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Loudspeaker Transducers with an Alternative Tubular Form Factor

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ABSTRACT

Three different multi-diaphragm loudspeaker transducers with a tubular form factor are investigated. The transducers consist of a conventional motor structure, a tubular housing, and multiple diaphragms. In one design, sound is generated by the relative motion between a housing that is driven by a single motor and diaphragms that are attached to the housing via flexible surrounds. In a second design, a single motor drives one set of diaphragms and sound is generated by the relative motion between the diaphragms and the fixed housing. In the final design, two motors are used to drive two sets of diaphragms in opposition and sound is generated by the relative motion between them.

1. INTRODUCTION

The maximum sound pressure achievable by a conventional electro-dynamic loudspeaker transducer at low frequencies is a function of the maximum volume velocity that is proportional to the effective diaphragm area multiplied by the maximum excursion and the frequency. Practical considerations, such as achievable suspension travel and motor efficiency, tend to limit the maximum excursion for a given cost. As a result, loudspeaker woofers required to generate large amounts of low frequency energy tend to employ large diameter diaphragms.

Further, diaphragms that need to withstand extreme drive levels are typically manufactured in a deep cone shape to reduce the stresses that can result in failure when the diaphragm flexes. Cone shapes are also widely used for diaphragms intended to be used for more than just low frequency reproduction. The much improved rigidity of the cone structure pushes resonances that can cause frequency response and distortion problems out of the intended frequency band (or it at least helps keep them under control.) However, the use of a cone shaped diaphragm and the motor depth required for large excursions combine to substantially increase the depth of the transducer. The large depth and diameter together can often times prevent the device from being used in certain space constrained applications.

The loudspeaker transducers described in this paper use multiple diaphragms that are small and flat and are housed within a tubular shell. This alternative form factor yields a large total surface area but small cross-sectional area in a package that can fit in spaces where traditional woofers providing the same performance cannot.

Three novel electrodynamic transducer designs are presented, each of which is capable of producing relatively loud low-frequency sound while employing the alternative tubular form factor.

2. A DESIGN USING INERTIALLY DRIVEN DIAPHRAGMS

2.1. Description

The transducer described in this section uses multiple diaphragms that are attached to a tube-shaped housing. Figure 1 is an illustration of the transducer. The diaphragms are connected to the shell with conventional surrounds resulting in a loudspeaker with a large total surface area and small cross-sectional area. Orifices, one for each diaphragm, are built into the housing. These orifices allow sound to radiate to the environment. Baffles built into the housing isolate the front and back waves and create a sealed air volume behind each diaphragm. The housing is rigidly attached to the voice coil and the motor is mechanically grounded. A spider or some other suspension component provides a restorative force for the housing and centers the voice coil. Sound is created by the relative motion between the diaphragms and the housing.

At very low frequencies, well below the resonances of the housing and diaphragms, the diaphragms will very nearly be in phase with the housing. In this case, there is no relative motion between the diaphragms and housing; thus, no sound will be produced. At some higher frequency, above the housing and diaphragm first resonances, the housing and diaphragms will move in opposition, thus producing sound. The overall response, as will be shown, is that of a fourth-order high-pass filter.

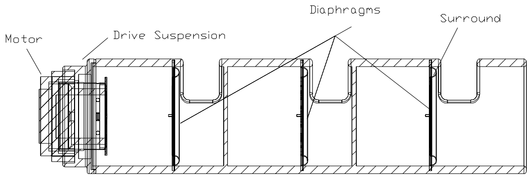

Figure 1. Inertially Driven Transducer With Multiple Diaphragms.

2.2. Modeling

The mechanical impedance of the voice coil and all of the parts rigidly attached to it is:

$$Zm1 = M1 * s + R1 + 1/(C1 * s) \tag{1}$$

where $s = j\omega$ (2)

M1 is the combined mass of the voice coil, housing, and effective mass of the spider. R1 is the effective mechanical resistance of the transducer excluding that of the surrounds and C1 is the compliance of the spider.

Of course, when the housing moves, the diaphragms must move and/or the surrounds must stretch. The mechanical impedance of the diaphragms is:

$$Zm2 = 1/\{1/(Msd * s) + 1/(1/(Cdb * s) + Rsd)\} \tag{3}$$

where Msd, Cd, and Rsd are the effective mass, compliance, and mechanical impedance of a single diaphragm/surround assembly. Cdb is the effective compliance of the diaphragm’s surround, Cd, combined with the compliance of the volume of air, Vb, trapped in the chamber between the diaphragm and the baffle.

The total mechanical impedance as seen by the motor is:

$$Zmech = Zm1 + NZm2 \tag{4}$$

where N is the number of diaphragms used.

Calculating velocity, displacement, and acceleration can be performed in the usual manner:

$$u1 = (Eg * BL/\mathrm{Re})/(Zmech + BL{}^\wedge 2/\mathrm{Re}) \quad (5)$$

$$x1 = u1/s \quad (6)$$

$$a1 = u1 * s \quad (7)$$

In this transducer, sound is generated by the difference between the motion of the housing and the diaphragms. The diaphragm velocity, displacement, and acceleration are calculated as:

$$u2 = u1 * (1/(Cdb * s) + Rsd)/(Msd * s + Rsd + 1/(Cdb * s)) \quad (8)$$

$$x2 = u2/s \quad (9)$$

$$a2 = u2 * s \quad (10)$$

The pressure generated is

$$P = 1.18 * (a2 - a1) * Sd * N/(2 * pi) \quad (11)$$

Where Sd is the area of a single diaphragm

For radiation into half-space, the calculated SPL is:

$$SPL = 20 * \log 10(abs(P/20e-6)) \quad (12)$$

2.3. Example Calculation

Figure 2 illustrates the calculated frequency response for a driver of the type described in Section 2.1 and modeled in Section 2.2. The parameters used were as follows:

m1 = 100 grams

R1 = 1 kg/sec

C1 = 0.25 mm/N

Msd = 100 grams

Cd = 1 mm/N

Rsd – 1 kg/sec

Bl = 13 N/A

Re = 4 ohms

Vb = 1 liter

Sd = 40 cm^2

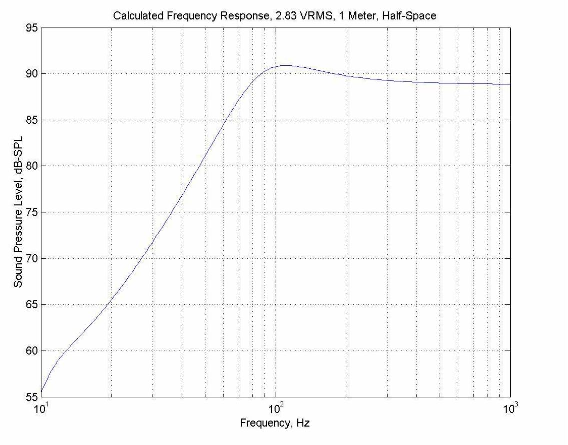

Figure 2. Calculated Frequency Response of an Inertially Driven Transducer.

While this type of transducer is interesting to study, it was not considered for development. Practical issues such as high tube mass and realizing the drive system were the main concerns. Further, the required volume of air behind each diaphragm would result in a transducer that would be considerably longer than the alternative designs considered in the following sections.

3. A DESIGN USING MULTIPLE DIAPHRAGMS AND BAFFLES

3.1. Description

The transducer described in this section has a tubular form factor and a single motor mounted on the end of the tube as shown in Figure 3. Sound is generated by the relative motion between the diaphragms and the baffles. The diaphragms are driven at their centers by a single rod passing through them and a hole in the baffles. Referring to Figure 3, if a positive going voltage is applied to the motor, the diaphragms will all move to the right and air will be squeezed out of the top openings while air will be drawn into the rear openings, creating front and back waves. As long as frequencies are low with the wavelengths of sound generated being long relative to the length of the transducer, the sound radiated will be omnidirectional and the front and back waves will behave the same as those generated by a traditional woofer.

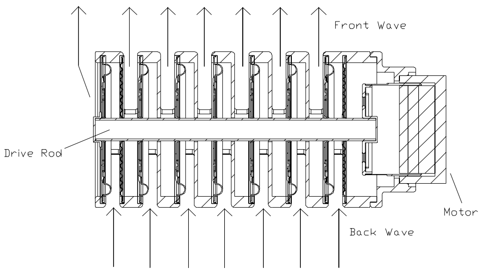

Figure 3. Transducer Using Multiple Diaphragms and Baffles.

3.2. Modeling

Unlike the transducer in the previous section, this device can be analyzed by using the standard loudspeaker parameters of Re, Bl, Fs, Qms, Qes, Sd, Mms, and Cms [2]. Sd is taken as the product of the effective surface area of a single diaphragm multiplied by the total number of diaphragms. Likewise, Mms is taken as the effective moving mass of a single diaphragm multiplied by the total number of diaphragms. Cms is the compliance of a single surround divided by the number of diaphragms. Standard methods of measuring the small signal parameters in conventional loudspeakers apply to this design.

3.3. Building a Prototype

A prototype transducer of this style was built with an 88 mm tube diameter and an overall length of 200 mm using a 50mm voice coil. The measured small-signal parameters were quite close to those calculated from measurements made on the motor and individual diaphragms. The frequency response shown in Figure 4 is as predicted up to about 200Hz. At this frequency, the flat disks (though only 62mm in diameter) exhibit a severe radial mode shape resonance that results in a large peak followed by a dip in the response. Above this frequency, this prototype device is no longer useful. The material choice used for the diaphragms in this exercise was limited by the prototyping process. This first resonance can be pushed up in frequency by using stiffer materials and composites.

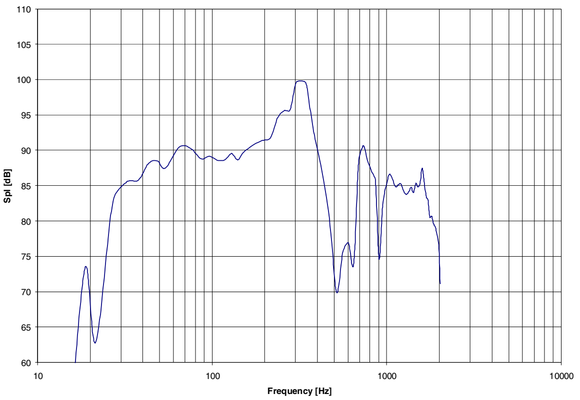

Figure 4. Frequency Response for Tubular Transducer with Baffles and Single Motor. 1W/1m Into Half Space With 27 Liter Sealed Enclosure (Preliminary Data.)

Another design preference issue is related to the baffles that separate the pistons. Since one of the goals of this work is to develop the smallest transducer possible for a given performance target, it is desirable to eliminate the baffles. Even though each of the baffles is only a few millimeters thick, the overall length of the device can be extended by a few centimeters when many diaphragms are used. These considerations provided the motivation for the design examined next.

4. A DESIGN USING MULTIPLE OPPOSING DIAPHRAGMS

4.1. Description

The transducer described in this section again employs a tubular form factor. However, it uses two motors wired so that their voice coils move toward each other with positive going voltages and away from each other with negative going voltages. The motor on the left drives half of the diaphragms which are interleaved with those driven by the other motor. Thus, adjacent diaphragms move in opposition to generate sound. This design is illustrated in Figure 5. The radiation characteristics are similar to those described for the transducer of Section 3 with front and rear waves being generated from opposite sides of the device.

The drive rods pass through holes in the opposing diaphragms that are only large enough to provide a small clearance around the rod. If the gap between the rod and diaphragm is too large, the air rushing through the holes becomes audible and the tuning of the system changes. The required hole size was studied prior to building prototypes, and it was determined the holes can be sufficiently small to avoid these problems yet still large enough to meet production requirements.

Since the motors work in opposition, the net mechanical vibration is essentially eliminated. This is an important feature of the design. It allows the transducer to be used in situations where transfer of vibration to the mounting structure would cause extraneous noise or fatigue of other components (for example, a computer chassis or a television monitor.)

An additional advantage of this design is that the drive force is delivered to the diaphragms through multiple rods with each rod at a considerable distance from the diaphragm center. This drive scheme increases the frequency of the first problem resonance in the diaphragm and extends the usable bandwidth of the device.

Finally, the two-motor system of this transducer does increase the cost somewhat, but it also doubles the power handling. This is important because the small motors likely to be used in such a design would typically have limited heat capacity.

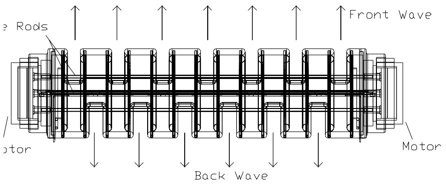

Figure 5. Transducer Using Dual Motors and Multiple Opposing Diaphragms

4.2. Modeling

Like the transducer described in Section 3, this device can be analyzed using the standard loudspeaker parameters of Re, Bl, Fs, Qms, Qes, Sd, Mms, and Cms. Re is taken as half the resistance of one voice coil (as they are wired in parallel.) Sd is taken as the product of the effective surface area of a single diaphragm multiplied by the total number of diaphragms. Likewise, Mms is taken as the product of the effective moving mass of a single diaphragm multiplied by the total number of diaphragms. Cms is the compliance of a single surround divided by the total number of diaphragms. Standard methods of measuring the small signal parameters in conventional loudspeakers also apply to this design.

4.3. Building A Prototype

A prototype of the transducer described in this section was built and measured. The results were very close to predictions. The prototype was 88mm in diameter, 390mm long and used a 50mm voice coil. The winding overhang (Xmax) was 6mm and the maximum excursion was 8mm (one way). Fourteen diaphragms were used and the max SPL achievable was 110 dB at 1 meter (half space radiation.) In this first implementation, the prototyping process used for the surrounds yielded very compliant parts and less than ideal small-signal parameters. Even so, the initial performance was quite encouraging. The measured response is shown in Figure 6. The prototype was completed just before press time and the data is preliminary.

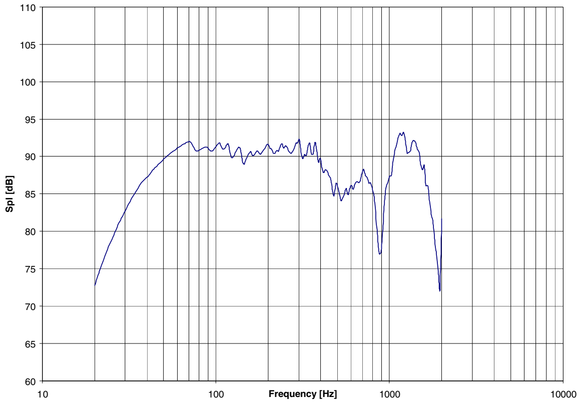

Figure 6. Frequency Response for Tubular Transducer With Opposing Diaphragms. 1W/1m (1/2W per motor) into Half Space with 27 Liter Sealed Enclosure (Preliminary Data.)

5. OTHER ALTERNATIVES

Other possibilities for implementing the tubular form factor were considered. One alternative is to simply stack multiple small speakers inside a tube with vents on opposite sides to create front and back waves. This implementation was quickly ruled out as being non-competitive to the designs of Sections 3 and 4. The primary limiting factor is the excursion requirement that dictates long coil windings in each of the speakers. The associated lowered efficiency means a large motor magnet size is necessary to match performance. If a ceramic ring magnet is used, the required outer diameter is so large it almost completely fills the tube and the chamber size becomes an issue. Further, using several of these motors makes the device quite heavy. Using individual cup style neodymium motors can provide some relief for these problems, but they rapidly drive up the cost. Regardless of the motor style used, the depth required for each driver (even if the cones are flat) makes the transducer quite long. Also, assembly and wiring of multiple speakers substantially increases the cost.

6. ACKNOWLEDGEMENTS

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