Win An Edgarhorn
See Sweepstakes, p. 53

HOW TO CHOOSE A GOOD CROSSOVER COIL

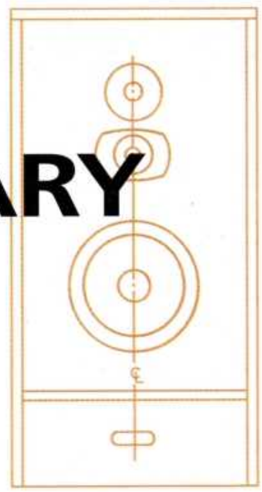
SIX: 1996

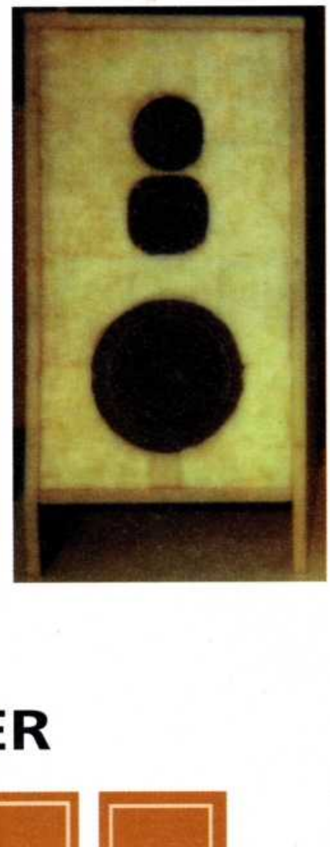
US$7.00
CANADA $8.00

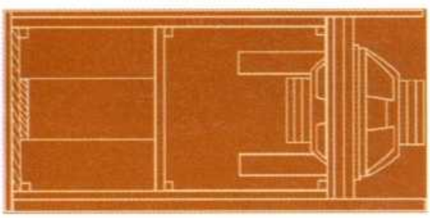
Speaker Builder

THE LOUDSPEAKER JOURNAL

BUILD THIS EXTRAORDINARY LOW-COST THREE-WAY

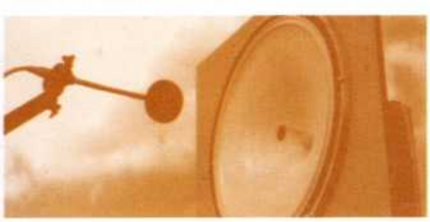






A BIG 15" SUBWOOFER

SHOULD WOOFERS POINT DOWNWARD?



STROBOSCOPIC CHECKS ON SPIDER ACTION

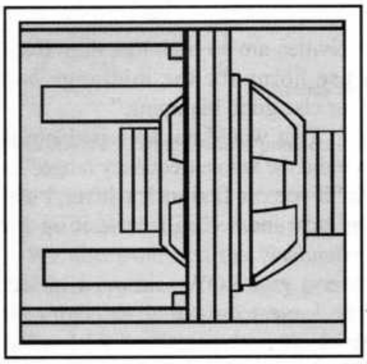
0 74470 84699 4
06

CHEAP, ULTRA HIGH QUALITY SPEAKER CABLES

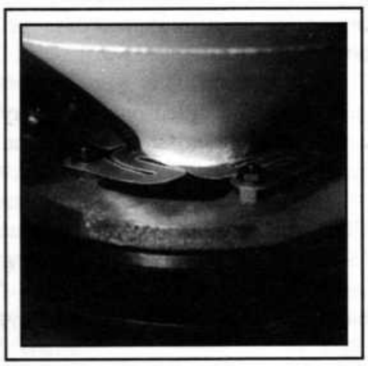
Speaker Builder

THE LOUDSPEAKER JOURNAL

VOLUME 17 NUMBER 6 OCTOBER 1996



34



54

DEPARTMENTS

KEEP IN TOUCH

EDITORIAL — Send letters, questions, and comments to: Speaker Builder, Editorial Dept., PO Box 494, Peterborough, NH 03458 USA, FAX (603) 924-9467, E-mail: audiodiy@top.monad.net.

Be sure to reference the issue, title, author, and page number of the article or letter in question; and if you request an answer from an author, please include a self-addressed envelope (and your FAX number and/or E-mail address, if applicable), with a loose stamp or postal coupon.

Due to the volume of correspondence, we cannot personally acknowledge or respond to each letter or query. All letters to the editor will be considered for publication unless you indicate otherwise. *Speaker Builder* reserves the right to edit your letters or technical queries for length and clarity.

Author guidelines are available by sending a self-addressed envelope with loose postage to the above address.

CIRCULATION — For subscriptions, renewals, back issues, or address changes, write to the Circulation Department (PO Box 494, Peterborough, NH 03458) or call (603) 924-9464 or FAX (603) 924-9467. E-mail: audiotech@top.monad.net.

ADVERTISING — Address advertising inquiries and information requests to the Advertising Department, Audio Amateur Corporation, PO Box 494, Peterborough, NH 03458-0576, voice (603) 924-7292 or 1-800-524-9464, FAX (603) 924-6230.

OLD COLONY SOUND LAB — For product information and ordering, contact Old Colony Sound Laboratory, PO Box 243, Peterborough, NH 03458-0243, voice (603) 924-6371 and (603) 924-6526, FAX (603) 924-9467.

SHOULD YOU DOWNLOAD YOUR WOOFER?

By Andy Lewis

Some audio systems include a woofer pointing toward the floor. This technique is sometimes referred to as *downloading* or *downfiring* the speaker. Listeners describe the sound of these systems in glowing terms, as if there were an inherent advantage to mounting a woofer in this way. They fail to specify, however, what this advantage is.

After considering this subject, I realized that I had many questions:

- Can this design technique offer better bass with a given woofer?
- Is a downfiring woofer really a selling point?
- What are its disadvantages?
- How far above the floor should I raise the bottom of the enclosure?
- Will a carpeted surface have an effect on its performance?

I decided to perform some simple tests to answer these questions.

DOWNLOADED SYSTEM

Figure 1 shows a traditional, or standard, system with the woofer oriented vertically and affixed to a panel. *Figure 2* shows a woofer mounted facing down, or downloaded, and the enclosure supported by nonspecific "feet," separating it from the floor. *Figure 3* shows the same downloaded system on a carpeted surface, to see what effect this might have on a system's performance.

In these illustrations, the enclosure is a simple sealed box, but in practice, the horizontal orientation is used in sealed, vented, and other systems. Although the measurements presented here are outside the discussion of primary loading methods (sealed versus ported, for example), we will see that positioning a woofer downward can affect your choice of enclosure type.

Three effects of downloading a woofer are: (1) an apparent change in the moving mass of the cone assembly, (2) a change in the damping characteristics (Q) of the driver, and (3) displacement of the cone assembly due to the force of gravity on the cone mass. While there may be other changes in performance, these three effects lend themselves to easy analysis.

MASS AND DAMPING

When a woofer "fires" into a restricted air space, as in the throat of a horn or in a downloaded system, the result is what horn theorists refer to as a "high pressure-low velocity" situation. This is a fancy way of saying that the air in the vicinity of the cone is moving (wind), instead of merely acting as a medium for traveling waves (sound). As a pressure front travels the length of a horn, of course, it undergoes a gradual transformation to a high velocity-low pressure condition, or sound wave.

In a downloaded system, no provision exists for this gradual transformation from moving air to sound wave. Instead, it is abrupt and unpredictable. We do know, however, that air has mass, which, when moving in conjunction with the speaker's cone, could have the effect of increasing the apparent moving mass of the driver. Horn designers, in fact, often calculate the volume of the air chamber behind their diaphragm expressly to compensate for the added air mass being "dragged" by the cone.[1] In a simple downloaded system, I had expected the result of this added mass to be insignificant, but this was not the case.

Also, as the speaker pushes air back and forth between the bottom of the downloaded system and the floor, energy is lost to friction. Frictional energy losses (damping) in the driver are expressed as Q_{MS}, and Q_{ES} for electrical damping. You would expect this new loss, when added to the soup, to cause a lowered Q_{MS}, which would in turn lower Q_{TS}. A carpeted surface under the speaker might tend to increase this loss and lower Q_{MS} still further.

SETUP

I figured that information about changes in mass and damping would be easy to express in numbers. I chose to measure the effects on the driver itself, and once I quantified and expressed the effects as a change in the parameters of the driver, then extending them to a finished downloaded system would become no more difficult than in a vertically oriented system. You could simply use these

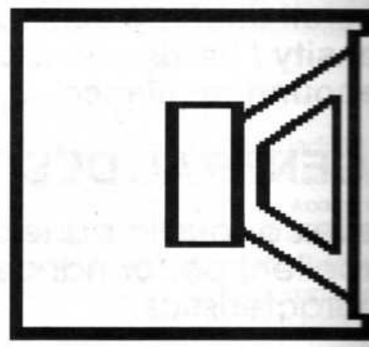


FIGURE 1: Standard vertical configuration.

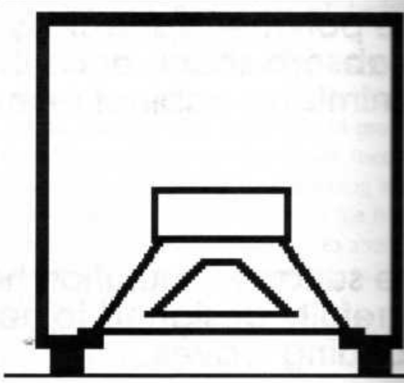


FIGURE 2: Downloaded (horizontal) system.

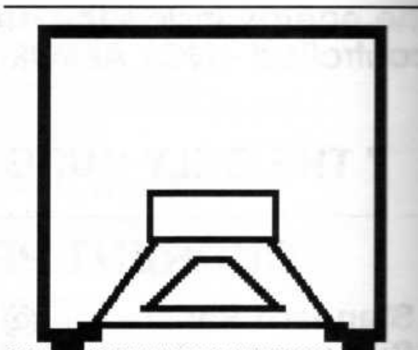


FIGURE 3: Downloaded system over carpeted surface.

ABOUT THE AUTHOR

Andy Lewis lives in Englewood, CO, with his wife Lori and two sons, Corey and Collin. He learned some physics at Hastings College, plays drums professionally in the Denver area, and has a consequent interest in bass guitar speakers. He can be reached by E-mail at Dadbag@aol.com.

amended driver parameters and proceed with a design in the usual way.

Since each design has its own problems, the changes in effective driver parameters would provide an easy way to extend the results into your finished system. Consequently, I chose to measure without an enclosure. I simply mounted a speaker to a baffle, oriented the baffle in different ways, and performed measurements in each position.

I chose an old Electro-Voice 12″ woofer I had pulled from an ancient Knight 3-way system. It has a fairly low-moving mass (41gm) and a fairly high Q_{TS} (in excess of .5). These characteristics would make any changes in damping and effective mass more apparent as I made my measurements, as the effects of downloading the speaker would have a larger effect relative to the speaker's inherent mass and damping. A woofer with high-moving mass or a very low Q_{TS} would be less affected on a relative basis than this somewhat underdamped woofer with its low moving mass.

I mounted the woofer in the center of a piece of ¾″ particleboard scrap, about 20″ × 30″ (*Photo 1*). I soldered a length of zip cord to the terminals, so I could then make my measurements at the end of the zip cord, rather than at the speaker terminals themselves. This would allow me to move the speaker/baffle assembly to different positions as I made the different measurements without adding any wire. Any measurements of Q made with my fixed length of zip cord would reflect the presence of this wire in the circuit, but the results would be reliable for purposes of comparison.

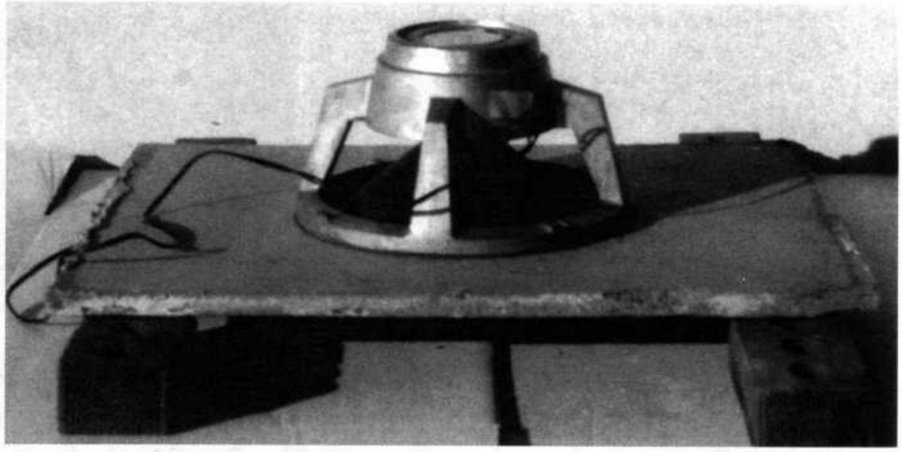


PHOTO 2: Test setup using bricks.

I could then orient this speaker/baffle assembly in different ways to measure the effects of downloading the woofer. With the speaker placed in different positions, I could isolate the effects of downloading the speaker as I measured the Q and resonance of the woofer.

TESTS

I performed tests with the speaker/baffle assembly in six different positions:

1. With the baffle standing vertically, as in a standard system (*Photo 1*). This would be the control, against which I would compare other scenarios.

2. With the baffle suspended woofer-down on bricks placed on their sides, one at each corner, with the baffle about 3½″ above a concrete surface. This is the first downloaded scenario.

3. With the baffle suspended woofer-down on bricks lying flat, one at each corner, with the baffle about 2¼″ above a concrete surface (*Photo 2*). This is the second downloaded scenario.

4. With the baffle suspended woofer-down on 2″ × 2″ blocks, one at each corner, with the baffle about 1½″ above a concrete surface (*Photo 3*). This is a more extreme downloaded scenario.

5. With the baffle suspended woofer-down on 2″ × 2″ blocks, one at each corner, with the baffle about 1½″ above a ½″ thick carpeted surface (*Photo 4*).

6. With the speaker oriented vertically, but with a mass of modeling clay added to the cone's moving mass, to simulate a mass of moving air, and as a consequence remove frictional loss. This is explained in greater detail below.

These first four positions measure the increasing effects as the baffle is lowered toward the floor. As the tests were run, I hoped a pattern might emerge that would provide a "feel" for what to expect from the downloading technique.

In each of the six positions, I connected a standard impedance-measuring setup and measured the damping (Qs) and resonance frequencies (f_S). The resonant frequency, of course, is the frequency of maximum impedance in the bass region. Q_{MS}, Q_{ES}, and Q_{TS} figures are derived from impedances measured at several frequencies. I use the standard derivation found in most popular texts.

While these tests give us a generalized

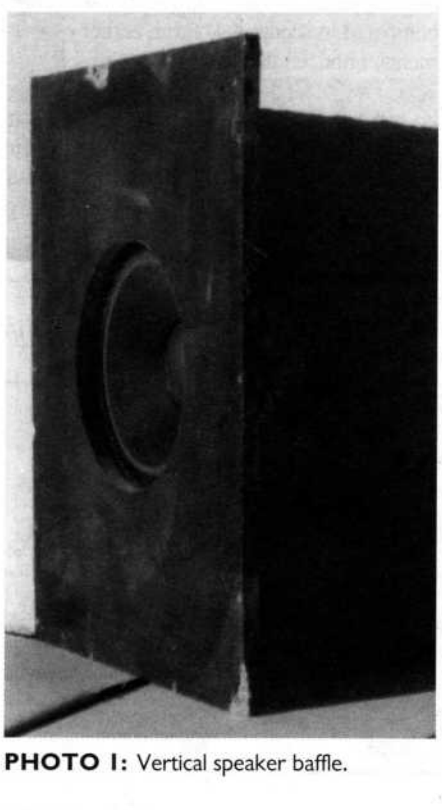


PHOTO 1: Vertical speaker baffle.

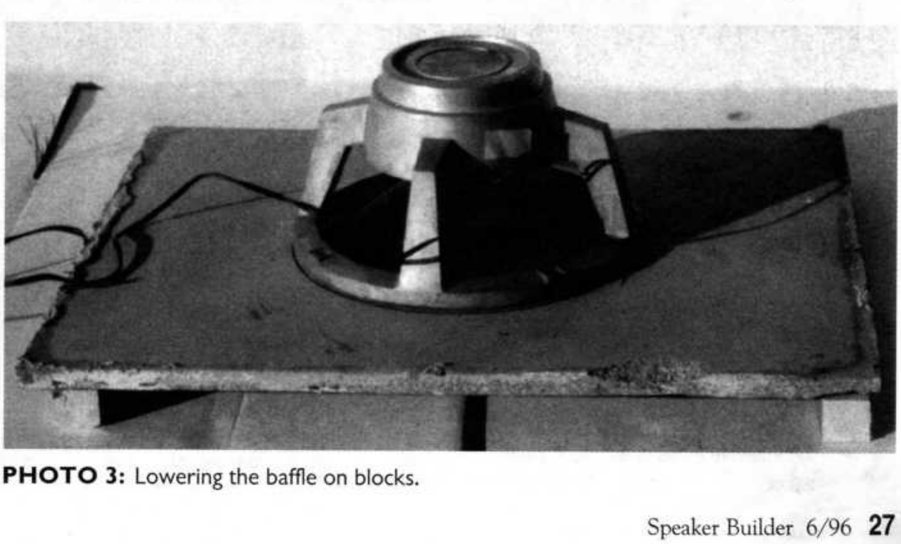


PHOTO 3: Lowering the baffle on blocks.

idea of the effects of downloading, it is important to realize that they should be performed with a setup that more closely approximates the finished system (with a more realistic baffle size and an enclosure). Otherwise, unpredictable results could occur.

RESULTS AND INTERPRETATION

Table 1 shows the measurement results. Please note that column 8, "EBP," lists the calculated "Efficiency Bandwidth Product," which is simply the ratio of f_S to Q_{ES}, for the speaker in each position. This refers to the popular, and very concise, method for evaluating whether a speaker is better-suited for a sealed or vented enclosure.[2] A rule of thumb states that an EBP around 50 indicates the driver will probably be better-suited to a sealed enclosure, while a value of 100 places the speaker in a vented system.

Interestingly, the change in resonance as the baffle is lowered toward the floor is dramatic. For example, going from 38.3Hz to 33.2Hz represents a change of about 13%! We know that the compliance of the woofer's suspension is unchanged, so the change in resonance must be due to the mass of the air in the vicinity of the cone, as it moves with the cone. We can, in turn, calculate the mass of this air for each test scenario.

An accepted test exists for determining the compliance and moving mass of a driver. When a known mass (such as a lump of modeling clay) is artificially added to a speaker's cone, the resonance is obviously lowered. The amount by which the frequency of resonance changes reveals the speaker's inherent moving mass. If we already know the cone's actual mass, however, we can determine the mass added to the cone.

ADDED MASS

A woofer's moving mass, the change in resonance, the speaker's original resonance, and the known mass of the clay (or air, in this case) are related by the following equation[3]:

$$M_{MD} = M' / [(f_S / f_S')^2] - 1 \quad (1)$$

where:

M_{MD} = the woofer's moving mass
M' = added test mass of clay (air)
f_S = speaker's natural resonance
f_S' = lowered resonance with test mass added.

If we know the speaker's true moving mass, we can determine the mass of the moving air:

$$M' = M_{MD} \times [((f_S / f_S')^2) - 1] \quad (2)$$

where:

M' = the effective mass of air moving with the cone.

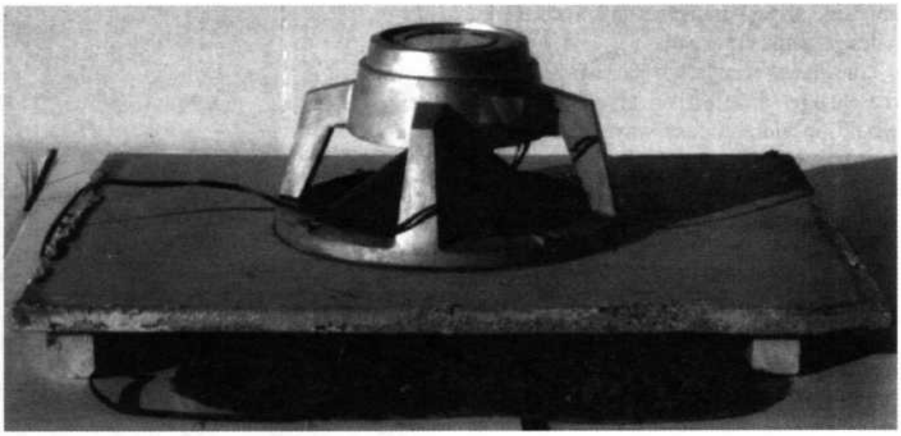


PHOTO 4: Testing the effects of a carpeted surface.

I made these calculations for each of the downloaded test scenarios, using an M_{MD} of 41gm and the relevant quantities in *Table 1*, and entered in column 7 the apparent mass that has been added to the cone in each case. As the enclosure is lowered toward the floor, the amount of air under the baffle decreases, but the amount of air which apparently moves with the cone increases! I was surprised by the amount the speaker's resonance changed in these tests.

When referring to masses of air, I find it interesting to consider the actual physical volume of the air in question. How much air represents a gram of mass? A typical figure for the density of air at sea level is 1.29×10^{-3}gm/cm^3. The volume of a gram of air, then, would be the inverse of this figure, or 775. A gram of air occupies about 775cm^3 of space, or about three quarters of a liter![3]

Within the context of this downloaded setup, this allows us to calculate, more or less, the volume of air under the speaker actually moving with the speaker's cone. If we multiply the mass of the air moving with the cone (6.99gm, column 7, 2¼″ bricks) by the volume per mass (775cm^3/gm), we get a figure of 5417cm^3, effectively about 5.4 liters of moving air.

Q AND DAMPING

With regard to damping (Qs), I expected to see a clear decrease in the figures for Q_{MS} as the woofer was lowered. The extra friction should tend to lower the Q_{MS} of the driver as the air is pushed and pulled through the restricted air space. As a general rule, when friction goes up, Q goes down! As Q_{MS} decreases, Q_{TS} decreases as well.

The test results, however, seem to contradict my expectations. Column 4 shows that unless carpet is added under the system to increase friction, the relationship between downloading and Q_{MS} is unclear at best. In fact, the Q_{MS} figures in the vertically oriented system and the very low (1½″) example change only from 5.70 to 5.71. The interim examples seem to gyrate somewhat, and no clear pattern occurs.

As friction is increased with the addition of a carpeted surface, Q_{MS} decreases when compared to scenario 4. From earlier experiments, I noticed that adding mass to a speaker's cone generally has the effect of raising both the Q_{MS} and Q_{ES} of a driver. Could it be that the Q_{MS}-lowering tendency of the air friction was being overwhelmed by the Q_{MS}-raising effect of the additional moving mass of the air?

TABLE 1

MASS AND Q TEST DATA

TEST #	ORIENTATION	F_S (Hz)	Q_{MS}	Q_{ES}	Q_{TS}	G_{MS} AIR	EBP
1	Vertical	38.3	5.70	0.651	0.584	N/A	58.8
2	On 3½″ bricks	37.3	5.90	0.676	0.607	2.23	55.2
3	On 2¼″ bricks	35.4	5.77	0.683	0.611	6.99	51.8
4	On 1½″ blocks	34.5	5.71	0.738	0.653	9.53	46.7
5	1½″ blocks, carpet	33.2	5.11	0.749	0.654	13.56	44.3
6	Added mass vertical	34.4	6.09	0.753	0.670	N/A	45.7

TABLE 2

AIR LOADING VS. ADDED MASS

TEST #	ORIENTATION	F_S (Hz)	Q_{MS}	Q_{ES}	Q_{TS}	G_{MS} AIR	EBP
4	On 1½″ blocks	34.5	5.71	0.738	0.653	9.53	46.7
6	Added mass vertical	34.4	6.09	0.753	0.670	N/A	45.7

ANOTHER TEST

This apparent conflict between two opposing consequences of downloading the woofer suggested the last test scenario, in which the woofer is oriented vertically, but with extra mass added to the cone to simulate a mass of moving air. By artificially lowering the effective f_S to the point of resonance in the downloaded example, you can effectively remove the frictional loss and measure the effects of added mass independently of the air friction.

Because the speaker is not firing into a restricted air space in this added-mass test, the friction of creating wind under the baffle is removed. Additionally, if you used a test mass similar to one of the previous downloaded examples, this added-mass test could isolate any Q_{MS}-decreasing effect of air friction associated with the woofer's downloading itself. I chose the third downloaded setup (#4) to simulate in this fashion. I simply added the modeling clay to the cone to decrease the resonant frequency to the desired point and to simulate the mass of the added air in the equivalent downloaded setup.

With the speaker oriented vertically and the correct mass added to the cone, I performed the (#6) test (*Table 2*). The #4 and #6 figures for f_S don't quite match, due to the limitations of the accuracy of my work and equipment. A difference between 34.4Hz and 34.5Hz is probably less than my measurement error itself, and I chose to ignore it.

But, when you compare the results of these two tests, the frictional loss in test #4 does appear to lower Q_{MS} substantially. When the frictional loss is removed, as in test #6, Q_{MS} is increased from 5.71 to 6.09. In the downloaded system, with the loss in place, Q_{TS} is decreased from .670 in test #6 to .653 in test #4. I characterize this change as substantial. Apparently, the frictional loss associated with downloading itself is significant; however, it tends to be obscured by the more influential effect of an increase in effective moving mass, resulting in a general increase in Q_{TS} when a woofer is downloaded.

EFFECT OF DISPLACEMENT

A woofer in its position of equilibrium, or zero excursion, in a standard vertical orientation (*Fig. 4*) normally is manufactured with its voice coil centered in the magnetic gap (note the position of the voice coil as indicated by the arrow). One effect of mounting the speaker face-down (or face-up) is that the earth's gravitational field exerts a force on the moving system of the unit, which tends to pull the voice coil out of its centered position. *Figure 5* shows a driver face-down, with the inset showing the voice coil slightly displaced from center (arrow).

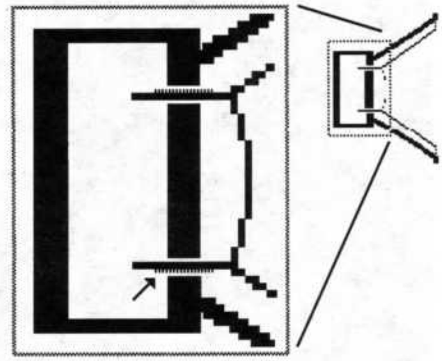


FIGURE 4: Voice coil centered in gap in vertically oriented mounting.

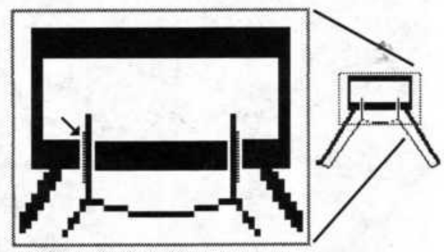


FIGURE 5: Voice coil pulled from center position when mounted horizontally.

The magnetic field of the speaker's magnet is concentrated in the magnetic gap. The turns of wire that make up the voice coil are immersed in this field. As electrical current passes through the voice coil, the magnetic field exerts a force on each turn of wire. The equation describing the force on a conductor in a magnetic field is:

$$F = Bli \qquad (3)$$

where:

- F = force on the conductor
- B = magnetic field strength
- l = length of the conductor immersed in the magnetic field
- i = electrical current in the conductor

You can see from this equation that when Bl remains constant, force is proportional to current. The length of the conductor in the field, in the special case of a loudspeaker, is equal to the length of each turn of wire times the number of turns in the gap. As long as the number of turns remains constant, the "Bl product" will be a constant as well, and the speaker will work as it should, with force on the voice coil in direct proportion to current through the wire voice coil.

In extreme situations, when a speaker is required to reproduce signals with long woofer excursions, a voice coil will sometimes move far enough to exceed the length of the windings. This over-excursion causes the number of turns of wire in the gap to be reduced from that when the driver is in its equilibrium position (*Fig. 5*). When this happens, the Bl product is reduced, because as the number of actual turns decreases when excursion is long, the effective length of wire in the field decreases.

As the Bl product decreases, the force on the voice coil is no longer in direct proportion to input current, and the performance of the motor is nonlinear, i.e., distortion or breakup occurs. The X_{MAX} parameter describes one-way linear excursion limit.

Small and others[4] have described "displacement-limited power handling" in terms of the volume of air displaced at maximum linear excursion:

$$P_{AR} = f_3^4 \times V_D^2/(3 \times 10^8) \qquad (4)$$

where:

P_{AR} = displacement-limited power handling
V_D = volume of air displaced at maximum linear excursion
f_3 = 3dB down point

In turn,

$$V_D = X_{MAX} \times S_{SD} \qquad (5)$$

where:

X_{MAX} = maximum linear excursion
S_{SD} = cone area

Consequently,

$$P_{AR} = f_3^4 \times (X_{MAX} \times S_{SD})^2/(3 \times 10^8) \qquad (6)$$

Actual displacement-limited power handling is proportional to the square of X_{MAX}, so any reduction in X_{MAX} will have a disproportionate effect on actual system power handling. As gravity exerts a force on the speaker's moving assembly, and the voice coil is in turn displaced from its centered position, power handling can be reduced.

POWER-HANDLING REDUCTION

Gravity's force on a speaker's moving assembly is equal to the mass of the moving system times the acceleration due to the earth's gravitational field:

$$F_{MD} = M_{MD} \times g \qquad (7)$$

where:

F_{MD} = force on the moving system in dynes
M_{MD} = the speaker's moving mass in grams
g = acceleration due to the earth's gravity
$= 9.80 \text{ m/s}^2 = 9.80 \times 10^2$ dyn/gm

Displacement due to gravity then will be equal to the downward force on the cone times the compliance of the speaker's suspension:

$$D_G = F_{MD} \times C_{MS} \quad (8)$$

where:
D_G = displacement due to gravity in cm
C_{MS} = speaker compliance in cm/dyn

Amended X_{MAX} would then be equal to the original linear excursion minus displacement due to gravity.

$$X_{MAX}' = X_{MAX} - D_G \quad (9)$$

where:
X_{MAX}' = amended linear excursion limit

Since displacement-limited power handling is proportional to the square of X_{MAX}, the factor relating vertical and downloaded power-handling figures will be equal to the square of the ratio of the two:

$$P_{AR}' / P_{AR} = (X_{MAX}' / X_{MAX})^2 \quad (10)$$

where:
P_{AR}' = amended displacement-limited power handling.

TABLE 3

POWER-HANDLING REDUCTION IN SEVERAL DRIVERS

DRIVER	M_{MD} (gm)	F_{MD} (dyn)	C_{MS} (m/N)	C_{MS} (cm/dyn)	DISP (cm)	X_{MAX} (cm)	X_{MAX}' (cm)	P_{AR}'/P_{AR}
Audax HM100XO	3.23	3165.4	0.00225	0.00000225	0.0071	0.23	0.2229	0.939
Peerless 1599	12.2	11956	0.00015	0.00000015	0.0018	0.3	0.2982	0.988
Eton 11-580	23	22540	0.000094	0.000000094	0.0021	0.4	0.3979	0.989
Audax PR300MO	33	32340	0.000264	0.000000264	0.0085	0.44	0.4315	0.962
Dynaudio 30 W-100	35.2	34496	0.000121	0.000000121	0.0042	0.8	0.7958	0.990
Madisound 12204	106	103880		0.00000048	0.0499	0.6	0.5501	0.841
Audax PR380MO	115	112700	0.000062	0.000000062	0.0070	0.38	0.3730	0.964
Madisound 15254	160	156800		0.00000048	0.0753	0.55	0.4747	0.745

Using these equations, along with a speaker's mass and compliance data, you can then see what effect gravity can have on power handling in a downloaded system. Without linear-excursion data (X_{MAX}) for my old Electro-Voice, I used the manufacturer's data for several drivers to calculate the anticipated loss in linear excursion and displacement-limited power handling (*Table 3*).

In the event you need to determine your own figures, here is the simple mathematical relationship between mass, compliance, and resonant frequency:

$$f_S = 1 / [2 \times \pi \times (M_{MD} \times C_{MS})^{1/2}] \quad (11)$$

You can derive compliance from figures provided for resonance and moving mass:

$$C_{MS} = 1/[(2 \times \pi \times f_S)^2 \times M_{MD}] \qquad (12)$$

Make sure you use consistent units. For example, in *Table 3* I converted m/N in column 4 to cm/dyn in column 5. This information indicates that the effects of gravity on voice-coil centering range from significant to inconsequential. The two woofers most affected (the two Madisound models) both exhibit high-moving masses and high compliances, as you'd expect.

Keep in mind that these calculations are parameter related, and indicate nothing about the relative quality of any of the units listed. They may, however, provide an insight into their relative usefulness for downloading.

As a rule of thumb, when evaluating a woofer's suitability for downloading, high mass and compliance are your enemies, if high power handling is a consideration. A high figure for a speaker's X_{MAX} is your friend, as gravitational displacement will be smaller compared with the original X_{MAX}.

CONCLUSIONS

These tests demonstrate that downloading a woofer can change a woofer's apparent parameters. As a system is oriented horizontally and lowered toward the floor, the driver's frequency of resonance decreases due to an apparent increase in moving mass, as air in the cone's vicinity moves with the cone itself. This added mass results in an increase in driver Q_{TS}, which the frictional loss associated with the movement of this air somewhat mitigates.

As the speaker designer, you can anticipate a moderate increase in effective Q_{TS} and a decrease in apparent f_S when you download a woofer. The best conditions involve a woofer with a somewhat low Q_{TS} or one with a somewhat high inherent f_S. In practice, this would suggest a speaker with an EBP that needs to be decreased, or that might become more useful through a reduction in EBP. In addition, using such a system over a carpeted or other "lossy" surface can significantly affect damping, and can lower Q_{TS}, or at least reduce the increase in Q_{TS}.

From this look at the effects on mass and damping, it is clear that to proceed with a design of this type without some careful consideration could produce a system that does not operate as intended. If you capriciously apply this technique to a woofer without accounting for its effects, you'll be working with design goals that could be vague, and achieve an unpredictable result. When carefully used, however, downloading can change effective driver parameters in special cases, i.e., when the driver could be helped by a lower f_S, higher Q_{TS}, or lower EBP.

Another effect of downloading is that the force of gravity tends to pull the voice coil from its centered position, resulting in a decrease in maximum linear excursion for the driver and a decrease in displacement-limited power handling. This effect will vary in importance from woofer to woofer, and will be most harmful in drivers exhibiting high compliance, large moving mass, and short inherent linear-excursion capability. Be sure to evaluate the effect gravity will have on the woofer before choosing your driver.

REFERENCES

1. Abraham B. Cohen, *Hi-Fi Speakers and Enclosures*, Hayden Book Company, 1968, pp. 248–249.

2. Vance Dickason, *Loudspeaker Design Cookbook*, Marshall Jones Co., Third Edition, 1987, p. 5. Attribution to Small.

3. David B. Weems, *How to Design, Build and Test Complete Speaker Systems*, Tab Books, 1978, pp. 73 and 75.

4. Richard Small, and Margolis, "Personal Calculator Programs," JAES, June 1981, p. 422.