover, it will be shown below how to determine all the parameters, including Bl , from the frequency dependence of the electrical impedance of the voice coil, without direct observations of the cone oscillations.

We use a free mounted small loudspeaker, 9 cm in diameter (8 Ω , 1 W). A light rectangular pointer made out of a metal foil, 20 mm in height and 5 mm in width, is glued to the cone at its centre and aligned to the axis of the cone. In all the experiments, the axis is oriented vertically. The loudspeaker is attached to a laboratory jack and can be gradually moved up and down. The ScienceWorkshop data-acquisition system with the DataStudio software from PASCO Scientific is used in the experiments.

2.2. The sensor

The sensor of the displacements of the cone consists of a low-power light bulb (12 V, 5 W) and a plastic light guide, 3 mm in diameter (a thicker one would be better). Both are mounted on a frame in such a way that the light guide acquires light from the light bulb and transmits it to a photodiode (figure 1). The loudspeaker is positioned to put the pointer between the light bulb and light guide. The pointer partly intercepts the light beam from the light bulb, so that the photodiode becomes sensitive to the vertical displacements of the cone. To achieve a linear response to the displacement, a rectangular window is set at the entrance to the light guide. When the cone oscillates, the ac output of the photodiode correctly represents the cone oscillations.

The sensor can be arranged without a light guide, but the latter is useful for conveniently positioning the photodiode. The photodiode, its 20 k Ω load resistor, and a 9 V battery are placed in a metal box with an opening for the light guide. The sensitivity can be maintained by adjusting the current through the light bulb. The sensor is more simple and reliable than that employed earlier by the author. It is good alternative to complicated interferometric techniques that were used in experiments with a loudspeaker (Diamond *et al* 1990, Freschi *et al* 2003).

The sensitivity of the sensor, which is independent of the oscillation frequency, was determined under static conditions with a dial indicator of 0.01 mm resolution. The dc voltage from the photodiode is measured by the PASCO Voltage sensor and seen with the Digits display. In the measurement range, of about 1 mm, the sensitivity is nearly 1 V mm⁻¹; that is, 1 mV corresponds to a displacement of 1 μ m. One can check the sensitivity by measuring the dc output voltage of the photodiode when the pointer does not intercept the light from the light bulb; in our case, this voltage is 2 V. Under measurements of the cone oscillations, the loudspeaker is positioned to reduce this voltage to 1 V.

2.3. The set-ups

The load resistor of the photodiode can be dc or ac coupled to the data-acquisition system with a Voltage sensor. The dc coupling is used for calibrating and positioning the sensor, and the ac coupling for measuring the cone oscillations. Another Voltage sensor acquires the voltage

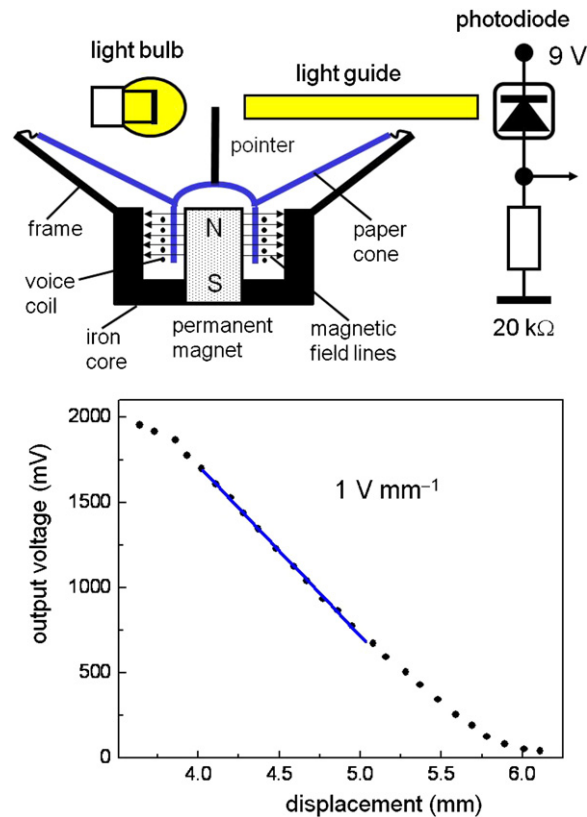


Figure 1. Design of the optical sensor and calibration data.

across the voice coil. A common dual-trace oscilloscope serves for observing the voltages from the photodiode and the voice coil. Diagrams of set-ups for different experiments are shown in a general scheme (figure 2). The experiments comprise free oscillations with positive feedback, self-excited oscillations, determination of the motional impedance of the voice coil and properties of the loudspeaker placed in a vacuum chamber.

3. Loudspeaker with feedback

3.1. Free oscillations of the cone

Free oscillations of the loudspeaker cone are triggered by short electrical pulses obtained by differentiating a square wave voltage (5 Hz, 5 V) from the Signal generator incorporated into the ScienceWorkshop 750 Interface (figure 2(a)). The generator output is connected to the voice coil through a $10\ \mu\text{F}$ capacitor. The capacitor and the voice coil form a differentiating RC circuit. The free oscillations of the cone are measured with the optical sensor. The Voltage sensor is connected to the load resistor of the photodiode through a $2\ \mu\text{F}$ capacitor. The second Voltage sensor measures the EMF generated in the oscillating voice coil.

The free oscillations can be modified by positive or negative feedback. For this aim, the EMF generated in the voice coil is amplified and then returned to the voice coil. An amplifier, a PASCO Digital function generator-amplifier set for its maximum gain, which equals 2, provides the positive feedback. The amplifier input is connected to the voice coil,

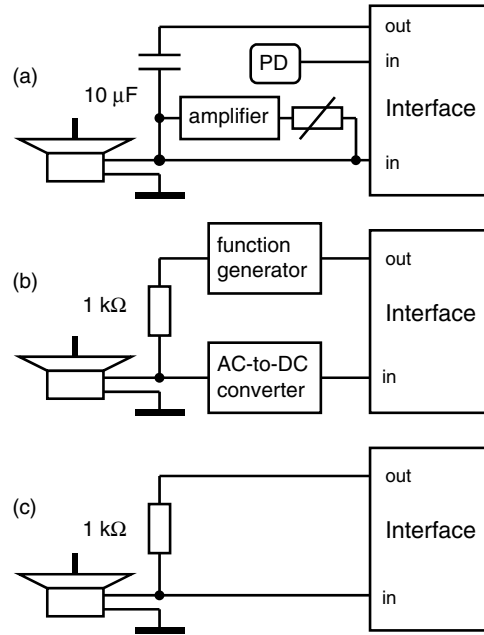


Figure 2. Diagrams of set-ups for different experiments: (a) positive feedback, free and self-excited oscillations; (b) modulus of the total impedance; and (c) real and imaginary parts of the total impedance. PD—photodiode.

while the output to the coil through a $100\ \Omega$ variable resistor. By varying the resistor, it is easy to reduce the decay constant of the free oscillations and attain self-excited oscillations. The latter are observed with no triggering pulses. A velocity versus displacement graph represents the so-called phase portrait of the oscillation (figure 3).

The Fit/user-defined fit option of DataStudio fits the experimental data for the EMF generated in the voice coil. The fit equation is

$$x = A * \exp(-B * x) * \cos(C * x + D) + E, \quad (6)$$

where $B = \gamma$, $C = \Omega \cong \omega_0$ is the angular frequency of the free oscillations, and A and D are the initial amplitude and phase of the oscillations. The offset E may appear due to insufficient precision of the zero adjustment of the Voltage sensor; usually, the offset does not exceed 1 mV. To perform the fit, initial guess values of some parameters should be introduced. It is sufficient to provide such values of A , B and C , which are seen from the measurement data.

The properties of a loudspeaker also depend on its environment. For instance, the restoring constant k and thus the natural frequency ω_0 of the cone are sensitive to the position of neighbouring objects. The phenomenon is easy to see from free oscillations of the cone for different positions of the loudspeaker over a table.

3.2. Self-excited oscillations

With positive feedback, the cone oscillations may become self-excited, like those of a pendulum clock or of some chaotic toys (Pippard 1978, Moon 1987). With feedback, the motion equation of the cone becomes

$$x'' + (2\gamma - \beta)x' + \omega_0^2 x = 0, \quad (7)$$

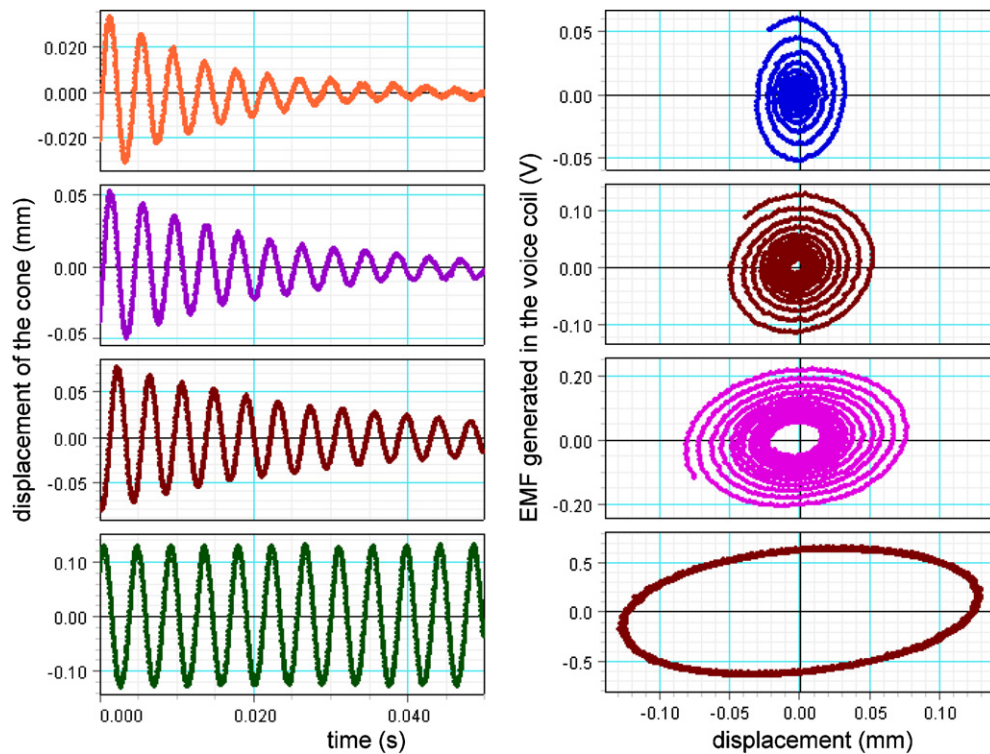


Figure 3. Free oscillations of the cone modified by positive feedback: time series and phase portraits. The last example is self-excited oscillations.

where β depends on the feedback factor; for positive feedback, $\beta > 0$. Self-excited oscillations arise when an external force applied to the voice coil outweighs the frictional force, that is, $2\gamma - \beta = 0$. For $2\gamma - \beta < 0$, the oscillation amplitude should unlimitedly increase. This is impossible because the coefficient β unavoidably decreases with increasing oscillation amplitude. The frequency of the self-excited oscillations is close to the natural frequency of the loudspeaker, and their steady amplitude depends on the feedback factor. An inverting amplifier is needed to obtain negative feedback.

4. The impedance of the loudspeaker

4.1. The measurements

Near the resonant frequency, the motional impedance of the loudspeaker becomes comparable to the usual electrical impedance of the voice coil. Therefore, the loudspeaker parameters are available from measurements of the total impedance. The voice coil is connected to the output of a GFG-8019G function generator through a $1 \text{ k}\Omega$ resistor, so that the current in the voice coil is almost independent of frequency (figure 2(b)). Clearly, this regime differs significantly from the usual regime of effectively producing sound waves in a wide frequency range. To scan the frequency, a ramp down wave voltage V (0.005 Hz, 0.5 V) from the Signal generator is applied to the VCF (voltage controlling frequency) input of the function generator. The frequency of the function generator linearly depends on the controlling voltage,

and this dependence can be determined in static measurements. When the generator is set at the 1 kHz range, the frequency change follows a relation $\Delta f \text{ (Hz)} = -193 \cdot V \text{ (V)}$ (positive input voltages decrease the frequency). The initial frequency of the function generator is set at 250 Hz. During a run lasting 200 s, the frequency f gradually increases from about 150 to 350 Hz. DataStudio calculates the angular frequency $\omega = 2\pi f$. The ac voltage across the voice coil proceeds to an ac-to-dc converter. We use a Keithley 177 model multimeter or an HP 400E model voltmeter. Their dc output voltages indicate the RMS values of ac input voltages. During a run, DataStudio displays the RMS value of the voltage across the voice coil versus the angular frequency of the driving force.

Due to the 1 k Ω resistor, the current through the voice coil is almost independent of frequency. However, the cone oscillations and thus their power drastically increase close to the resonant frequency. An evident question arises about the source of the additional power needed for these oscillations. The answer is very simple: the impedance of the voice coil (close to the resonance, it is mainly real) also increases! When a definite ac voltage is applied to the voice coil, the back EMF generated in it reduces the current. This means that the effective impedance of the coil increases. If the cone is fastened, no EMF is generated in the voice coil, and only the usual electrical impedance of the coil, that is, its resistance (the main part) and inductance, is measured.

4.2. The mass of the cone and the Bl parameter

The measurement data (figure 4) are fitted using the Fit/user-defined fit option of DataStudio. According to equation (5), the fit equation (note the redefinition of the variables) should be

$$|Z_{\text{total}}| = ((D + 2 \cdot A \cdot x \wedge 2 \cdot C / ((B \wedge 2 - x \wedge 2) \wedge 2 + 4 \cdot C \wedge 2 \cdot x \wedge 2)) \wedge 2 + (A \cdot x \cdot (B \wedge 2 - x \wedge 2) / ((B \wedge 2 - x \wedge 2) \wedge 2 + 4 \cdot C \wedge 2 \cdot x \wedge 2) \wedge 2)) \wedge 0.5, \quad (8)$$

where D is the resistance of the voice coil, $A = B^2 l^2 / m$, $B = \omega_0$, $x = \omega$, and $C = \gamma$. With an additional ac-to-dc converter, the moduli of the total impedance and of the cone displacement can be recorded simultaneously. For the loudspeaker used, the theoretical relation (8) fairly fits the experimental data (the fit parameters are seen in figure 4).

The mass of the oscillating system, the cone with the voice coil, can be determined by measuring the natural frequency of the system when a known mass is added to it. A 1.41 g piece of plasticine was pasted to the cone, and the natural frequency was found by observing the free oscillations and the frequency dependence of the modulus of the total impedance. From the data, the mass m of the cone, including the air loading mass, appeared to be 1.04 and 1.10 g, respectively. Now the quantity Bl can be calculated from the fit parameter A and the mass, for which the mean value, 1.07 g, was accepted. With no mass added, $A = 1180$ and $Bl = 1.12 \text{ T m}$. With the mass added, $A = 466$ and $Bl = 1.08 \text{ T m}$. These values are close to those obtained by observing free oscillations of the cone (Kraftmakher 2009).

4.3. Real and imaginary parts of the total impedance

The phase angle of the total impedance can be determined at discrete frequencies. For this aim, the output of the Signal generator is connected to the voice coil through a 1 k Ω resistor (figure 2(c)). The Voltage sensor measures the voltage across the coil. Along with other options, DataStudio provides a fit for sine wave signals. The Fit/sine fit tool fits such signals with an equation $y = A \sin[2\pi(x - C)/B] + D$, where A and B are the amplitude and the period of an oscillation, C depends on the initial phase and D is an offset. The initial phase

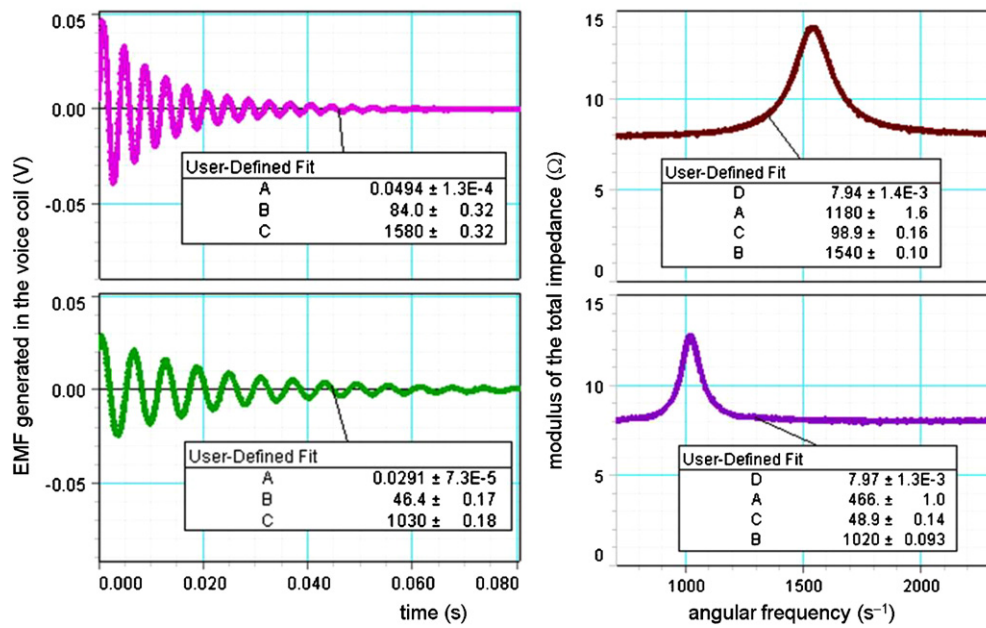


Figure 4. Determinations of the mass of the cone from changes of the natural frequency observed from the free oscillations (left) and from the modulus of the total impedance (right).

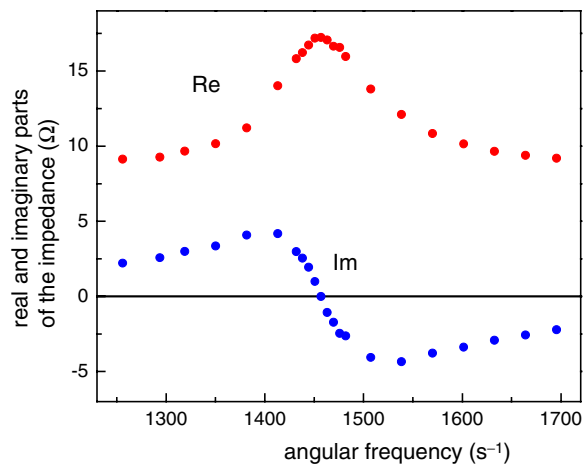


Figure 5. Real and imaginary parts of the total impedance of the voice coil versus the angular frequency. The real part includes the usual resistance of the coil.

of the oscillation is $\varphi = 2\pi C/B = \omega C$. If the current through the voice coil and the voltage across the coil are measured simultaneously, the phase shift between the two quantities is $\Delta\varphi = \omega(C_1 - C_2)$, where C_1 and C_2 are taken from the two fits. The Output current of the Signal generator represents the current through the voice coil. After the phase angle of the total impedance is determined, the real and imaginary parts of the impedance become available. The results obtained with this approach are quite satisfactory (figure 5). In this measurement, another example of the same model of the loudspeaker was employed; therefore, the change of

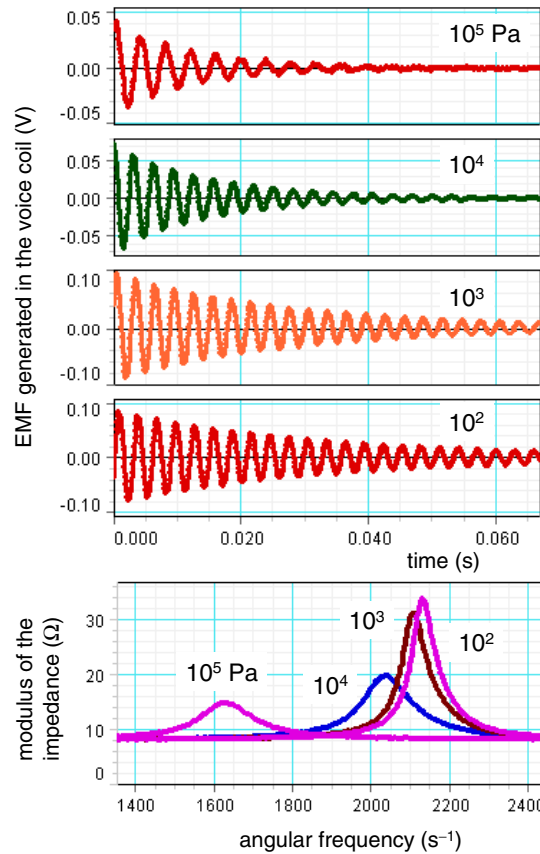


Figure 6. Free oscillations of the cone and modulus of the impedance for different air pressures, from 10^2 to 10^5 Pa. The changes of the natural frequency and decay constant are evident.

the natural frequency is quite explainable. The real and imaginary parts of the total impedance are thus obtainable without using a lock-in amplifier.

5. Loudspeaker under the bell jar

5.1. Loudspeaker at reduced air pressures

Being placed into a vacuum chamber, the loudspeaker loses its capability of producing sound waves, but remains an oscillating system. The increase of the natural frequency of the cone after removing the surrounding air clearly shows the contribution of the air loading mass, m_A (Tan 1982). This mass is added when the effective mass of the cone m is measured in air: $m = m_0 + m_A$, where m_0 is the usual mass of the cone. In vacuum, the natural frequency of the cone increases. A decrease of the pressure to 1% of the atmospheric pressure is sufficient to exclude m_A . The second result of removing the surrounding air is a decrease of the dissipation constant $b = 2m\gamma$. Really, both m and γ decrease. The energy dissipation is partly caused by the viscous force exerting on the voice coil moving in a narrow gap in the magnetic structure of the loudspeaker.

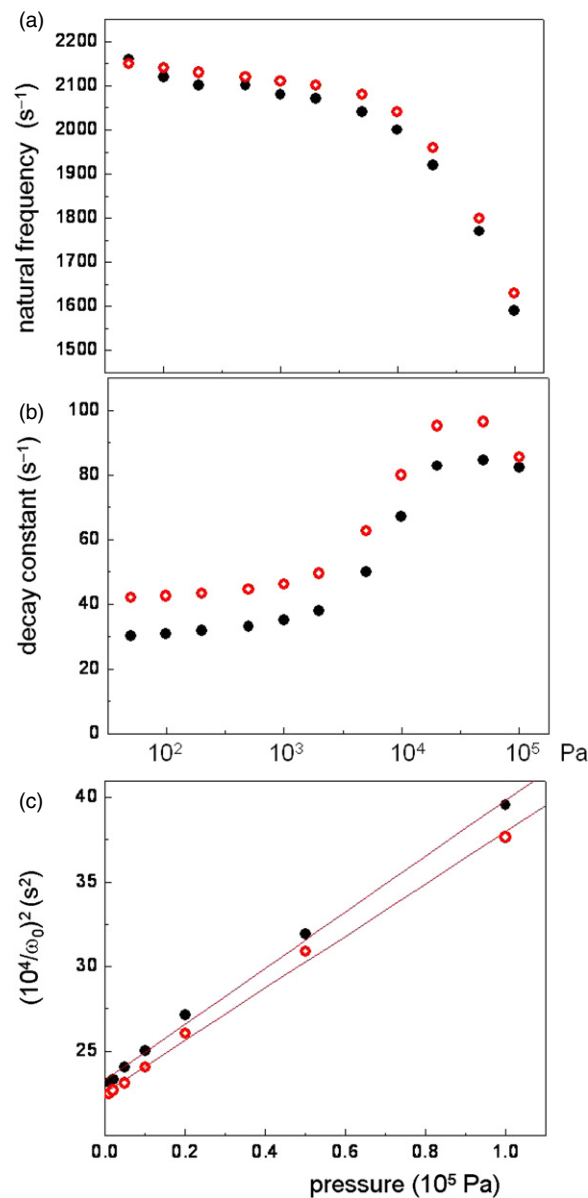


Figure 7. Properties of the loudspeaker observed (●) from free oscillations and (○) from the modulus of the total impedance: (a) natural angular frequency versus air pressure; (b) decay constant; and (c) determination of the air loading mass from changes of the natural frequency.

The loudspeaker is placed under a bell jar pumped out by a rotary pump. The vacuum chamber has insulated lead-in terminals. The pressure is measured with a Bourdon gauge (10^5 to 10^3 Pa) and a Pirani gauge (below 10^3 Pa). The Pirani gauge is a TR 211 model from Oerlikon Leybold Vacuum GmbH. This sensor measures air pressures in the range from 0.05 Pa to 10^5 Pa, but above 10^3 Pa the Bourdon gauge is more reliable. The effect of pumping is clearly seen from the free oscillations of the cone and from the frequency dependence of the modulus of the total impedance (figure 6). The data on the natural frequency obtained by

the two methods are in good agreement. Significant changes of this parameter occur between 10^5 and 10^3 Pa (figure 7(a)). For the decay constant, the data from the two methods somewhat differ, but the general behaviour is the same. Significant changes of the decay constant occur between 10^4 and 10^3 Pa (figure 7(b)).

5.2. The air loading mass

According to theory, the air loading mass should be proportional to the density of the gas, i.e. to the air pressure under the bell jar. If the restoring constant does not depend on the air pressure, the quantity ω_0^{-2} should be a linear function of the pressure. This guess is confirmed by the data on the pressure dependence of the natural frequency observed from the free oscillations of the cone and from the frequency dependence of the impedance of the voice coil (figure 7(c)). The natural frequency of the cone at normal pressure and in vacuum was accepted to be 1600 and 2100 s⁻¹, respectively. From these data and the mean value of m , 1.07 g, it follows that $m_0 \cong 0.62$ g, and $m_A \cong 0.45$ g.

6. Conclusion

Experiments with a loudspeaker may include all basic topics related to oscillations and can be used as laboratory works or lecture demonstrations. The mechanical and electrical parameters of the loudspeaker are tightly connected, so that all the properties of this oscillating system can be determined through electrical measurements. The loudspeaker parameters determined in very different experiments are in reasonable agreement. Additional topics appear when the loudspeaker is placed into a vacuum chamber. The experiments seem to be very attractive for student projects.

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