# Electrical Analogs
# for
# Knowles Electronics, LLC. Transducers

## Version 9.0

by
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# Contents

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# ELECTRICAL ANALOGS FOR KNOWLES ELECTRONICS TRANDUCERS

## I. Introduction

Acoustical and mechanical systems have resistive and reactive elements that behave like their electrical counterparts. These elements can be replaced by their analogs to build a circuit model that will simulate the response of a transducer. The Knowles analogs break down microphones and receivers into equivalent circuits for PSpice simulations. This report gives an overview of the transducer analog circuits and components. There is detailed information on node numbering and device specification for linking these files to your own models.

## II. Circuit Topology and Components

Microphone Analog

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

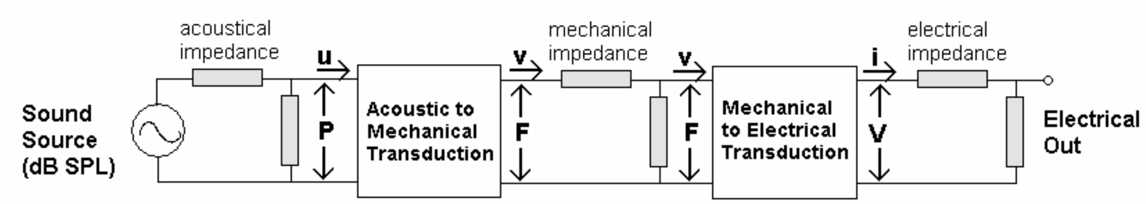



**FIG. 1:** Acoustical ⇔ mechanical ⇔ electrical transduction of a microphone.

The circuit representing a Knowles microphone is shown in Fig. 2a. On the acoustic side of the transformer (i.e., to the left), voltage corresponds to the pressure in the microphone. In cgs units, we define 1 volt to be equivalent to 74 dB SPL (i.e., in SI / MKS units 0.1 volt equivalent to 74 dB SPL or 0.1 Pa). Starting at the port tube, there is a small moving mass of air (i.e., inertance) represented by an inductor (see Figure 2b on next page). The tube has a damping screen with a large acoustic resistance that is in series with the port inertance. At the end of the tube is the opening into the main body of the microphone. The enclosed front volume is subject to compression and can be represented by a capacitor. All sides of the cavity except one side 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 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 labeled “lump parameters”. Since the circuit components are combined there is no longer a one to one correspondence to the parts in the microphone. Most module files and subcircuit definitions use the same circuit topology, component names, and node numbers shown in Fig. 2.

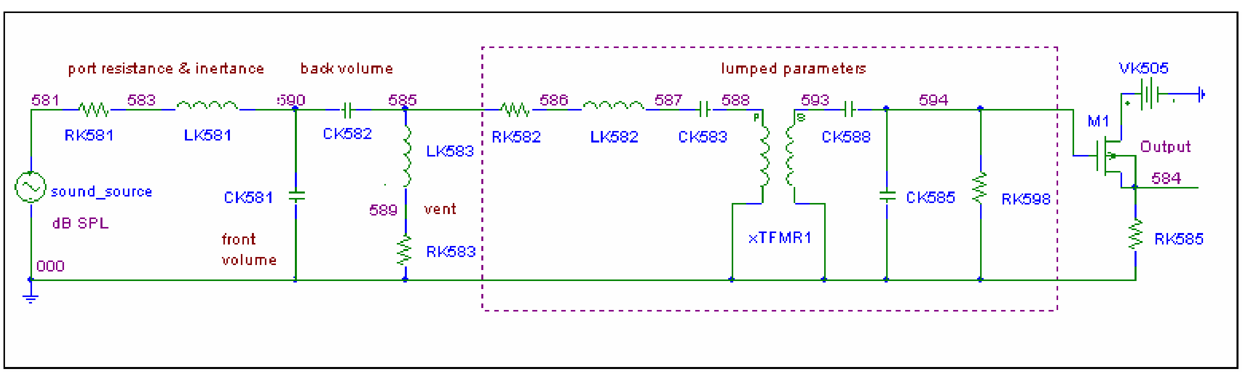



**FIG. 2a:** Schematic of a Knowles microphone analog.

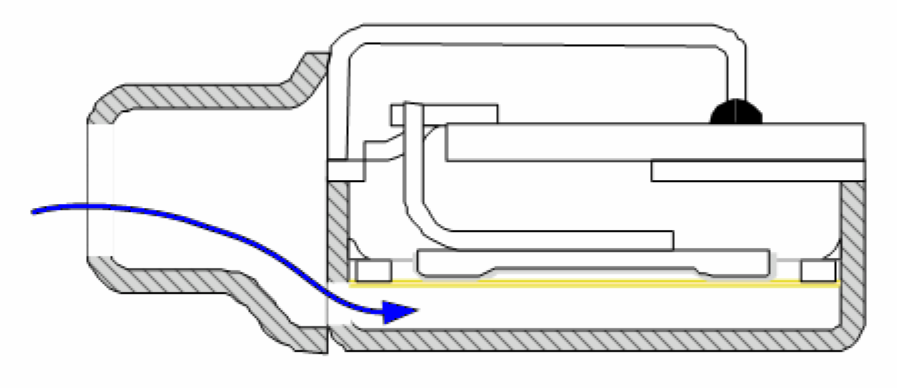


**FIG. 2b:** Cross-section of EM microphone showing acoustical elements that correspond to components in the analog (i.e., components in Figure 2a).

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).

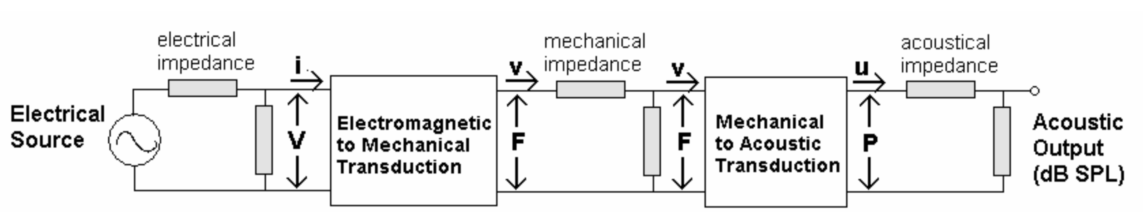



**FIG. 3:** Electrical ⇔ magnetic ⇔ mechanical ⇔ acoustical transduction

The circuit topology for a receiver analog is shown in Fig. 4a. On the acoustic side (i.e., to the right of the gyrator), some of the components are the same as the microphone (i.e., front volume, back volume, etc.). Like the microphone analog, receiver components have been combined to reduce the size of the circuit and are labeled "lumped parameters". Since the circuit components are combined there is no longer a one to one correspondence to the parts in the receiver. Most module files and subcircuit definitions use the same circuit topology, component names, and node numbers shown in Fig. 4.

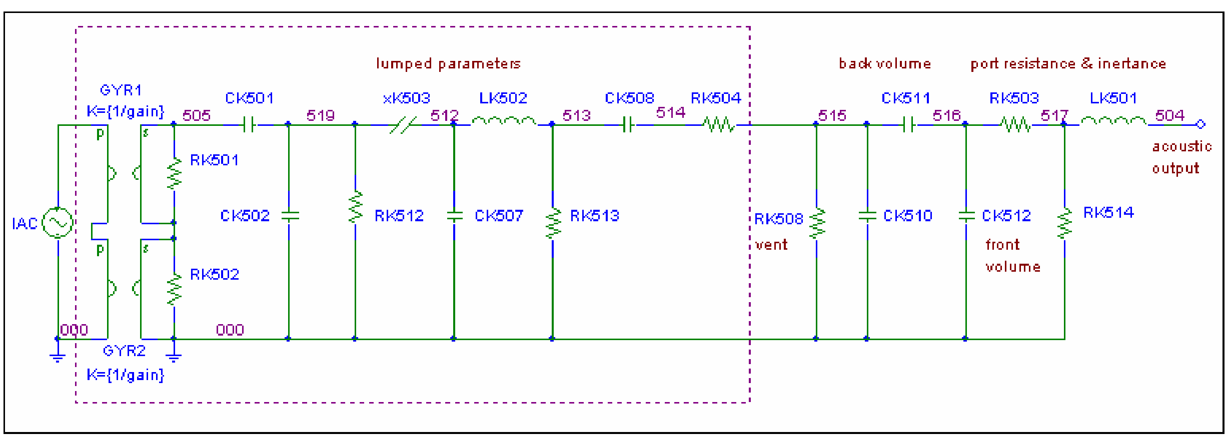



**FIG. 4a:** Schematic of a Knowles Receiver analog.

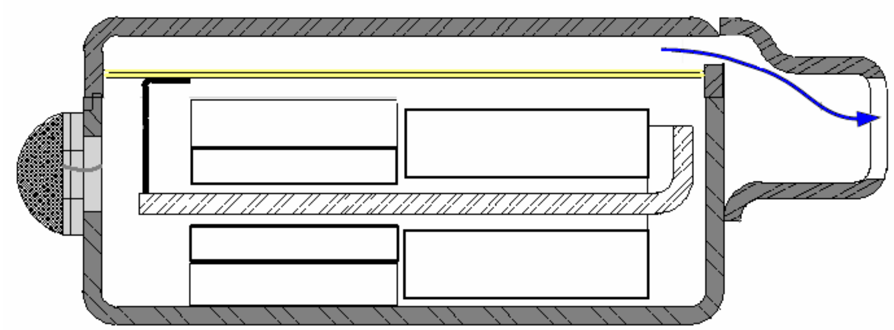


**FIG. 4b:** Cross-section of ED receiver showing elements that correspond to components in the analog (i.e., components in Figure 4a).

**Analogs only approximate the behavior of the devices they are to simulate.** These circuits are linear. They apply only at power levels within the linear capabilities of the devices they simulate. They cannot simulate any non-linearity or power limitation in the device. The performance of these modules outside of the range 100 Hz to 10 kHz may be unpredictable.

## III Netlist Modules and Libraries

Electrical Analogs for Knowles Electronics Transducers are designed to be used with a PSpice circuit analysis program. The complete set contains over 300 transducer analogs.

- Modules for building netlists[1] (*.TXT)
- Library files for Orcad Schematics[2] (*.SLB, *.LIB)
- Schematics files for Orcad Schematics (*.SCH)
- PDF copy of the circuit schematic (*.PDF)
- Library files for Orcad Capture (*.OLB, *.LIB)

The .LIB library files are text files containing subcircuit definitions of the transducers (e.g., ke.FC.LIB for FC receiver analogs). The subcircuits use the standard PSpice format. Even if you are not using the Orcad circuit simulator, you can use the subcircuits to create parts for your circuit program.

Node Numbering, Device Specifications, & Modules
Appendix F contains detailed information on node numbers and device specifications for the Knowles analogs. This section contains a brief overview.

- All device and node numbers are in the range 400 to 699.

- To distinguish parts of these analogs from others in your application, all device specifications have the letter 'K' after the reserved device specifying letter. That is, all capacitor devices in the analog have a designation such as CK5xx.

- The programs are grouped by functional modules or subcircuits. Each module has a generic name and a serial identification. The block diagrams in Fig. 5 show the layout of nodes for attachment to the program modules that are provided.

[1] Module files are text files that contain the .SUBCKT and .MODEL definitions of the transducers and the components. The same SUBCKT and MODEL definitions are also found in the *.LIB files.
[2] Orcad Schematics formerly called Microsim Schematics (identical programs)

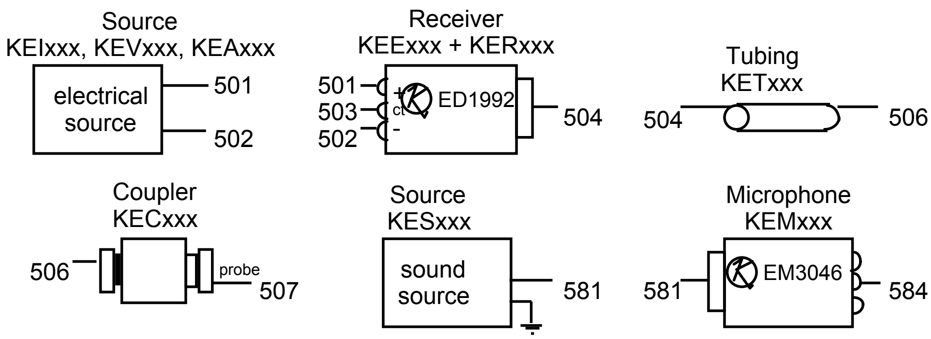



**Fig. 5:** Modules and terminating node numbers for the transducer analogs.

Any PSpice simulation must contain the appropriate combination of modules. The use of modules such as KETxxx (tubing), KECxxx (coupler) and/or KEFxxx (end of file statement) are optional, depending on the nature of the simulation. For example, to generate a receiver's response curve found on the Knowles product specifications Sheet 2.1, you need a current source, the electrical and mechanical components of the receiver, tubing, and a coupler cavity. The modules that are needed to simulate an ED-21913 in its Sheet 2.1 configuration are shown in Fig. 6a. The same simulation is shown using parts from the library files for Orcad Schematics Capture (Fig. 6b).

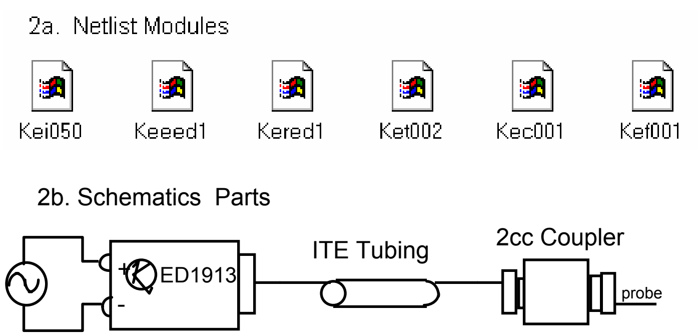



**Fig. 6:** Netlist modules and Schematics Capture parts to simulate the Knowles Electronics 2.1 sheet specification for ED-21913 receiver.

<u>Receiver Subcircuits</u>

A receiver requires two modules: KEExxx and KERxxx. The two-part model allows many combinations of coils and damping within one series of receivers. The library files (*.LIB) define all of the modules as subcircuits. The *.SLB and *.OLB library files contain the part symbol, pin attributes, and links the symbol to the subcircuits. Appendix A. has a list of all available transducer models and their associated subcircuit modules (i.e., module name + serialized number)

Receiver subcircuit in the keED.LIB library:

```
.SUBCKT ED21913  501 502 504
xKEE  501 502 503 505 KEEED1
xKER  505 504         KERED1
.ENDS
```

| | |
|---|---|
| Subcircuit name = | ED21913 |
| Input nodes (+) and (-) = | 501 and 504 |
| Output node (pressure & volume velocity) = | 504 |
| Coil subcircuit = | keeED1 |
| Receiver subcircuit = | kerED1 |

**When the input is in terms of volts and amperes the output energy is in terms of watt-seconds. To convert a node voltage to dB SPL you must add 144 dB**. The usual query would be DB(V(507))+144 (or DBV(507)+144) for the SPL in a coupler. (70 dB of this factor is to change from a watt-second to an erg reference frame and 74 dB to change from dynes/cm$^2$ to 0.0002 dynes/cm$^2$ which is the 0 dB SPL reference level.). The 70dB factor is a consequence of using cgs units for acoustical and mechanical analogs (i.e., centimeter-gram-second unit system).

Microphone Subcircuits

The microphone modules have the designation KEMxxx. The device designations follow the convention used for receivers. All Knowles microphones are active devices. No attempt has been made to simulate the D.C. voltage levels. There is no substantial bidirectional interaction between the acoustical and electrical portions of the analog. Unlike the receiver subcircuit, the microphone subcircuit

Microphone subcircuit in the keEM.LIB library:

```
*KEMEM10, EM-23346
.SUBCKT EM3346      581 584
RK581         581 583  2.55E+3
RK582         585 586  0.95E+3
(Deleted components in this example)
M1            596 594  584 584  MOS_2
VK505         596   0  1.5
.ENDS
```

| | |
|---|---|
| Subcircuit name = | EM3346 |
| Input nodes (pressure & volume velocity) = | 581 |
| Output node (+) = | 584 |

The applied voltage is numerically equal to the applied sound pressure in dynes/cm$^2$ (i.e., 1 volt is equivalent to 74dB SPL). The electrical output signal is volts and /or amperes. **70 dB must be subtracted from the output voltage** or scale the input voltage by -70dB (i.e., scale sound source by 1/3162). The 70 dB of this factor is to change from a watt-second to an erg reference frame. The sound pressure is referenced to node 0 (i.e., ground). The electrical output signal is also referenced to node 0.

Circuit Components, Tubes and Coupler Cavities

The analogs are built from standard circuit components (i.e., R, L and C) and custom circuit components (Table 1.). In the analog modules, these non-standard components are defined in subcircuit statements. The same components can also be found in the KNOWLES.SLB and KNOWLES.LIB libraries.

| | **Subcircuit / Component Name** |
|---|---|
| Ideal Transformer | TFMR |
| Gyrator (k= 1/gain) | GYR |
| Semi-capacitance ( $\propto 1/\sqrt{j \cdot \omega}$ ) | CMAG |
| Semi-inductance ( $\propto \sqrt{j \cdot \omega}$ ) | LMAG |

**TABLE 1.:** Non-standard circuit components

The available tube models, special tubing, and coupler cavities are listed in Table 2. Analogs Release 8 or newer include new tube model. The new tube model does not have the length limitation of the older model. In addition, length and radius are changeable parameters.

| | |
|---|---|
| Tube Segments (variable length and radius) | Tube_cgs, Tube_SI (new) |
| Special Tubing (per Knowles specifications) | ITE and BTE |
| Coupler Cavities | IEC 711, Zwislocki ear simulator, and $2cm^3$ |

**TABLE 2.:** Tubing and couplers

It may be necessary to load the obsolete tube models for older schematics. The tube parts and subcircuits were deleted from the KNOWLES.SLB and the KNOWLES.LIB files and moved to separate library files appropriately named “Old tube models.slb” and “Old tube models.lib”.

## IV. Schematics and Capture Libraries

The electrical analogs of Knowles Electronics transducers can be added to the Parts Browser of Orcad Schematics and Capture. To place a transducer on your schematic, simply type the Knowles part number into the Parts Browser without a dash (e.g., ED21913). The analog libraries consist of subcircuit definitions which are identical to the netlist modules. The KNOWLES library contains parts that simulate standard Knowles ITE and BTE tubing, $2cm^3$ coupler cavity, IEC 711 or Zwislocki ear simulators, and more. The receiver and microphone libraries are organized according to the series name. For example, the ED-21913 analog is in the “keED” library. All analogs require both symbol library (e.g., *.SLB for Schematics or *.OLB for Capture) and model library (e.g., *.LIB) to run. Follow the directions in Appendix C to configure Schematics and Capture to use these libraries.

Receivers

The receiver analogs libraries are organized according to series (e.g., keED.lib, keFC.lib, etc.). When the input is in terms of volts or amperes the output energy is in terms of watt-seconds. **To convert the output voltage to dB SPL, add 144 dB**. 70dB is added to change from watt-second to erg and 74dB is added to change from dyne/$cm^2$ to 0.0002 dynes/$cm^2$ which is the 0 dB SPL reference level. The setup that is shown in Fig. 7 will generate the response curve for the ED-21913 receiver found in the Knowles product specification Sheet 2.1. The voltage on the ‘probe’ pin of the 2cc Coupler is equal to the sound pressure at the reference microphone in the coupler. Place a VdB marker (i.e., voltage probe) on this pin. To convert the output voltage of this model to dB SPL, double click on the trace in Probe and type the following: VDB(2cc_Coupler:pin2)+144.

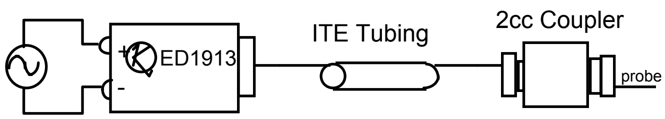



**FIG. 7.:** Example schematic

Microphones

The microphone analogs libraries are also organized according to series (e.g., keEM.lib, keFG.lib, etc.). The applied voltage is equal to the applied sound pressure in dynes/$cm^2$ (i.e., 1 volt is equivalent to 74dB SPL). The electrical output signal is volts or amperes. **70 dB must be subtracted from the output voltage** or scale the input voltage by -70dB (i.e., scale sound source by 1/3162). The sound pressure is referenced to node 0 (i.e., ground). The electrical output signal is also referenced to node 0. See Appendix D for more information on noise modeling.

## V. ACOUSTIC TRANSMISSION TUBES

Tubes are one of the most popularly used acoustic elements in acoustic designs. The acoustic properties of tubes were studied as early as the era of Helmholtz [1], Kirchhoff [2], and Rayleigh [3]. The first approximation of the full Kirchhoff solution was given by Kirchhoff [2] himself for “wide" tubes and by Rayleigh [3] for “narrow" tubes. However, those solutions are Bessel functions with complex argument, which are difficult to deal with in old days. In fact, even today they are not easy to implement in programs such as PSpice. Effort has been made in simplifying the solutions [4, 5, 6]. The original tube models by Knowles were based on the work by Zuercher [7] who obtained quite simple algebraic expressions that can accurately approximate (with discrepancies being less than 3%) the value of the acoustic impedance of small tubes (radii less than 1/16 acoustic wavelength) including isothermal and viscous effects. However, the older PSpice model has limitations: 0.2cm length limit per segment and fixed diameter. Recently, PSpice has become more powerful and it provides the users the Analog Behavior Modeling (ABM) feature. Applying this feature, we have built a tube acoustic model that is more meaningful and more accurate using piecewise functions.

The tube models are available as library parts for Schematics and Capture. Build any tubing by simply entering in the length and diameter for each segment. The PARAMS: LEN (length) and RAD (radius) are expressed in centimeters for Tube_cgs and meters for Tube_SI.

## VI. HELPFUL HINTS AND TROUBLESHOOTING

### Converting Analogs to Subcircuits for Other Programs

The analogs can be integrated into an electronic circuit (netlist), *filename.CIR*, using any text editor. This circuit file can be read directly by PSpice without use of a schematics program. To convert an analog into a part for a different schematics program, you need to find the subcircuit and to create a symbol or package. The transducer subcircuits can be found in the *.LIB library files which can be opened with a text editor. For example, the analog for the EM-3046 microphone in keEM.LIB is shown below:

```
*KEMEM1, EM-3046
*EM-PA (standard response, 12B port, WS)
.SUBCKT KEMEM1         581 584

RK581          581 583  1.85E+3
RK582          585 586  1.00E+3
RK583          589   0  33.0E+3
RK585            0 584  22E+3
RK586            0 594  7.0E+9
RK587          595 594  1.0E+12
RK591          595 584  1.0E+6
RK593          594 596  1E4
RK592          594 596  1E4
CK581            0 590  1.20E-9
CK582          585 590  8.80E-9
CK583          587 588  12.0E-9
CK585            0 594  1.42E-12
CK587          595 594  1.60E-12
CK586          584 594  3.20E-12
CK588          593 594  -0.77E-12
LK581          583 590  8.50E-2
LK582          586 587  2.65E-2
LK583          585 589  1.00E-2
xTFMR1         593   0  588   0 TFMR PARAMS: PRI=261.55, SEC=1
GK581          595 584  596 584 .325E-3
VK581          595   0  AC .000E+1
.ENDS

.SUBCKT TFMR    1   2   3   4   PARAMS:PRI=1, SEC=1
R1  1   2   1E+12
R3  3   4   1E+12
V1  1   5
G1  4   3   VALUE = {I(V1)*PRI/SEC}
E1  5   2   VALUE = {V(3,4)*PRI/SEC}
.ENDS
```

The first step is to create a new symbol / package for the microphone. The symbol can be a box with two pins. The pins must be correctly mapped to the input (581) and output (584) nodes of the microphone subcircuit (i.e., Pin 1 = 581, Pin 2 = 584). The symbol or package must also reference the subcircuit. Otherwise, you will see the part on your schematic but you will not be able to run a simulation. Remember that you will also need to have subcircuit statements for any nonstandard components such as CMAG and TFMR. You do not need to create symbols but the subcircuit statements should be in the same library as your transducer. It may be helpful to refer to your software manuals for more information on netlists and subcircuit definitions.

**Converting CGS ⬄ SI Units**

Historically, all Knowles' analogs use CGS units. This practice dates back to the time when analogs were built using real components. The CGS unit system has been maintained for new analogs as well. The advantage of CGS units is the component values are more typical of real-life devices. High resistor values in SI units can lead to simulation errors in some programs (e.g., bias point or convergence errors). The disadvantage of CGS is the correction factors for receivers (+70dB) and microphones (-70dB). In SI units, you need only add 94dB to the output of a receiver to convert dB Pa to dB SPL. The output of the microphone requires no change.

A CGS acoustical ohm has units of $Z_{CGS}$ = gm/(cm$^4$ * sec) . In order to convert the components to SI units $Z_{SI}$= kg/(m$^4$ * sec), scale the acoustical impedances: $Z_{SI} = Z_{CGS}*10^5$ .

***Pressure***

CGS Units

0.1 Pa = 1.0 volt

SI Units

0.1 Pa = 0.1 volt

***Receivers***

- Acoustical impedance: $Z_{SI} = Z_{CGS}*10^5$ (R*$10^5$, L*$10^5$, & C /$10^5$ )
- Correct the gain of the voltage controlled current sources:
  - GK501 and 503 => $\text{gain}_{SI} = \text{gain}_{CGS}$ / [sqrt($10^5$)]
  - GK502 and 504 => $\text{gain}_{SI} = \text{gain}_{CGS}$ / [sqrt($10^5$)]
- Increase values of resistors RK509, RK510, RK511 from 0.1E+9 to 0.1E+12. Lower values cause error in input impedance (i.e., raises DCR). Higher values may cause convergence errors during simulations.
- Add 94dB to convert dB V at output to dB SPL (i.e., 1 V = 1 Pa).

***Microphones***

- Acoustical impedance: $Z_{SI} = Z_{CGS}*10^5$ (R*$10^5$, L*$10^5$, & C /$10^5$ )
- Correct turns ratio of transformer: N(sec) / sqrt($10^5$)
- 74 dB sound source is represented by a 0.1 V voltage source (i.e., 0.1 Pa = 0.1 V).

**Micro-Cap Circuit Simulator – Known Conflicts**

If you use Micro-Cap, there are some known conflicts:

- The negative terminal in the receiver analogs (i.e., node 502) must be grounded due to differences in the voltage controlled current source model (i.e., grounding not required in Orcad Schematics or Capture).

- The comma was removed from the transformer subcircuit (i.e., TFMR) "PARAM" statement to fix a MicroCAP error message. The comma between parameters is optional in PSpice and does not affect Orcad.
  ```
  xTFMR1    593  0  588  0 TFMR PARAMS: PRI=261.55, SEC=1
  ```
  changed to:
  ```
  xTFMR1    593  0  588  0 TFMR PARAMS: PRI=261.55 SEC=1
  ```

- Equal sign was added to the tube subcircuits in the KNOWLES.LIB file. The missing "=" caused an error in MicroCap. Orcad Schematics will run with or without the "=" sign:
  ```
  GR1 1  5  FREQ  {V(1,5)/LREF}=
  ```

- The CMAG subcircuit causes an error "no DC path to ground" in Micro-Cap. The CMAG subcircuit has NOT been changed. Replace the CMAG circuit with this revised version:
  ```
  .SUBCKT CMAG  1  2  PARAMS:CMAG = 1
  R1  1  2  1E+9
  ```

```
EB 3    0   VALUE={.707*V(1,2)*CMAG*6282}
G1  1    2   FREQ    {V(3,0)} =
+ (20,-17,45)
+ (20000,13,45)
.ENDS
```

**Transcient Analysis and CMAG Component**

CMAG is a special "semi-capacitance" used in the magnetic modeling of receivers. It represents the 1/sqrt(f) eddy current loss in magnetic materials. The CMAG subcircuit is defined by a look-up table that can cause errors when a transient analysis is run. The CMAG subcircuit can be replaced by the ladder network, which is shown in Figure 8 (cgs units).

EK = voltage controlled voltage source
FK = current controlled current source

Set gain for EK and FK equal to: Gain=1/sqrt(6283.2*CMAG) = 0.012616/sqrt(CMAG)
Example: CI analog: CMAG=0.107E-6, Gain = 38.6

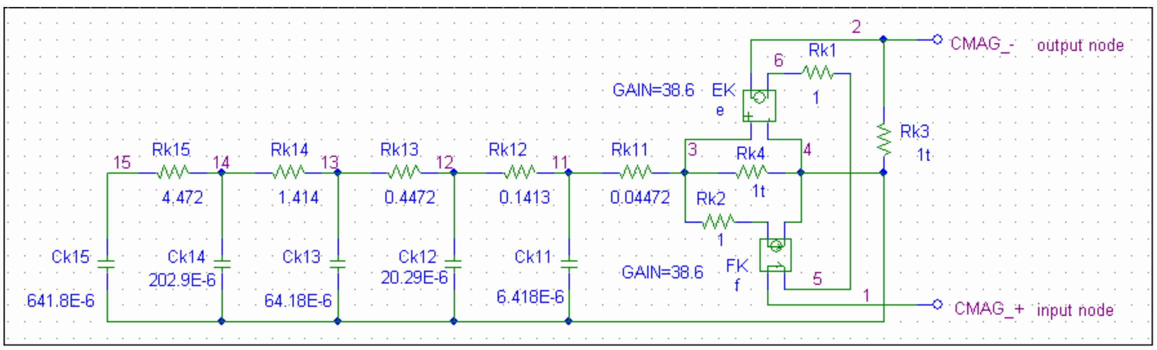



**FIG.8:** Ladder network that can replace CMAG component.

**References from Tube Model section:**


[1] H. L. F. Helmoltz, "On the Influence of Friction in the Air on Sound Motion," Verh. Natur. Histor. Medizin. Ver Heidelberg III, 16 (1863)

[2] G. R. Kirchhoff, "On the Influence of Thermal Conduction in a Gas on the Motion of Sound," Poffendorfer Ann. 134, 177-193 (1868)

[3] Lord Rayleigh, Theory of Sound Volume II (The Macmillan Company, London, Second Edition)

[4] A. H. Benade, "On the Propagation of Sound Waves in a Cylindrical Conduit," J. Acoust. Soc. Am. 44, 616-623 (1968)

[5] H. Tijdeman, "On the propagation of sound waves in cylindrical tubes," J. Sound and Vib. 39(1), 1-33 (1974)

[6] Douglas H. Keefe, "Acoustical wave propagation in cylindrical ducts: Transmission line parameter approximations for isothermal and nonisothermal bounday conditions," J. Acoust. Soc. Am. 75, 58-62 (1984)

[7] Joseph C. Zuercher, Elmer V. Carlson, and Mead C. Killon, "Small acoustic tubes: New Approximations including isothermal and viscous effects," J. Acoust. Soc. Am. 83(4), 1653-1660 (1984)


**Acknowledgments & Comments:**


E. V. Carlson began this project and released Revision #1 of the Knowles Electronics, Inc. Analogs in 1991. The analogs have continued to evolve and to be revised. The current collection contains over 300 analogs. If you have any suggestions, questions, or problems, please contact me.



J. L. LoPresti (janice.lopresti@knowles.com)

# Appendix A
## Catalog of Available Transducer Analogs

All transducer analogs are listed in this appendix grouped by transducer type (receiver or microphone) and series designation (ED, EM, etc.). All part numbers have been updated to reflect the new Knowles 5-digit numbering system.

Changes in Release 9.0

- Newer product families added to collection: WBHC, WBFK, TWFK, TEC, DTEC
- Subcircuit names reflects current Knowles part number system
- Coil model for receivers corrected to ensure proper polarity per Sheet 1.1 specifications
- Old tube models deleted from "KNOWLES" library and moved to separate "OLD TUBE MODELS" library

### RECEIVERS

| MODEL # | KEExxx | KERxxx | Nominal Drive | Tubing | # Pads |
|---|---|---|---|---|---|
| BK-21600 | keeBK1 | kerBK1 | 1.00 mA | BTE (HA-2 coupler) | 2 |
| BK-21604 | keeBK16 | kerBK1 | 0.33 mA | BTE (HA-2 coupler) | 2 |
| BK-21606 | keeBK10 | kerBK1 | 0.71 mA | BTE (HA-2 coupler) | 2 |
| BK-21610 | keeBK2 | kerBK1 | 0.45V, 50 Ohm | BTE (HA-2 coupler) | 2 |
| BK-21612 | keeBK12 | kerBK1 | 0.55 mA | BTE (HA-2 coupler) | 2 |
| BK-21613 | keeBK9 | kerBK1 | 0.78 mA | BTE (HA-2 coupler) | 3 |
| BK-21615 | keeBK9 | kerBK1 | 0.78 mA | BTE (HA-2 coupler) | 3 |
| BK-21618 | keeBK10 | kerBK1 | 0.71 mA | BTE (HA-2 coupler) | 2 |
| BK-21669 | keeBK17 | kerBK1 | 3.61 mA | BTE (HA-2 coupler) | 2 |
| BK-21706 | keeBK6 | kerBK1 | 1.20 mA | BTE (HA-2 coupler) | 3 |
| BK-21888 | keeBK7 | kerBK2 | 1.73V, 890 Ohm | BTE | 3 |
| BK-21968 | keeBK1 | kerBK1 | 1.00 mA | BTE (HA-2 coupler) | 3 |
| BK-28507 | keeBK18 | kerBK2 | 0.35V, 30 Ohm | BTE | 2 |
| | | | | | |
| CI-22746 | keeCI3 | kerCI1 | 2.40 mA | BTE | 3 |
| CI-22748 | keeCI2 | kerCI1 | 2.00 mA | BTE | 3 |
| CI-22762 | keeCI3 | kerCI1 | 2.40 mA | BTE | 3 |
| CI-22764 | keeCI2 | kerCI1 | 2.00 mA | BTE | 3 |
| CI-22955 | keeCI4 | kerCI1 | 3.75 mA | BTE | 3 |
| CI-22960 | keeCI1 | kerCI1 | 1.60 mA | BTE | 3 |
| CI-28203 | keeCI7 | kerCI1 | 2.00 mA | BTE | 3 |
| CI-28204 | keeCI1 | kerCI1 | 1.60 mA | BTE | 3 |
| CI-28220 | keeCI4 | kerCI1 | 3.75 mA | BTE | 3 |
| CI-28226 | keeCI7 | kerCI1 | 2.00 mA | BTE | 3 |
| CI-28267 | keeCI7 | kerCI1 | 2.00 mA | BTE | 3 |
| CI-28268 | keeCI3 | kerCI1 | 2.40 mA | BTE | 3 |
| CI-28329 | keeCI3 | kerCI1 | 2.40 mA | BTE | 3 |
| CI-28352 | keeCI4 | kerCI1 | 3.75 mA | BTE | 3 |
| CI-28409 | keeCI1 | kerCI1 | 1.60 mA | BTE | 3 |
| CI-28417 | keeCI4 | kerCI1 | 3.75 mA | BTE | 2 |
| CI-28434 | keeCI6 | kerCI1 | 3.18 mA | BTE | 2 |
| CI-28487 | keeCI6 | kerCI1 | 3.18 mA | BTE | 3 |
| | | | | | |
| dTEC-30008 | dtec30008 | | .154 V | BTE | 4 |
| | | | | | |
| EC-23095 | keeEC2 | kerEC1 | 0.54 mA | 10mm x 1mm ID | 2 |
| EC-23096 | keeEC1 | kerEC1 | 0.77 mA | 10mm x 1mm ID | 2 |

| | | | | | |
|---|---|---|---|---|---|
| EC-23097 | keeEC3 | kerEC1 | 1.09 mA | 10mm x 1mm ID | 2 |
| EC-23098 | keeEC1 | kerEC1 | 0.77 mA | 10mm x 1mm ID | 3 |
| EC-23104 | keeEC2 | kerEC1 | 0.54 mA | 10mm x 1mm ID | 3 |
| | | | | | |
| ED-21739 | keeED1 | kerED3 | 0.50 mA | 10mm x 1mm ID | 2 |
| ED-21744 | keeED5 | kerED3 | 0.35 mA | 10mm x 1mm ID | 3 |
| ED-21912 | keeED2 | kerED1 | 0.70 mA | 10mm x 1mm ID | 2 |
| ED-21913 | keeED1 | kerED1 | 0.50 mA | 10mm x 1mm ID | 2 |
| ED-21914 | keeED5 | kerED1 | 0.35 mA | 10mm x 1mm ID | 2 |
| ED-21915 | keeED7 | kerED1 | 0.25 mA | 10mm x 1mm ID | 2 |
| ED-21925 | keeED3 | kerED1 | 0.88 mA | 10mm x 1mm ID | 2 |
| ED-21932 | keeED2 | kerED1 | 0.70 mA | 10mm x 1mm ID | 3 |
| ED-21950 | keeED3 | kerED2 | 0.88 mA | 10mm x 1mm ID | 3 |
| ED-21975 | keeED1 | kerED1 | 0.50 mA | 10mm x 1mm ID | 2 |
| ED-21983 | keeED2 | kerED2 | 0.70 mA | 10mm x 1mm ID | 2 |
| ED-21985 | keeED7 | kerED2 | 0.25 mA | 10mm x 1mm ID | 2 |
| ED-21987 | keeED7 | kerED3 | 0.25 mA | 10mm x 1mm ID | 2 |
| ED-21992 | keeED2 | kerED3 | 0.70 mA | 10mm x 1mm ID | 3 |
| ED-23004 | keeED1 | kerED3 | 0.50 mA | 10mm x 1mm ID | 3 |
| ED-23009 | keeED7 | kerED3 | 0.25 mA | 10mm x 1mm ID | 3 |
| ED-23012 | keeED2 | kerED3 | 0.70 mA | 10mm x 1mm ID | 2 |
| ED-23087 | keeED1 | kerED4 | 0.50 mA | 10mm x 1mm ID | 3 |
| ED-23088 | keeED3 | kerED3 | 0.88 mA | 10mm x 1mm ID | 3 |
| ED-23093 | keeED2 | kerED4 | 0.70 mA | 10mm x 1mm ID | 3 |
| ED-23099 | keeED5 | kerED4 | 0.35 mA | 10mm x 1mm ID | 2 |
| ED-23100 | keeED7 | kerED4 | 0.25 mA | 10mm x 1mm ID | 2 |
| ED-23145 | keeED1 | kerED1 | 0.50 mA | 10mm x 1mm ID | 2 |
| ED-23146 | keeED14 | kerED1 | 1.00 mA | 10mm x 1mm ID | 2 |
| ED-23147 | keeED10 | kerED1 | 2.00 mA | 10mm x 1mm ID | 2 |
| ED-23162 | keeED10 | kerED3 | 2.00 mA | 10mm x 1mm ID | 2 |
| ED-27045 | keeED2 | kerED1 | 0.70 mA | 10mm x 1mm ID | 3 |
| ED-27055 | keeED7 | kerED1 | 0.25 mA | 10mm x 1mm ID | 2 |
| ED-27288 | keeED11 | kerED3 | 1.98 mA | 10mm x 1mm ID | 2 |
| ED-27304 | keeED12 | kerED4 | 1.00 mA | 10mm x 1mm ID | 2 |
| ED-27305 | keeED11 | kerED4 | 1.98 mA | 10mm x 1mm ID | 2 |
| ED-27398 | keeED2 | kerED2 | 0.43 V | 10mm x 1mm ID | 2 |
| ED-27488 | keeED2 | kerED3 | 0.70 mA | 10mm x 1mm ID | 2 |
| ED-28331 | keeED5 | kerED4 | 0.35 mA | 10mm x 1mm ID | 3 |
| ED-29689 | keeED9 | kerED1 | 6.30 mA | 10mm x 1mm ID | 3 |
| | | | | | |
| EF-21763 | keeEF1 | kerEF1 | 0.85 mA | BTE | 2 |
| EF-21933 | keeEF1 | kerEF1 | 0.85 mA | BTE | 3 |
| EF-21935 | keeEF3 | kerEF1 | 1.56 mA | BTE | 3 |
| EF-21937 | keeEF2 | kerEF1 | 1.13 mA | BTE | 3 |
| EF-21942 | keeEF2 | kerEF1 | 1.13 mA | BTE | 2 |
| EF-21943 | keeEF2 | kerEF1 | 1.13 mA | BTE | 3 |
| EF-21958 | keeEF1 | kerEF1 | 0.85 mA | BTE | 3 |
| EF-23025 | keeEF3 | kerEF1 | 1.56 mA | BTE | 3 |
| EF-23094 | keeEF2 | kerEF1 | 1.13 mA | BTE | 3 |
| EF-23168 | keeEF6 | kerEF4 | 0.33 V | BTE | 2 |
| EF-26161 | keeEF5 | kerEF1 | 1.27 mA | BTE | 2 |
| EF-26348 | keeEF8 | kerEF6 | 0.14 V | BTE | 2 |
| EF-26356 | keeEF8 | kerEF6 | 0.14 V | BTE | 2 |
| EF-26363 | keeEF9 | kerEF1 | 2.49 mA | BTE | 2 |
| EF-26665 | keeEF12 | kerEF1 | 1.15mA | BTE | 2 |
| EF-27428 | keeEF2 | kerEF1 | 1.13 mA | BTE | 3 |
| EF-27534 | keeEF7 | kerEF1 | 2.82 mA | BTE | 2 |

| | | | | | |
|---|---|---|---|---|---|
| EF-27715 | keeEF3 | kerEF1 | 1.56 mA | BTE | 3 |
| EF-28321 | keeEF1 | kerEF1 | 0.85 mA | BTE | 3 |
| EF-29615 | keeEF3 | kerEF1 | 1.56 mA | BTE | 3 |
| EF-29734 | keeEF3 | kerEF1 | 1.56 mA | BTE | 3 |
| EF-29802 | keeEF10 | kerEF1 | 0.5 mA | BTE | 3 |
| | | | | | |
| EH-23030 | keeEH1 | kerEH1 | 0.71 mA | 10mm x 1mm ID | 2 |
| EH-23043 | keeEH1 | kerEH2 | 0.71 mA | 10mm x 1mm ID | 2 |
| EH-23044 | keeEH1 | kerEH1 | 0.71 mA | 10mm x 1mm ID | 2 |
| EH-23048 | keeEH3 | kerEH1 | 0.61 mA | 10mm x 1mm ID | 2 |
| EH-23050 | keeEH2 | kerEH1 | 1.03 mA | 10mm x 1mm ID | 2 |
| EH-23052 | keeEH4 | kerEH1 | 0.51 mA | 10mm x 1mm ID | 2 |
| EH-23053 | keeEH4 | kerEH2 | 0.51 mA | 10mm x 1mm ID | 2 |
| EH-23054 | keeEH1 | kerEH1 | 0.71 mA | 10mm x 1mm ID | 2 |
| EH-23061 | keeEH2 | kerEH2 | 1.03 mA | 10mm x 1mm ID | 3 |
| EH-23063 | keeEH1 | kerEH2 | 0.71 mA | 10mm x 1mm ID | 3 |
| EH-23066 | keeEH5 | kerEH1 | 0.43 mA | 10mm x 1mm ID | 2 |
| EH-23067 | keeEH5 | kerEH2 | 0.43 mA | 10mm x 1mm ID | 2 |
| EH-27157 | keeEH1 | kerEH2 | 0.71 mA | 10mm x 1mm ID | 2 |
| EH-27232 | keeEH6 | kerEH6 | 1.63 mA | 10mm x 1mm ID | 2 |
| EH-27250 | keeEH5 | kerEH1 | 0.43 mA | 10mm x 1mm ID | 2 |
| EH-29833 | keeEH2 | kerEH2 | 1.03 mA | 10mm x 1mm ID | 2 |
| | | | | | |
| EP-24073 | keeEP1 | kerEP1 | 0.032 V | 10mm x 1mm ID | 3 |
| EP-24074 | keeEP4 | kerEP1 | 0.032 V | 10mm x 1mm ID | 3 |
| EP-24075 | keeEP5 | kerEP1 | 0.032 V | 10mm x 1mm ID | 3 |
| EP-24106 | keeEP1 | kerEP3 | 0.032 V | 10mm x 1mm ID | 3 |
| EP-24107 | keeEP4 | kerEP3 | 0.032 V | 10mm x 1mm ID | 3 |
| EP-24108 | keeEP5 | kerEP3 | 0.032 V | 10mm x 1mm ID | 3 |
| EP-24123 | keeEP1 | kerEP2 | 0.032 V | 10mm x 1mm ID | 3 |
| EP-24124 | keeEP4 | kerEP2 | 0.032 V | 10mm x 1mm ID | 3 |
| EP-24125 | keeEP5 | kerEP2 | 0.032 V | 10mm x 1mm ID | 3 |
| EP-24135 | keeEP1 | kerEP6 | 0.032 V | 10mm x 1mm ID | 3 |
| EP-24136 | keeEP4 | kerEP4 | 0.032 V | 10mm x 1mm ID | 3 |
| EP-24137 | keeEP5 | kerEP4 | 0.032 V | 10mm x 1mm ID | 3 |
| EP-27103 | keeEP2 | kerEP1 | 0.032 V | 10mm x 1mm ID | 3 |
| EP-27104 | keeEP3 | kerEP1 | 0.032 V | 10mm x 1mm ID | 3 |
| EP-27107 | keeEP2 | kerEP3 | 0.032 V | 10mm x 1mm ID | 3 |
| EP-27108 | keeEP3 | kerEP3 | 0.032 V | 10mm x 1mm ID | 3 |
| EP-27109 | keeEP2 | kerEP2 | 0.032 V | 10mm x 1mm ID | 3 |
| EP-27110 | keeEP3 | kerEP2 | 0.032 V | 10mm x 1mm ID | 3 |
| EP-27202 | keeEP2 | kerEP6 | 0.032 V | 10mm x 1mm ID | 3 |
| EP-27284 | keeEP3 | kerEP4 | 0.032 V | 10mm x 1mm ID | 3 |
| | | | | | |
| ES-23126 | keeES1 | kerES1 | 0.025 V | 10mm x 1mm ID | 3 |
| ES-23127 | keeES2 | kerES1 | 0.025 V | 10mm x 1mm ID | 3 |
| ES-23139 | keeES1 | kerES2 | 0.025 V | 10mm x 1mm ID | 3 |
| ES-23140 | keeES2 | kerES2 | 0.025 V | 10mm x 1mm ID | 3 |
| ES-23153 | keeES1 | kerES4 | 0.025 V | 10mm x 1mm ID | 3 |
| ES-23154 | keeES2 | kerES4 | 0.025 V | 10mm x 1mm ID | 3 |
| ES-23166 | keeES1 | kerES1 | 0.025 V | 10mm x 1mm ID | 3 |
| ES-23167 | keeES2 | kerES1 | 0.025 V | 10mm x 1mm ID | 3 |
| ES-23171 | keeES1 | kerES3 | 0.025 V | 10mm x 1mm ID | 3 |
| ES-23172 | keeES2 | kerES3 | 0.025 V | 10mm x 1mm ID | 3 |
| ES-23174 | keeES1 | kerES2 | 0.025 V | 10mm x 1mm ID | 3 |
| ES-23175 | keeES2 | kerES2 | 0.025 V | 10mm x 1mm ID | 3 |

| | | | | | |
|---|---|---|---|---|---|
| FC-23265 | keeEH1 | kerFC2 | 0.71 mA | 10mm x 1mm ID | 2 |
| FC-23300 | keeEH1 | kerFC1 | 0.71 mA | 10mm x 1mm ID | 2 |
| FC-23306 | keeEH5 | kerFC2 | 0.43 mA | 10mm x 1mm ID | 2 |
| FC-26170 | keeFC2 | kerFC5 | 0.81 mA | 10mm x 1mm ID | 2 |
| FC-26171 | keeFC1 | kerFC5 | 1.63 mA | 10mm x 1mm ID | 2 |
| FC-26184 | keeFC3 | kerFC5 | 1.02mA | 10mm x 1mm ID | 2 |
| FC-26314 | keeEH6 | kerFC6 | 1.63 mA | 10mm x 1mm ID | 2 |
| FC-26654 | keeFC4 | kerFC5 | 2.41 mA | 10mm x 1mm ID | 2 |
| | | | | | |
| FD-23266 | keeFD1 | kerFD1 | 0.025 V | 10mm x 1mm ID | 3 |
| FD-23283 | keeFD2 | kerFD1 | 0.025 V | 10mm x 1mm ID | 3 |
| FD-23284 | keeFD1 | kerFD2 | 0.025 V | 10mm x 1mm ID | 3 |
| FD-23285 | keeFD2 | kerFD2 | 0.025 V | 10mm x 1mm ID | 3 |
| | | | | | |
| FH-23371 | keeFH2 | kerFH1 | 1.59 mA | 10mm x 1mm ID | 2 |
| FH-23373 | keeFH3 | kerFH1 | 1.14 mA | 10mm x 1mm ID | 2 |
| FH-23375 | keeFH1 | kerFH1 | 0.80 mA | 10mm x 1mm ID | 2 |
| FH-23377 | keeFH4 | kerFH1 | 0.56 mA | 10mm x 1mm ID | 2 |
| | | | | | |
| FK-23451 | keeFK1 | kerFK1 | 0.50 mA | 10mm x 1mm ID | 2 |
| FK-23466 | keeFK1 | kerFK1 | 0.50 mA | 10mm x 1mm ID | 2 |
| FK-23989 | keeFK6 | kerFK1vented | 0.085 V | 10mm x 1mm ID | 2 |
| FK-30018 | keeFK4 | kerFK1vented | 0.174 V | 10mm x 1mm ID | 2 |
| | | | | | |
| HC-23761 | keeHC1 | kerHC1 | 0.060 V | 10mm x 1mm ID | 2 |
| HC-23762 | keeHC2 | kerHC1 | 0.071 V | 10mm x 1mm ID | 2 |
| HC-23763 | keeHC3 | kerHC1 | 0.084 V | 10mm x 1mm ID | 2 |
| HC-23764 | keeHC4 | kerHC1 | 0.100 V | 10mm x 1mm ID | 2 |
| HC-23765 | keeHC5 | kerHC1 | 0.119 V | 10mm x 1mm ID | 2 |
| HC-23766 | keeHC6 | kerHC1 | 0.142 V | 10mm x 1mm ID | 2 |
| HC-23767 | keeHC7 | kerHC1 | 0.169 V | 10mm x 1mm ID | 2 |
| HC-23724 | keeHC8 | kerHC1 | 0.200 V | 10mm x 1mm ID | 2 |
| HC-23768 | keeHC9 | kerHC1 | 0.238 V | 10mm x 1mm ID | 2 |
| HC-23769 | keeHC10 | kerHC1 | 0.283 V | 10mm x 1mm ID | 2 |
| HC-23770 | keeHC11 | kerHC1 | 0.336 V | 10mm x 1mm ID | 2 |
| HC-23771 | keeHC12 | kerHC1 | 0.399 V | 10mm x 1mm ID | 2 |
| HC-23772 | keeHC13 | kerHC1 | 0.475 V | 10mm x 1mm ID | 2 |
| HC-23773 | keeHC14 | kerHC1 | 0.564 V | 10mm x 1mm ID | 2 |
| HC-23774 | keeHC15 | kerHC1 | 0.671 V | 10mm x 1mm ID | 2 |
| HC-23776 | keeHC16 | kerHC1 | 0.797 V | 10mm x 1mm ID | 2 |
| | | | | | |
| TEC-30006 | keeTEC1 | kerTEC1 | 0.154 V | BTE | 2 |
| TEC-30033 | keeTEC2 | kerTEC1 | 0.109 V | BTE | 2 |
| | | | | | |
| TWFK-23991 | twfk23991 | Module file name same as part number. | | | |
| TWFK-23992 | twfk23992 | keTWFK library requires keFK & keWBFK libraries be loaded | | | |
| TWFK-30017 | twfk30017 | LFD analog differs slightly from FK1vented | | | |
| | | | | | |
| WBFK-23990 | keewbfkHFD3 | kerwbfkHFD1 | 0.188 V | 10mm x 1mm ID | 2 |
| WBFK-30019 | keewbfkHFD1 | kerwbfkHFD1 | 0.094 V | 10mm x 1mm ID | 2 |
| WBFK-30058 | keewbfkHFD4 | kerwbfkHFD1 | 0.266 V | 10mm x 1mm ID | 2 |
| WBFK-30095 | keewbfkHFD1 | kerwbfkHFD1 | 0.094 V | 10mm x 1mm ID | 2 |
| | | | | | |
| WBFK-30000 | keeWBFK4 | kerWBFK1 | 0.211 V | 10mm x 1mm ID | 2 |
| WBFK-30042 | keeWBFK4 | kerWBFK1 | 0.211 V | 10mm x 1mm ID | 2 |
| WBFK-30055 | keeWBFK5 | kerWBFK1 | 0.300 V | 10mm x 1mm ID | 2 |

| | | | | | |
|---|---|---|---|---|---|
| WBHC-23902 | keeWBHC2 | kerWBHC1 | 0.071 V | 10mm x 1mm ID | 2 |
| WBHC-23903 | keeWBHC3 | kerWBHC1 | 0.084 V | 10mm x 1mm ID | 2 |
| WBHC-23904 | keeWBHC4 | kerWBHC1 | 0.100 V | 10mm x 1mm ID | 2 |
| WBHC-23905 | keeWBHC5 | kerWBHC1 | 0.119 V | 10mm x 1mm ID | 2 |
| WBHC-23906 | keeWBHC6 | kerWBHC1 | 0.142 V | 10mm x 1mm ID | 2 |
| WBHC-23907 | keeWBHC7 | kerWBHC1 | 0.169 V | 10mm x 1mm ID | 2 |
| WBHC-23908 | keeWBHC8 | kerWBHC1 | 0.200 V | 10mm x 1mm ID | 2 |
| WBHC-23909 | keeWBHC9 | kerWBHC1 | 0.238 V | 10mm x 1mm ID | 2 |
| WBHC-23910 | keeWBHC10 | kerWBHC1 | 0.283 V | 10mm x 1mm ID | 2 |
| WBHC-23911 | keeWBHC11 | kerWBHC1 | 0.336 V | 10mm x 1mm ID | 2 |
| WBHC-23912 | keeWBHC12 | kerWBHC1 | 0.399 V | 10mm x 1mm ID | 2 |
| WBHC-23913 | keeWBHC13 | kerWBHC1 | 0.475 V | 10mm x 1mm ID | 2 |
| WBHC-23914 | keeWBHC14 | kerWBHC1 | 0.564 V | 10mm x 1mm ID | 2 |
| WBHC-26825 | keeWBHC10 | kerWBHC1 | 0.283 V | 10mm x 1mm ID | 2 |
| WBHC-26836 | keeWBHC10 | kerWBHC1 | 0.283 V | 10mm x 1mm ID | 2 |
| WBHC-26892 | keeWBHC11 | kerWBHC1 | 0.336 V | 10mm x 1mm ID | 2 |

## FERROFLUID-DAMPED RECEIVERS

| MODEL # | KEExxx | KERxxx | Nominal Drive | Tubing | # Pads |
|---|---|---|---|---|---|
| **FED-21932-i06** | keeED2 | kerFED6 | 0.44 V | 10mm x 1mm ID | 3 |
| FED-21932-i04 | keeED2 | kerFED4 | 0.44 V | 10mm x 1mm ID | 3 |
| FED-21932-i02 | keeED2 | kerFED2 | 0.44 V | 10mm x 1mm ID | 3 |
| | | | | | |
| **FED-23732-i06** | keeED2 | kerFED6 | 0.44 V | 10mm x 1mm ID | 2 |
| FED-23732-i04 | keeED2 | kerFED4 | 0.44 V | 10mm x 1mm ID | 2 |
| FED-23732-i02 | keeED2 | kerFED2 | 0.44 V | 10mm x 1mm ID | 2 |
| | | | | | |
| **FED-23147-i06** | keeED10 | kerFED6 | 0.146 V | 10mm x 1mm ID | 2 |
| FED-23147-i04 | keeED10 | kerFED4 | 0.146 V | 10mm x 1mm ID | 2 |
| FED-23147-i02 | keeED10 | kerFED2 | 0.146 V | 10mm x 1mm ID | 2 |
| | | | | | |
| **FED-29457-i06** | keeED2 | kerFED6 | 0.44 V | 10mm x 1mm ID | 2 |
| FED-29457-i04 | keeED2 | kerFED4 | 0.44 V | 10mm x 1mm ID | 2 |
| FED-29457-i02 | keeED2 | kerFED2 | 0.44 V | 10mm x 1mm ID | 2 |
| | | | | | |
| **FEH-27232-i06** | keeEH6 | kerFEH6 | 0.24 V | 10mm x 1mm ID | 2 |
| FEH-27232-i04 | keeEH6 | kerFEH4 | 0.24 V | 10mm x 1mm ID | 2 |
| FEH-27232-i02 | keeEH6 | kerFEH2 | 0.24 V | 10mm x 1mm ID | 2 |
| | | | | | |
| **FEP-24074-i06** | keeEP4 | kerFEP6 | 0.032 V | 10mm x 1mm ID | 3 |
| FEP-24074-i04 | keeEP4 | kerFEP4 | 0.032 V | 10mm x 1mm ID | 3 |
| FEP-24074-i02 | keeEP4 | kerFEP2 | 0.032 V | 10mm x 1mm ID | 3 |
| | | | | | |
| **FES-23127-i04** | keeES2 | kerFES4 | 0.025 V | 10mm x 1mm ID | 3 |
| FES-23127-i02 | keeES2 | kerFES2 | 0.025 V | 10mm x 1mm ID | 3 |
| | | | | | |
| **FFC-6171-i04** | keeFC1 | kerFFC34 | 0.24 V | 10mm x 1mm ID | 2 |
| FFC-6171-i02 | keeFC1 | kerFFC32 | 0.24 V | 10mm x 1mm ID | 2 |
| | | | | | |
| **FFD-23284-i04** | keeFD1 | kerFFD4 | 0.025 V | 10mm x 1mm ID | 3 |
| FFD-23284-i02 | keeFD1 | kerFFD2 | 0.025 V | 10mm x 1mm ID | 3 |
| | | | | | |
| **FFH-23375-I06** | keeFH1 | kerFFH6 | 0.25 V | 10mm x 1mm ID | 2 |
| FFH-23375-I04 | keeFH1 | kerFFH4 | 0.25 V | 10mm x 1mm ID | 2 |
| FFH-23375-I02 | keeFH1 | kerFFH2 | 0.25 V | 10mm x 1mm ID | 2 |

## MICROPHONES

All microphone analogs have new circuit topology for noise modeling. However only select models have been verified to have the correct noise spectrum. A “(N)” designation in the third column indicates that an analog will accurately simulate noise. See Appendix D. for more information.

| MODEL # | KEMxxx | |
|---|---|---|
| EA-21842 | kemEA1 | |
| EA-21843 | kemEA19 | |
| EA-21845 | kemEA20 | |
| EA-21867 | kemEA3 | |
| EA-21868 | kemEA2 | |
| EA-21939 | kemEA8 | |
| EA-21972 | kemEA18 | |
| EA-21986 | kemEA1 | |
| EA-23003 | kemEA9 | |
| EA-23006 | kemEA11 | |
| EA-23015 | kemEA9 | |
| | | |
| EK-23024 | kemEK1 | |
| EK-23027 | kemEK5 | |
| EK-23028 | kemEK2 | |
| EK-23029 | kemEK3 | |
| EK-23032 | kemEK8 | |
| EK-23033 | kemEK9 | |
| EK-23092 | kemEK7 | |
| EK-23132 | kemEK10 | |
| EK-23133 | kemEK11 | |
| | | |
| EL-29924 | kemEL.txt | directional |
| | | |
| EM-23046 | kemEM1 | (N) |
| EM-23047 | kemEM2 | |
| EM-23058 | kemEM4 | |
| EM-23059 | kemEM3 | |
| | | |
| EM-23346 | kemEM10 | (N) |
| EM-23368 | kemEM11 | (N) |
| EM-23976 | kemEM15 | |
| EM-24346 | kemEM12 | (N) |
| EM-24368 | kemEM13 | (N) |
| EM-25346 | kemEM14 | |
| EM-26739 | kemEM16 | |
| | | |
| EM-26091 | kemEM20 | directional |
| | | |
| FG-23329 | kemFG1 | (N) |
| FG-23452 | kemFG2 | |
| FG-23453 | kemFG3 | |
| FG-23629 | kemFG11 | |
| FG-23652 | kemFG12 | |
| FG-23653 | kemFG14 | |
| FG-26163 | kemFG4 | |
| FG-26480 | kemFG13 | |

| | | | |
|---|---|---|---|
| TM-23546 | kemTM1 | (N) | |
| TM-24546 | kemTM2 | (N) | |
| TO-24603 | keTOTDTP.txt | | |
| TO-24606 | keTOTDTP.txt | | |
| TD-24607 | keTOTDTP.txt | directional | |
| Pairs | Omni | Directional | |
| TP-24612 | TO-24606 | TD-24607 | keTOTDTP.txt |

# Appendix B

## List of Special Components
## Modules / Subcircuits for Tubing, Couplers, and Sources

**Tubing:**

| | | |
|---|---|---|
| KET001 | BTE (ear hook simulator + tubing) | [8mm x 1.0mm ID] + [28mm x 1.5mm ID] + [25mm x 2.0mm ID] + [18mm x 3.0mm ID] |
| KET002 | ITE tubing | [10 mm x 1.0mm ID] |
| ~~KET003~~ | obsolete | |
| KET004 | no tube | |
| | BTE (tubing + HA-2 coupler) | [38.1mm x 1.35mm ID] + [18mm x 3.0mm ID] |

All KETxxx.TXT modules use NEW tube model subcircuits.

Subcircuits for new tube models available in Knowles.lib (cgs and SI units)

**Couplers:**

| | |
|---|---|
| KEC001 | 2cc coupler |
| KEC002 | Zwislocki coupler |

Other subcircuits available in Knowles.lib file such as B&K 711 coupler

**Sources:**

| | |
|---|---|
| KEIxxx | constant current source, where xxx = x.xx mA (035=0.35mA) |
| KEVxxx | constant voltage source, where xxx = x.xx V (003=0.032V) |
| KEAxxx | constant power source, where xxx = input resistor (037=368 Ohms, 1mW) |
| KESxxx | sound source (dB SPL) |

**End of File:**

| | |
|---|---|
| KEF001 | .END for circuit with .PROBE |
| KEF002 | .END for circuit |

| **Node Numbers:** | range |
|---|---|
| KEVxxx, KEIxxx, KEAxxx | 500-502, 529 |
| KEExxx & KERxxx | 501-519 |
| KETxxx | 504, 506, 531-559 |
| KECxxx | 506, 507, 561-569 |
| KEMxxx | 571-599 |

# Appendix C

## Add Knowles Libraries to Orcad Schematics or Capture Parts Browser

The electrical analogs of Knowles Electronics transducers can be added to the Parts Browser of Orcad Schematics and Orcad Capture. To place a transducer on your schematic, simply type the Knowles part number into the Parts Browser without a dash (e.g., ED1913). The analog libraries consist of subcircuit definitions which are identical to the netlist modules. The KNOWLES.LIB library contains parts that simulate standard ITE and BTE tubing, $2cm^3$ coupler cavity, IEC711 and Zwislocki ear simulators, and more. The receiver and microphone libraries are organized according to the series name. For example, the ED1913 analog is in the keED library files (e.g., .SLB, .LIB, and .OLB). All analogs require both symbol libraries (e.g., ED.SLB) and model libraries (e.g., ED.LIB) to run. Follow the directions in the next sections to configure Schematics or Capture to use these libraries.

**LIBRARY FILES**

The Electrical Analogs Release 9 Zip file contains modules and libraries in both Orcad Schematics and Orcad Capture formats. I recommend copying the Knowles library files to the UserLib directory. Default path to UserLib for Capture version 9.2 is: C:\Cadence\PSD_14.2\tools\pspice\UserLib.

### SCHEMATICS

**ADDING A SYMBOL LIBRARY (.SLB)**

**1.** Select *Editor Configuration...* from the *Options* menu to display the Editor Configuration dialog box.
**2.** Click on the *Library Settings* button to display the Library Settings dialog box.
**3.** There are two ways to add a new library to your list of global libraries:
(i) Type the library name including the path into the text box. Do not type the file extension .SLB.
C:\MSim_8\UserLib*library_name* or C:\MSim_8\UserLib*folder_name**library_name*
(ii) Click on the *Browse* button to locate the library file. Select the library file and click on the *Open* button. The library name and path will be displayed in the Library Settings dialog box.
**4.** Click on *Add** to include the library in the list of global libraries that are available to all schematics designs. See the Orcad manuals for more information on local and global libraries.

Repeat steps 1-4 to install more symbol libraries.

**ADDING A MODEL LIBRARY (.LIB)**

**1.** Select *Library and Include Files..* from the *Analysis* menu to display the Library dialog box (Fig. C4).
**2.** There are two ways to add a new model library:
(i) Type the library name including the path into the text box. Do not type the file extension .lib.
C:\MSim_8\UserLib*library_name* or C:\MSim_8\UserLib*folder_name**library_name*
(ii) Click on the *Browse* button to locate and open the library file in the UserLib folder. Select the library file and click on the *Open* button. The library name and path will be displayed in the Library dialog box.
**3.** Click on *Add Library** to include the library in the list of global libraries
Repeat steps 1-3 to install more model libraries.

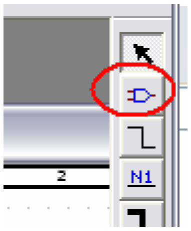
### CAPTURE

The OLB file is the package file which contains the part graphic, pin definitions and properties. It defines the appearance of the part on the schematics page. The LIB file contains the .MODEL and the .SUBCKT statements. The LIB file is the PSpice model. It is the programming language that defines the part. If you see the part on your schematic but receive an error "Model __*MODEL or SUBCKT name*__ used by __*Part name*__ is undefined", then Capture sees only the OLB package file. You must point the program to the LIB file by editing the PSPICE.INI file.

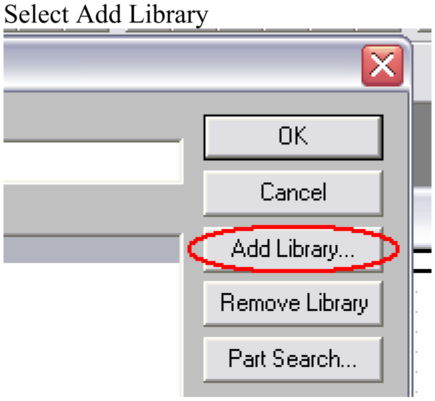
The next part of this section will instruct you on how to load the OLB files, edit Capture settings to locate the LIB files, and purge the Design Cache to ensure that all parts are the most current revisions without modifications. Unfortunately, it is easy to break the link between the part in design cache (on your schematic) and the library part in OLB/LIB libraries. The part on the schematic becomes a local instance and does not update when the library is updated. I recommend reading the manual for more detailed information on Capture libraries: "Capture Users Guide Version 9.2.3" chapters 11 and 12 (file: capug.pdf).

**ADDING A SYMBOL (PACKAGE) LIBRARY (.OLB)**

1. Copy all library files (.OLB & .LIB) to your preferred directory.
   EXAMPLE: C:\Cadence\PSD_14.2\tools\pspice\UserLib
2. Open any project file and then open the schematic page.
3. Click on the Place Part Icon




4. Select Add Library




5. Locate the OLB library files, select the file and click the OPEN button
6. The library now appears in the Parts Browser. It will be available in all Project files (i.e., not just the open project but all project files).

**ADDING A MODEL LIBRARY (.LIB)**
I prefer to edit the PSPICE.INI with a text editor. You may also be able to make these changes within the program. The most important lines are copied below. You should make changes to the path statements to match the file structure on your hard drive.

**PSPICE.INI**
Default file location = C:\Cadence\PSD_14.2\tools\pspice

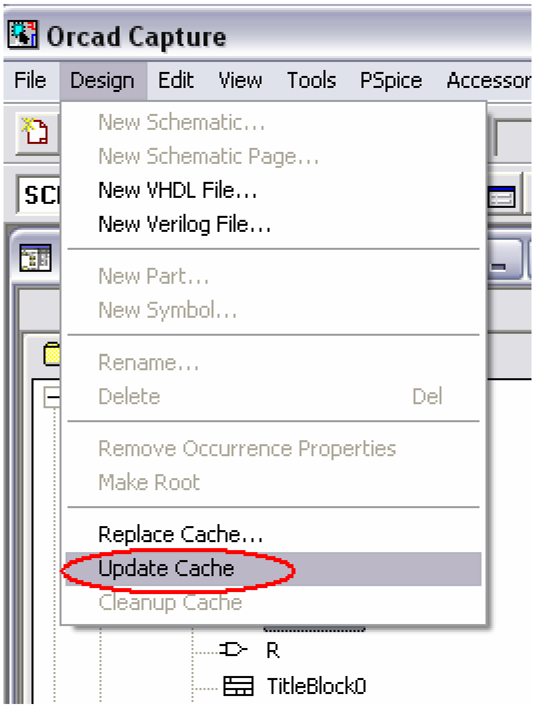
[PSPICE]
**LIBPATH=""C:\Cadence\PSD_14.2\tools\PSpice\UserLib";"C:\Cadence\PSD_14.2\tools\PSpice\Library""**
*Make sure that the search path includes the directory containing the Knowles libraries as shown above.*

[PSPICE NETLIST]
LINE1=.lib "nom.lib"
LINE2=
*Many libraries may be listed in this section depending on your configuration. Add new libraries to the end of the list as shown below.*
**LINE3=.lib "C:\Cadence\PSD_14.2\tools\pspice\UserLib\Knowles.lib"**

**Update the Design Cache**
You may already see parts from these libraries listed in the Design Cache. However, it is best to update your Project file to reference the original libraries. The Design Cache is not always current and can have outdated

versions of parts. In order to purge and update the cache, do the following:

1. Select the part or parts to update from the Design Cache list
2. Choose **Update Cache** from the Design menu to replace local instances of parts with the original library part. If **Update Cache** gives you an error message that it cannot find the library file then select **Replace Cache**.



# Appendix D
## Noise Simulations with Microphone Analogs

The circuit topology of microphone analogs was changed in Revision 6 to allow noise modeling. The newer analogs in Revision 6.1 and later (i.e., improved EM, FG and TM) will simulate acoustic and electrical noise.

**NOISE MODELING WITH SCHEMATICS OR CAPTURE**

The “Noise Enabled” option must be selected in the simulation setup or profile. The sound source (enter VAC for I/V) and output node (enter 584 for Output Voltage) must also be identified to run a noise simulation. In the Probe window, Trace Expression VDB(584) will display the frequency response and Trace Expression DB(SQRT(NTOT(ONOISE))) will display spectral noise.

**NOISE MODELING WITH NETLISTS**

The module files (i.e., KEMxxx) can be used with any PSpice circuit simulation program. The netlist shown below is set up to simulate the response of the FG-3329 microphone and includes the following:

- FG-3329 analog (KEMFG1)
- .AC sweep between 100 Hz and 10 kHz (60 points per decade)
- .NOISE enabled where 584 is the output node and VK501 is the voltage source
- .PROBE enabled to create data file
- VK501 is the 74 dB SPL sound source with a -70 dB correction (i.e., unit conversion)

The 1 volt input is equivalent to 74 dB SPL. Since the analogs are in cgs units, the output voltage at node 584 requires a –70 dB correction to convert erg to Watt/sec (i.e., `VdB(584)-70`). Rather than subtracting 70 dB from the output, I prefer to scale the voltage source: VK501=1 volt*0.3162E-3 where 70 dB=0.3162E-3.

```
*===============================================================
.AC DEC 60 100Hz 10kHz
VK501  581  0  AC  .3162E-3
*===============================================================
* KEMFG1
* FG-3329 standard FG (flat response)
* component values in SI units listed after the comment marker ";"

RK581         581 583  .600E+2 ; 6.00e+6
RK582         585 586  .660E+4 ; 6.60e+8
RK583         589   0  .100E+7 ; 1.00e+11
RK585         584   0  .220E+5 ; 2.20e+4

CK581           0 590  .250E-9 ; 2.50e-15
CK582         585 590  5.50E-9 ; 5.50e-14
CK583         587 588  2.23E-9 ; 2.23e-14
CK585           0 594  1.36E-12 ; 1.36e-12

LK581         583 590  .100E-1 ; 1.00e+3
LK582         586 587  .470E-1 ; 4.70e+3
LK583         585 589  .900    ; 9.00e+4

xTFMR1        588   0  594   0  TFMR PARAMS: PRI=1 SEC=111.854 ; 0.3537
M1            596 594  584 584  MOS_1
VK505         596   0  1.5

.SUBCKT TFMR   1   2   3   4   PARAMS:PRI=1 SEC=1
R1  1   2   9E+12
R3  3   4   9E+12
V1  1   5
G1  4   3   VALUE = {I(V1)*PRI/SEC}
E1  5   2   VALUE = {V(3,4)*PRI/SEC}
.ENDS

.MODEL MOS_1 NMOS
+ GAMMA=0.5 KP=61.85u L=3.6u LEVEL=1 VTO=-0.5 W=100u
+ RD=2.75k RS=2.75k RSH=30 NLEV=2 AF=0.8 KF=3E-25

*===============================================================
.NOISE V(584)  VK501
.PROBE
```

```
.END
*===============================================================
```

The netlist can be opened into a program such as Orcad PSpice and a simulation can be run which creates a data file. The results can be plotted in Orcad Probe™. The sensitivity of the FG (i.e., dB V relative to 1 V/0.1 Pa) is given by `VDB(584)` where node 584 is the electrical output node. Since I choose to scale the input voltage in this example, I do not need to subtract 70 dB from the output. **The spectral noise is given by DB(SQRT(NTOT(ONOISE))).** Noise modeling is available in only selected microphone analogs (see Appendix A).

# Appendix E

## Acoustical and Mechanical Analogs and Units

There are two types of analogs: mobility and impedance. In the impedance analog, mechanical force or sound pressure is equated with voltage and velocity or volume velocity is represented by current. In the mobility analog, the reverse is true. Voltage represents velocity and current equates force or pressure. Both methods produce equivalent results. We use the impedance analog to define equivalent circuit elements for the components in the Knowles microphones and receivers. Table E1 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<br>**R** (Ohms) | Resistance<br>$\mathbf{r_m}$ | $gm*sec^{-1}$ | Drag in a viscous fluid or damping | Resistance<br>$\mathbf{R_A}$ | $gm*cm^{-4}*sec^{-1}$ | Air flow through a screen |
| Inductance<br>**L** (Henries) | Mass<br>**m** | gm | Mass | Inertance<br>**M** | $gm*cm^{-4}$ | Air in a tube |
| Capacitance<br>**C** (Farads) | Compliance<br>$\mathbf{c_m}$ | $sec^2*gm^{-1}$ | Spring | Compliance<br>$\mathbf{C_A}$ | $gm^{-1}*cm^4*sec^2$ | Air in a cavity |
| Voltage<br>**V** (Volts) | Force<br>**F** | $gm*cm*sec^{-2}$ | | Pressure<br>**P** | $gm*cm^{-1}*sec^{-2}$ | |
| Current<br>**i** (Amperes) | Velocity<br>**v** | $cm*sec^{-1}$ | | Volume velocity<br>**u** | $cm^3*sec^{-1}$ | |

**Table E1**: Acoustical and mechanical quantities and their electrical analogs.

# Appendix F
## Netlist Modules and Library Subcircuits

Electrical Analogs for Knowles Electronics Transducers are designed to be used with a PSpice circuit analysis program. The library files (*.LIB) are text files containing subcircuit definitions of over 300 transducers. These subcircuits use the standard PSpice format. Even if you are not using the Orcad circuit simulator, you may find these files helpful for your own circuit program. This section contains detailed information on node numbers and device specifications for using these analogs in your models.

<u>Node Numbering, Device Specifications, & Modules</u>
The electrical analogs observe the same constraints as previously released models (described in reports 10531-1 and 10531-2). The constraints for node numbers and for device specifications are:

- All device and node numbers are in the range <u>400 to 699</u>.

- To distinguish parts of these analog modules from others in your application, all device specifications have the letter 'K' after the reserved device specifying letter. That is, all capacitor devices in the analog have a designation such as CK5xx.

- The programs are grouped by functional modules. Each module has a generic name and a serial identification. The block diagrams in Fig. F1. show the layout of nodes for attachment to the program modules that are provided.

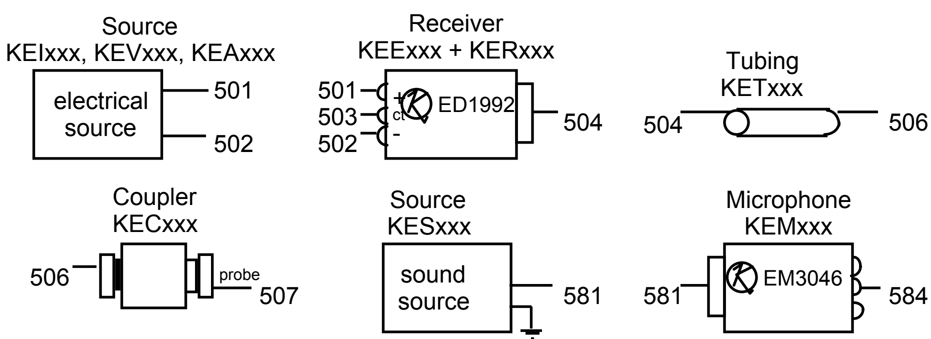



**FIG. F1:** Module names and terminating node numbers for the transducer analogs.

<u>Receiver Modules, Node Numbers and Subcircuits</u>
PSpice receiver simulation must contain the appropriate combination of KEExxx and KERxxx modules. The generic module names are listed below followed by xxx to indicate the three-digit serial number. Appendix A. has a list of all available transducer models and their associated modules (i.e., module name + serial number).

| Module Name | Description |
|---|---|
| KEExxx | electrical parameters of a particular receiver |
| KERxxx | basic transducer construction |
| KETxxx | acoustic transmission paths |
| KECxxx | standard test couplers |
| KEFxxx | program termination modules: KEF001 enables .PROBE and exits the program and KEF002 exits the program. |

Three types of receiver input modules are included. They set up an AC analysis from 100 Hz to 10 kHz with 100 points per decade.

KEIxxx provide input conditions to simulate the constant current conditions such as an amplifier with high output impedance. They represent values frequently found on Knowles product specifications, Sheet 2.1. The three digits specify the hundredth's of rms milliamperes (e.g., KEI033 = 0.33 mA AC constant current source).

KEVxxx provide input conditions to simulate the constant voltage conditions such as an amplifier with low output impedance. They are also appropriate for the amplified versions of receiver transducers. They represent values frequently found on Knowles product specifications, Sheet 2.1. The three digits specify the hundredth's of rms volts (e.g., KEV100 = 1.00 volt AC constant voltage source).

KEAxxx provides input conditions to simulate the maximum available power conditions (MAP) such as an amplifier with finite output impedance and is not limited by other considerations. The maximum power available from these sources is 1 mW. They represent values found on Knowles product specifications, Sheet 2.1. The three digits specify the source impedance in tens of ohms.

All Knowles electrical analogs are restricted to node numbers in the range 400 to 699. Specific node numbers are reserved for terminating each module and joining modules.

501 the positive electrical terminal in any KEExxx module.

502 the negative electrical terminal in any KEExxx module.

503 the center-tap of any three terminal receiver represented by a KEExxx module. While the node will always be present, it should only be used when the device being examined has three terminals.

For Knowles amplified receivers (i.e., EP and ES), node 503 provides a access point where power supply feedback can be introduced. As the program is supplied, a 0.0 volt D.C. source (VK502) is connected to this node to satisfy program requirements.

504 the acoustical terminal of any KERxxx module. It will also be the node number of the input end of any KETxxx acoustical transmission line.

505 joins the KEExxx and KERxxx modules. No other interpretation should be attached to the function of this node.

506 the output terminal of any KETxxx transmission path module and the input terminal of any KECxxx coupler module.

507 the output terminal of any KECxxx coupler module. It will yield the sound pressure at the microphone in the coupler.

**When the input is in terms of volts and amperes the output energy is in terms of watt-seconds. To convert a node voltage to dB SPL you must add 144 dB**. The usual query would be DB(V(507))+144 (or DBV(507)+144) for the SPL in a coupler. (70 dB of this factor is to change from a watt-second to an erg reference frame and 74 dB to change from dynes/cm$^2$ to 0.0002 dynes/cm$^2$ which is the 0 dB SPL reference level.). The 70dB factor is a consequence of using cgs units for acoustical and mechanical analogs (i.e., centimeter-gram-second unit system).

A receiver requires two module files KEExxx and KERxxx. This allows many combinations of coils and damping within one series of receivers (see Appendix A). The library files (*.LIB) define all of the module files as subcircuits. The library format has changed from Rev 6 making it easier to create new analogs with existing modules files and to make updates. The *.SLB library file contains the part symbol, pin attributes, and links the symbol to the subcircuits.

Receiver subcircuit:

```
.SUBCKT ED1913  501 502 504
xKEE  501 502 503 505 KEEED1
xKER  505 504         KERED1
.ENDS
```

<u>Microphone Modules, Node Numbers and Subcircuits</u>

The circuit topology of the microphone analog has been changed from the original topology used in previous releases (i.e., Release 1 through 5). This change was necessary to provide the option for noise modeling which is available for some selected analogs (see Appendices A). The microphone modules have the designation KEMxxx and utilize the node numbers between 581 and 599. The device designations follow the convention used for receivers. All Knowles microphones are active devices. No attempt has been made to simulate the D.C. voltage levels. There is no substantial bidirectional interaction between the acoustical and electrical portions of the analog. KESxxx modules are supplied to apply a frequency independent sound pressure to input node of the microphone (i.e., node 581). The three digits xxx are the sound pressure in SPL. Modules are supplied for 50, 55, 60, 65, 70, 74 and 90 SPL.

The applied voltage is numerically equal to the applied sound pressure in dynes/cm$^2$ (i.e., 1 volt is equivalent to 74dB SPL). The electrical output signal is volts and /or amperes. **70 dB must be subtracted from the output voltage** or scale the input voltage by -70dB (i.e., scale sound source by 1/3162). The 70 dB of this factor is to change from a watt-second to an erg reference frame. The sound pressure is referenced to node 0 (i.e., ground). The electrical output signal is also referenced to node 0.

The new analogs observe the same constraints for node numbers and for device specifications as previously released modules.

581 the principal acoustical terminal. The electrical signal applied here is to be numerically equal to the applied sound pressure in dynes/cm$^2$ (i.e., 1 volt is equivalent to 74 dB SPL).

584 the electrical output node. The signal will be in volts and/or amperes.

VK581 is a dummy voltage source connected to node 595. It is included to provide a place to insert power supply fluctuations either through redefining it as an A.C. source or deleting it and inserting the power supply signal on node 585.