Introduction to Analogs

Acoustical and mechanical systems have resistive and reactive elements that behave like their electrical counterparts. These elements can be replaced by their electrical analogs to build a circuit model that will simulate the response of a transducer. The Knowles analogs break down microphones and receivers into components that can be represented by equivalent electrical parts. There are a number of very good references that discuss electrical analogs in more detail (see Refs. 1-4). This paper is intended to give a quick overview as it applies to the modeling of Knowles transducers.

There are two types of analogs: mobility and impedance. In the impedance analog, mechanical force or sound pressure is equated with voltage and volume velocity is represented by current. In the mobility analog, the reverse is true. Voltage represents volume velocity and current equates force or pressure. Both methods produce equivalent results. We will use the impedance analog to define equivalent circuit elements for the components in the Knowles microphones and receivers. Table 1 is a quick overview of the analogs and their units.

Electrical Quantity	**Mechanical Analog**	**Mechanical Units**	**Mechanical Example**	**Acoustical Analog**	**Acoustical Units**	**Acoustical Example**
Resistance **R** (Ohms)	Resistance $\mathbf{r_m}$	$gm*sec^{-1}$	Drag in a viscous fluid or damping	Resistance $\mathbf{R_A}$	$gm*cm^{-4}*sec^{-1}$	Air flow through a screen
Inductance **L** (Henries)	Mass **m**	gm	Mass	Inertance **M**	$gm*cm^{-4}$	Air in a tube
Capacitance **C** (Farads)	Compliance $\mathbf{c_m}$	$sec^{2}*gm^{-1}$	Spring	Compliance $\mathbf{C_A}$	$gm^{-1}*cm^{4}*sec^{2}$	Air in a cavity
Voltage **V** (Volts)	Force **F**	$gm*cm*sec^{-2}$		Pressure **P**	$gm*cm^{-1}*sec^{-2}$	
Current **i** (Amperes)	Velocity **v**	$cm*sec^{-1}$		Volume velocity **u**	$cm^{3}*sec^{-1}$	

Table 1: Acoustical and mechanical quantities and their electrical analogs.

Mechanical Analogs

Let us first look at the mechanical analog where voltage is equivalent force (F) and current is equivalent to velocity (v). From Newton's second law of motion we know that a mass undergoes an acceleration proportional to the applied force. By replacing force with voltage (V) and velocity with current (I), the same equation describes the voltage across an inductor (L):

$$F = m\frac{d^2x}{dt^2} = m\frac{dv}{dt} \qquad V = L\frac{d^2q}{dt^2} = L\frac{dI}{dt}$$

Compliance (C) is defined as the inverse of stiffness (k). A good example of a mechanically compliant element is a spring. The restoring force of a spring is proportional to the spring's displacement (x) from its equilibrium position (i.e., x=0). This is analogous to the equation describing the voltage across a capacitor with charge q:

$$F = k \cdot x \qquad V = \frac{1}{C} \cdot q$$

A resistor is the analog for an element whose force is proportional to velocity. Consider the equation for the drag force acting on an object moving slowly in a viscous fluid where μ is the drag coefficient. It is analogous to the voltage across a resistor R:

$$F = \mu \cdot v \qquad V = R \cdot I$$

The last mechanical element to consider is the lever. The lever transforms force and velocity from one level to another like a transformer transforms voltage and current levels:

$V_2=V_1/N$ and $I_2=I_1 \cdot N$, where the turns ratio $N=N_1/N_2$

Acoustical Analogs

The basic acoustic elements are compliance, inertance, and resistance. The equations used to describe these elements have the same form as the mechanical equations. For the acoustical analogs, voltage is equated with pressure (P) and current is particle velocity (u). A fluid that undergoes compression under an applied force where V is volume (not voltage) has an acoustic compliance C_A equal to:

$$P = \frac{1}{C_A} \cdot \Delta V \quad \text{where: } C_A = \frac{V}{\rho \cdot c^2} \quad (\rho = \text{density of air and } c = \text{speed of sound in air})$$

A fluid that undergoes a displacement under an applied force (i.e., no compression) has an acoustic inertance M equal to:

$$P = M\frac{du}{dt} \quad \text{where: } M = \frac{\text{mass}}{\text{area}^2}$$

An acoustic resistance R_A such as a screen is defined by the equation:

$$P = R_A \cdot u$$

The last component to consider is the transducer. A transformer represents a transducer that converts mechanical energy to electrical energy (e.g., electret) or acoustical energy to mechanical energy (e.g., diaphragm).

Units for Pressure and Output Voltage

The Knowles transducers convert sound energy into electrical energy or electrical energy into sound energy. The performance of a device is characterized by its response. For a microphone, response refers to variation of the sensitivity with frequency. In the Knowles specifications, the sensitivity is expressed as a logarithmic ratio with a reference of 1 volt (i.e., dB re 1 V). For voltage V_{out}, the output is given in dB by: $dB = 20 \cdot LOG_{10}(V_{out}/1V)$. For a receiver, response refers to the variation of the acoustic output at nominal drive (current or voltage) with frequency. Sound pressure is usually expressed as a logarithmic ratio of the absolute pressure to 20×10^{-6} N/m^2 = 20 μPa or 0.0002 microbars of pressure: $dB\ SPL = 20 \cdot LOG_{10}(P/P_{ref})$.

Microphone Analog:

The microphone analog is represented schematically in Fig. 1. The microphone motor converts acoustic energy (pressure, volume velocity) into mechanical energy (force, velocity) and mechanical energy (force, velocity) into electrical energy (voltage and current).

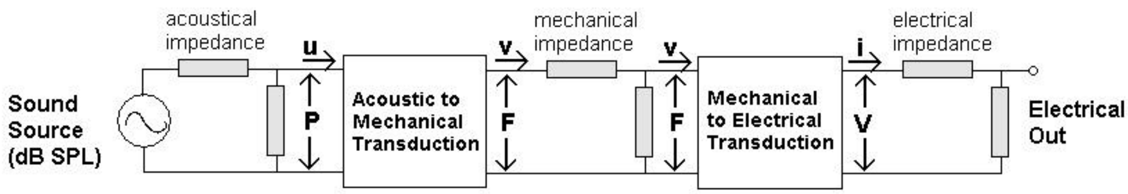

Fig. 1. Acoustical ⇔ mechanical ⇔ electrical transduction of a microphone.

For the Knowles analogs, components have been combined to reduce the size of the circuit. The topology for a microphone analog is shown in Fig. 2. On the acoustic side of the transformer (i.e., to the left of the box labeled acoustical to electrical transduction), voltage corresponds to the pressure in the microphone. For these analogs we define 1 volt to be equivalent to 74 dB SPL (i.e., centimeter-gram-second, cgs units). Starting at the port tube, there is a small air volume (inertance) represented by an inductor and a resistor (M_port and R_port). The tube has a damping screen with a large acoustic resistance that is in series with the port resistance (R_screen). At the end of the tube is an opening into the main body of the microphone. This opening is a narrow slot with a small resistance and inertance (not shown) that has been lumped together with the components for the port. The enclosed front volume is subject to compression and can be represented by a capacitor. All sides of the cavity but one, are solid and the sound pressure can act no further. Therefore one side of the capacitor is connected to ground. On the remaining side of the cavity is the diaphragm (not shown on circuit) and beyond the diaphragm is the rear volume shown as another capacitor. Other components have been combined to reduce the size of the circuit and are represented by the box labeled acoustical to electrical transduction. Since the circuit components are combined there is no longer a one to one correspondence to the parts in the microphone.

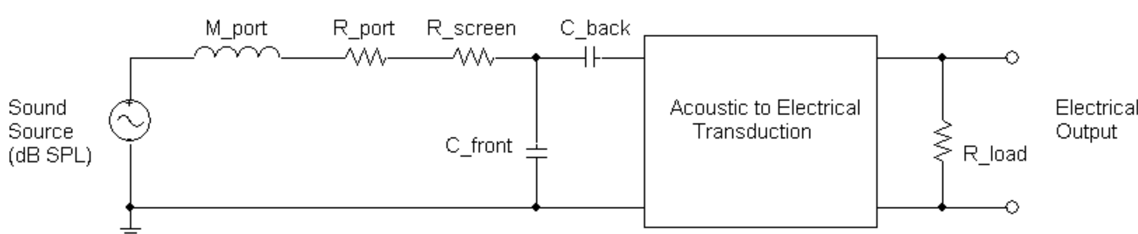

Fig. 2: Microphone analog

Receiver Analog:

The receiver analog is represented schematically in Fig. 3. The motor in the receiver (i.e., coil, armature, etc.) converts electrical and magnetic energy into mechanical energy (force, velocity) then the diaphragm converts mechanical energy (force, velocity) into acoustic energy (pressure, volume velocity).

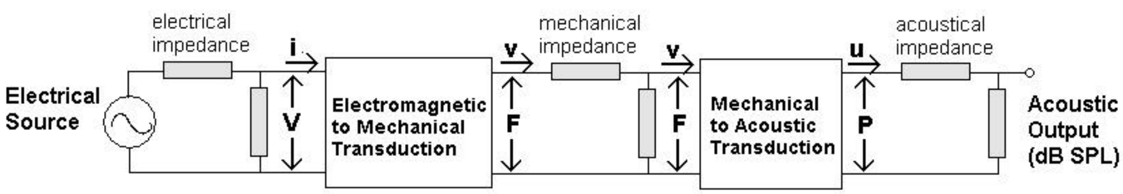

Fig. 3: Electrical ⇔ magnetic ⇔ mechanical ⇔ acoustical transduction

The topology for a receiver analog is shown in Fig. 4. On the acoustic side of the transformer (i.e., to the right of the box labeled electrical to acoustical transduction), the components are the same as the microphone except that they are in reverse order. Like the microphone analog, receiver components have been combined to reduce the size of the circuit and are represented by the box labeled electrical to acoustical transduction. Since the circuit components are combined there is no longer a one to one correspondence to the parts in the receiver.

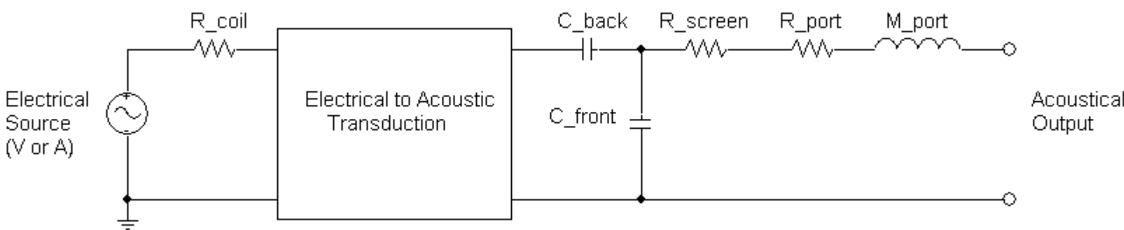

Fig. 4: Receiver analog

For more information see the report "Electrical Analogs for Knowles Electronics, Inc. Transducers".

<u>References:</u>

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3. Allan D. Pierce, *Acoustics: An Introduction to Its Physical Principles and Applications*, McGraw-Hill Book Company, New York (1981).
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5. J. L. LoPresti and E. V. Carlson, *Electrical Analogs for Knowles Electronics Inc. Transducers*, Report Number 10531-3, Release 6.1 (1999).