

# COMPUTER-AIDED DESIGN OF LOUDSPEAKER ENCLOSURES PART I

Here's how to let your computer predict an enclosure's performance.

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■The most-complex system is the ducted port enclosure. The other systems can be thought of as simplifications of this type. Figure 1 shows a cross section of a dynamic loudspeaker mounted in a ducted port enclosure. When driven at low frequencies, the behaviour of this system is simpler than it is at higher frequencies. The cone moves as a single, rigid mass. All the air inside the duct moves in

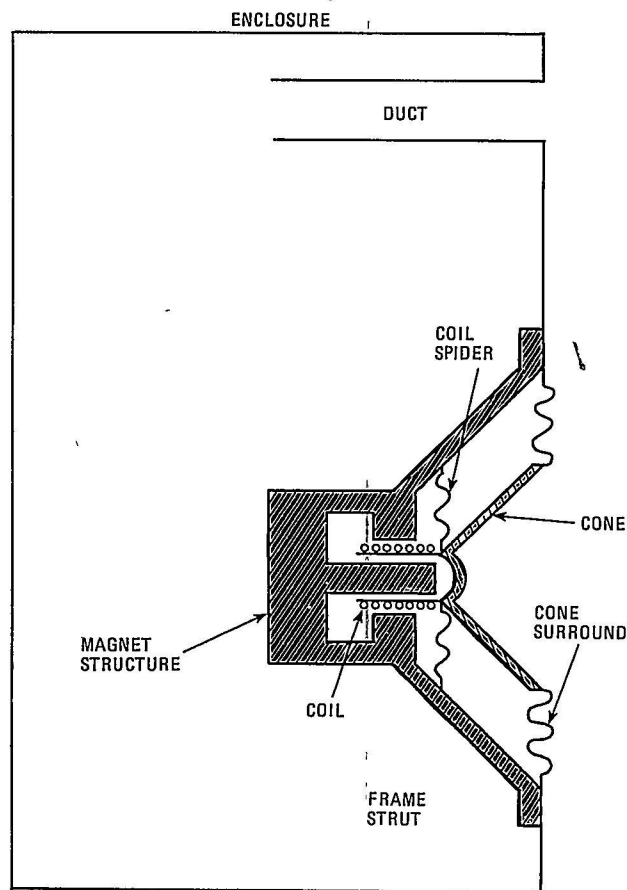


FIG. 1—CROSS SECTION of a dynamic woofer mounted in a ducted port enclosure.

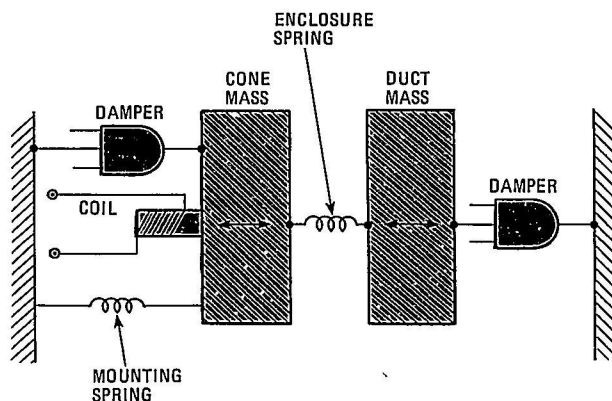


FIG. 2.—MECHANICAL SYSTEM, equivalent at low frequencies, to the speaker shown in Fig. 1. Cone mass and the mass of air are assumed to move only in one direction, indicated by arrows. Coil applies oscillatory force to cone in this direction. Dampers are sources of mechanical resistance. One end of each damper and mounting spring has a fixed point of attachment.

unison, acting as another single mass. The volume of air within the enclosure acts like a spring, coupling the cone mass to the mass of air in the duct. The front of both the cone and the air in the duct experience a frictional drag due to the acoustic power they radiate. This effect is called the radiation resistance, and is frequency dependent. The program retains only the first term in the Taylor expansion of the Bessel function that gives this frequency dependence. A small additional mass is added to the cone and the duct by the effect of the outside air and, here too, we keep only the first term of the Taylor expansion. Additional springiness and resistance result from the cone surround and the coil spider. More resistance is sometimes included in such enclosures in the form of fiberglass batting lining the box, across the port, or behind the woofer.

When the simplifications described are applicable, a ducted port enclosure behaves much like the lumped parameter mechanical device shown in Figure 2. For this mechanical system comprised of masses, springs and dampers there are two electrical circuits composed of capacitors, inductors and resistors which exhibit analogous behaviour. They have the same governing equations with a renaming of the quantities.

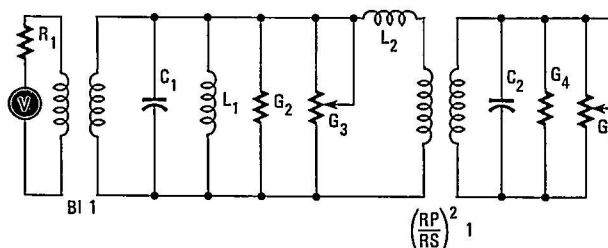


FIG. 3.—ELECTRICAL CIRCUIT analogous to systems in Figs. 1 and 2. Corresponding parameters are:  $R_1$  = Coil resistance,  $C_1$  = Mass of cone and co-moving air,  $L_1$  = Compliance of cone mountings,  $G_2$  = Mechanical resistance of cone mountings,  $G_3$  = Radiation resistance of cone,  $L_2$  = Compliance of enclosure volume,  $RP$  = Port (duct) radius,  $RS$  = Speaker radius,  $C_2$  = Mass of air in duct and co-moving air,  $G_4$  = Mechanical resistance,  $G_5$  = Radiation resistance of duct.

involved. In Figure 3, you see one of those circuits which is equivalent to Figure 2. The equivalent quantities are as follows.

Voltage = Velocity

Current = Force

Capacitance = Mass

Inductance = Spring Compliance

Electrical Conductance = Mechanical Resistance

Each mass in Figure 2 has associated with it a capacitor to ground in Figure 3 whose voltage is numerically equal to the velocity of the mass. The force being applied to the mass equals the current flowing into the capacitor. The sources of this current (force) are the resistors (dampers) and inductors (springs) attached to the capacitor (mass).

The computer program assumes that a 1-volt AC source is attached across the coil. The program establishes a set of differential equations (the node equations) which describe the behaviour of the circuit in Figure 3. The assumption of a steady-state response causes these equations to take the form of a set of simultaneous algebraic equations in terms of complex variables. These are solved for a selection of frequencies between 15 and 250 Hz. Outputs from the program include the acoustic intensity one meter from the speaker (resulting from the vector sum of the woofer and port amplitudes and given in watts per square meter), and the current drawn at the speaker terminals (which is the admittance since we assume a one-volt input, given in mhos). The program asks only for fundamental system parameters and does so using prompts to guide the user. Quantities such as the radiation resistances as a function of frequency are calculated internally. The program is listed and may be checked by running the design example described. The tabular output for this case is also given.

### Parameter measurements

There are several of the woofer parameters which must be determined experimentally. These include cone radius, DC coil resistance, the BI product for the magnet-coil combination, the compliance of the cone mountings, the free resonance of the woofer and the mechanical resistance of the cone mountings. Let's talk about how to make these measurements and present typical numbers from a design example using a 12-inch woofer. We use MKS units exclusively.

The effective cone radius may be measured from the center line of the cone to the mid-point of the cone surround. This number will be less than the nominal radius of the woofer. In the design example, the effective cone radius is 125 meters (4.92 inches).

The DC resistance of the coil may be measured with a multimeter. For the design example, this was 5.3 ohms. (This number is not to be confused with the nominal AC impedance of eight ohms.)

The BI product is the product of the magnetic induction (B) in the magnet gap, and the length of coil wire, (l) in the gap. B is measured in Teslas. The BI product determines the force exerted on the cone for a given coil current. This product is measured, as shown in Figure 4, by placing the woofer face-up on a

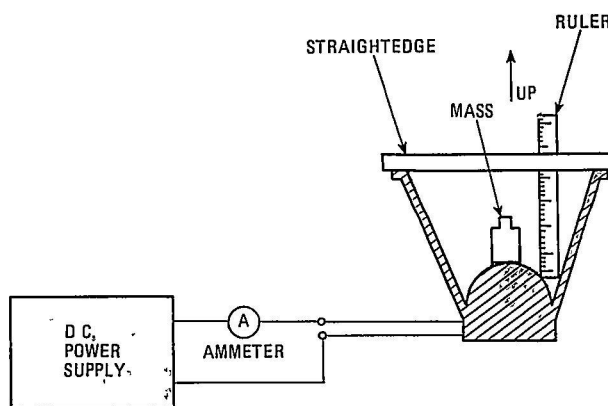


FIG. 4—ARRANGEMENT USED to measure the BI product and the mounting compliance.

horizontal surface with a DC power supply and an ammeter attached to the coil. A straightedge is laid across the face of the woofer, and a light plastic ruler is stood upright in the cone so that the vertical position of the cone may be measured. Determine the position of the cone with no current in the coil, a known mass (M) is then carefully placed in the cone and current (I) necessary to lift the cone and mass back to the unloaded position is determined. The BI product is then given as

$$C \left( \frac{M}{Nt} \right) = \frac{d (M)}{9.81 \times M (kg)}$$

The design example needed 237 amps to lift a 305 Kilogram mass back to the unloaded position, implying a BI of 12.6 (T × M)

The compliance is also measured while the woofer is lying on its back with the straightedge and plastic ruler in place. The power supply is disconnected. The distance, d, which the mass causes the cone to depress is determined from the difference in the readings on the plastic ruler in both loaded and unloaded conditions. The compliance is then given by

$$BI (T \times M) = \frac{9.81 \times M (kg)}{I (A)}$$

For the design example, the 305 kilogram mass depressed the cone by .002 meters thereby implying a compliance of .000668 (Meters/Newton)

The free resonance and mechanical resistance of the woofer are determined using the arrangement shown in Figure 5. The bare woofer is suspended in a large room away from any objects or walls. We measure the current drawn and the voltage applied at various frequencies. At each frequency, we divide the current by the voltage to obtain the admittance. Note that if the same multimeter is used for both current and

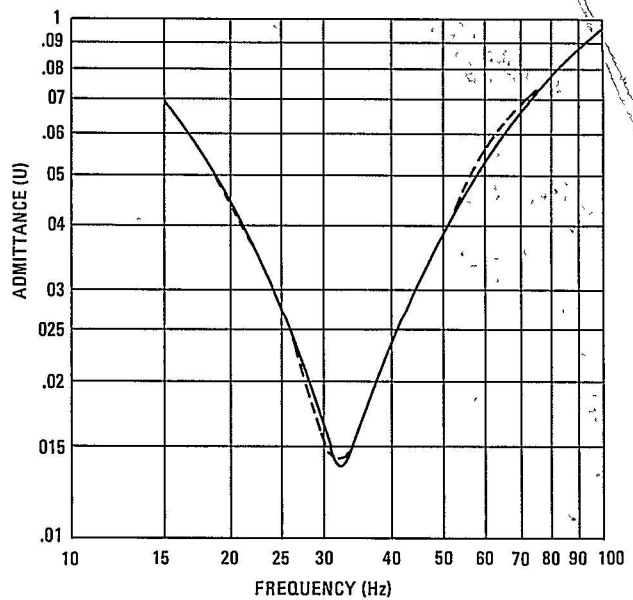


Fig. 5—HOW WOOFER ADMITTANCE was measured. Admittance is used as a diagnostic to determine several parameters.

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10 DIM G(4,4)
20 DIM C(4,4)
30 DIM B(4,4)
40 DIM A(4,4)
50 DIM T(4)
55 E=1
60 INPUT "COIL RESISTANCE?";RC
70 INPUT "MOUNTING COMPLIANCE?";MC
80 INPUT "SPEAKER RADIUS?";RS
90 INPUT "ENCL VOLUME?";V
100 INPUT "BL PRODUCT?";BL
110 INPUT "FREE RESONANCE?";FO
120 INPUT "PORT RADIUS?";RP
130 INPUT "PORT LENGTH?";LP
134 INPUT "SPEAKER DAMPING?";SD
136 INPUT "PORT DAMPING?";PD
140 B1=1/MC
150 C1=B1/(39.478418*FO*FO)
160 B2=1.43E6*RS*RS*RS*RS/V
170 C2=(3.03*LP+5.67*RP)*RS*RS*RS*RS/(RP*RP)
180 B(1,1)=-B1+B2
190 B(1,3)=B2
200 B(2,2)=-B1+B2
210 B(2,4)=B2
220 B(3,1)=B2
230 B(3,3)=-B2
240 B(4,2)=B2
250 B(4,4)=-B2
260 C(1,1)=C1
270 C(2,2)=C1
280 C(3,3)=C2
290 C(4,4)=C2
300 IS=BL/RC
305 PRINT#-2,TAB(5)"FREQ. ";TAB(28);"POWER";TAB(48)"ADMIT."
306 PRINT#-2
310 F=10
320 FOR Z=1 TO 48
330 F=F+5
340 G0=.219*F*F*RS*RS*RS*RS
350 G1=G0+BL*BL/RC+SD
360 G(1,2)=G1
370 G(2,1)=-G1
375 G2=G0+PD
380 G(3,4)=G2
390 G(4,3)=-G2
400 FOR I=1 TO 4
410 FOR J=1 TO 4
420 A(I,J)=39.4784*F*F*C(I,J)+6.2832*F*G(I,J)+B(I,J)
430 NEXT J
440 NEXT I
450 GOSUB 1010
460 A0=D
470 FOR I=1 TO 4
480 T(I)=A(I,1)
490 A(1,1)=0
500 NEXT I
510 A(2,1)=-6.2832*F*IS
520 GOSUB 1010
530 A1=D
540 FOR I=1 TO 4
550 A(1,1)=T(I)
560 T(I)=A(I,2)
570 A(1,2)=0
580 NEXT I
590 A(2,2)=-6.2832*F*IS
600 GOSUB 1010
610 A2=D
620 FOR I=1 TO 4
630 A(1,2)=T(I)
640 T(I)=A(I,3)
650 A(1,3)=0
660 NEXT I
670 A(2,3)=-6.2832*F*IS
680 GOSUB 1010
690 A3=D
700 FOR I=1 TO 4
710 A(1,3)=T(I)
720 A(1,4)=0
730 NEXT I
740 A(2,4)=-6.2832*F*IS
750 GOSUB 1010
760 VA=A1/A0
770 VB=A2/A0
780 VC=A3/A0
790 VD=-D/A0
792 IA=IS-VA*BL*BL/RC
794 IB=-VB*BL*BL/RC
796 IM=SQR(IA*IA+IB*IB)/BL
800 P=3.49E-2*(F^2*RS^4)
810 PS=P*((VA+VD)*(VA+VD)+(VB+VD)*(VB+VD))
880 PRINT#-2,TAB(5)F;TAB(25)PS;TAB(45)IM
900 NEXT Z
910 END
1010 D=0
1020 FOR I=1 TO 4
1030 FOR J=1 TO 4
1040 IF J=I THEN GOTO 1220
1050 FOR K=1 TO 4
1060 IF K=I THEN GOTO 1210
1070 IF K=J THEN GOTO 1210
1080 FOR X=1 TO 4
1090 IF X=I THEN GOTO 1200
1100 IF X=J THEN GOTO 1200
1110 IF X=K THEN GOTO 1200
1120 D=D+E*A(I,1)*A(2,J)*A(3,K)*A(4,X)
1125 E=-E
1200 NEXT X
1210 NEXT K
1220 NEXT J
1230 NEXT I
1240 RETURN

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-- -- EXPERIMENT  
— — SIMULATION

**FIG. 6—MEASURED AND COMPUTER SIMULATED admittance of the woofer used as a design example in text. Curves represent behaviour of bare, unenclosed woofer.**

voltage measurements, the low-frequency roll-off of that instrument is cancelled in the division of one quantity by the other. A graph of the admittance for our design example is offered in Figure 6. The free resonance is that frequency at which the minimum admittance occurs (33 Hz for the design example.)

We determine the mechanical resistance by running the computer program with various assumed mechanical resistances until the computed admittance versus frequency matches the experimental results (Fig 6). In the program we approximate suspending the bare woofer in a large room by assuming a very large enclosure volume (1000 cubic meters) and port dimensions (001 meter radius, 1000 meter length) for which the port has no effect at any frequency of interest. The design example shows a good match between the computer result and the experimental measurement for an assumed mechanical resistance of 2.45 mechanical ohms.

### Computer experiments with various enclosures

Continuing with the design example previously introduced, we use the measured parameters and compute the response for this woofer in several different enclosures. Figure 7 shows the response given by an infinite baffle of 2 cubic meters. For this run, the lack of a port is simulated by using a port radius of 001 meters and a port length of 1000 meters. As it happens, this is a rather lightweight woofer and does not perform well in a small closed box. The frequency response begins to roll off above 100 Hz.

We're sorry, but we've run out of space in this issue. This article will be concluded next month.