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Compact Magnetic Suspension Transducer

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ABSTRACT

The role of compliant parts in the operation of loudspeaker drivers is discussed, and a new method of construction employing a magnetic suspension system is presented. Audio transducers require a complex interaction between moving and non-moving structures, placing conflicting demands on the soft parts typically employed to interface between them. The limitations of current materials and of manufacturing technology suggest that replacing flexible and compliant mechanical parts with a system based on magnetic forces might yield several benefits. Such a system, which utilizes a moving magnet balanced between static repulsive forces, is discussed conceptually, analytically and experimentally. Proposed advantages include increased linear excursion, convenient form-factor, reduced wear and fatigue, and the simplification of certain production processes.

1. BACKGROUND

Shrinking consumer products place significant size and form-factor demands on audio transducers [1]. Even though audio remains a critical element in the customer experience, highly integrated and space-constrained designs inevitably force serious compromises in sound quality. Space constraints, in particular, impact low frequency extension and maximum output level, both of which will often be limited by the maximum air volume displacement (V_D) of the transducer [2]. This is a firm limitation, set by diaphragm radiating area and maximum displacement, and it resists efforts to overcome it with equalization or additional amplifier power.

Further, the quest for extended displacement may also lead to increased fatigue and failure of the soft parts, as stress goes up and materials selection must favor flexibility over pure strength. A good example of this tradeoff are the compressed foam surrounds originally used in high excursion, high compliance woofers. Though the engineering of foam surrounds is now mature, and reliability is acceptable, softer surround materials are still not as durable as stiffer materials.

The goal of more displacement from smaller transducers is not a new quest in the history of audio reproduction. Consumer demand for compact and more fully integrated products, co-existing with the desire for deep and dynamic bass, has driven the intimately linked sciences of both transducer and enclosure development for many decades. Some of audio's most important developments have stemmed from the desire to get more sound from smaller boxes.

Developing new types of transducers with form factors optimized with respect to defined applications (such as Flat Panel TV's, headphones or laptop computers) can mitigate output constraints in many situations. Available space can often be better utilized if a given volume displacement can be achieved from a transducer with a shape that departs from that of a flat cone. Of particular interest are transducers with a tubular form factor, which can be located in a thin product, such as an FPTV, without requiring substantial front panel real estate. Still, a reliance on mechanical springs remains a significant limitation in all situations.

This presentation describes the development of a compact, magnetically suspended audio transducer. Our work has been motivated by an effort to eliminate mechanically compliant "soft parts" and, in turn, to increase the linear excursion of small diameter speakers. It is our hope that, along with increasing the output capabilities of compact transducers, magnetic suspension designs can lead to improved reliability, manufacturing simplicity and performance consistency.

The first commercial application of the magnetic suspension loudspeaker discussed here is for use in high performance headphones. This application makes good use of the transducers advantages, and minimizes the impact of sensitivity limitations.

2. MECHANICAL SOFT PARTS

The task of designing and manufacturing loudspeaker soft parts is not trivial, as the mechanical system must meet a wide range of sometimes mutually exclusive engineering goals. Vibrating elements within the transducer have to be free to move along one axis (one degree of freedom), while accurately constrained in all other directions. A restoring force must also be provided, one which stays as linear as possible over a target range of displacement, but which increases progressively at the extremes of excursion so as to avoid damage and reduce high-order distortion resulting from excessive input. The engineering difficulty is exacerbated by ever-increasing demands for improved excursion and power handling.

In a practical sense, some elements of the transducer are constrained to remain at rest with respect to the listener's frame of reference, so that the device can be usefully assembled into other structures. At the same time, the moving elements that are used to excite sound vibrations must be able to travel over a distance defined by the required extremes of frequency and output level. Conventionally, elastic and compliant parts are employed to allow the necessary range of motion while positioning the moving parts properly within their constraining structures. The standard configuration for electrodynamic cone loudspeakers is the very well known combination of a spider and a surround [3]. The mechanical spring forces within the driver typically operate in conjunction with acoustic compliance, particularly at lower frequencies.

However, a variety of mechanical considerations make it very difficult to design a small driver that is capable of long linear excursion, has a usable efficiency, and has a sufficiently low resonant frequency to maintain this efficiency down into the bass range. Much of the difficulty arises from the interaction between the geometric constraints of small drivers with the non-ideal characteristics of the flexible materials themselves. Attempting to deform a compliant part too far from equilibrium will result in, at best, highly non-linear forces and, at worst, immediate or premature failure. Roll or accordion-like construction geometries improve the situation, but the fact remains that small mechanical parts cannot be expected to flex over distances substantially greater than their minimum perpendicular dimension. Further, highly compliant materials that allow a maximized range of motion and extended low frequency response are often susceptible to wear and fatigue, and are difficult to handle on a high-volume production line, due to the fact that their softness complicates automated handling and alignment. Conversely, stiffer materials that are easier to handle may limit linear excursion and raise the resonant frequency of the transducer, thus reducing bass extension. Stiffer materials generally also have lower internal energy damping and may introduce undesirable structural resonances.

3. MAGNETIC SUSPENSION ALTERNATIVE

In order to overcome the limitations of traditional suspension techniques, one can postulate a transducer in which magnetic forces replace soft parts, potentially allowing much greater excursion while eliminating friction, resonance and material fatigue. A small variety of magnetic suspension approaches have been documented over the years, including hybrid combinations applying both magnetic and mechanical compliance. The majority of these inventions are relatively large, with moving masses most suitable to low frequency applications.

In contrast, the primary attention of the present research has been focused on very compact motors (<10 cm^3), which are capable of covering a substantial portion of the audible frequency range when driven at moderate levels. The fundamental motive force employed is the electrodynamic interaction between a fixed coil and a moving magnet. A tubular housing supports the energizing coil and contains the moving magnet. Extremely low primary resonances and long linear excursions can readily be achieved from transducers of about 10 mm in diameter.

Significantly, no mechanically flexible elements are needed, and the transducer further employs a novel magnetic suspension system based on balanced repulsive forces.

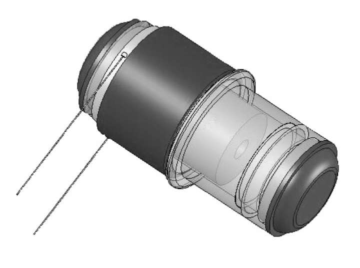

Figure 1 Magnetic Suspension Transducer

The motor shown operates with peak forces in the range of several Newtons and is capable of actuating substantial coupled mass throughout the audible band. Devices with primary resonances between 2 Hz and 35 Hz have been constructed in tubular forms of less than 30 mm in length, with high frequency extension ranging to over 25 KHz. Applications for these motors include direct radiators, vibration actuators and headphones.

The moving magnet design results in a sensitivity somewhat lower than conventional moving coil transducers. However, adequate performance may be obtained using the best available magnetics and careful optimization of the magnetic system.

4. DESIGN APPROACHES

In our current motor design, the moving magnet travels along the inside of a tubular enclosure, centered radially by two “skates” of ferromagnetic liquid. The shape of the magnet concentrates the fluid into two rings, one at each magnetic pole, which aggregate around the ends of the slug. Careful matching of fluid properties with the magnet dimensions and the available gap between the moving slug and the outer tube provides extremely stable and low friction bearings, as shown in Figure 2.

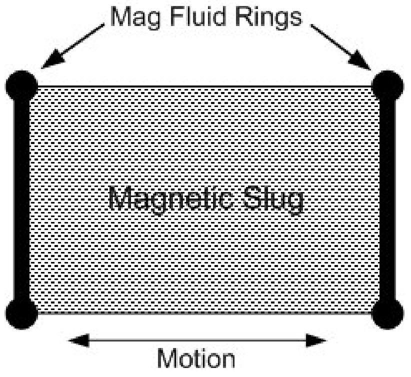

Figure 2 Magnetic Fluid Bearings

The containment tube supports one (or more) solenoidal coil sections, which together present an impedance and sensitivity essentially similar to a conventional electrodynamic speaker. A novel means of providing restoring and centering force is also described below.

In order to improve upon the performance of mechanically compliant suspensions, various fixed magnet configurations were explored. The goal was to develop a force vs. displacement profile that is sufficiently linear so as not to produce excessive distortion over an unusually long range of motion, and which inherently creates a stable rest position for the moving parts. An initial approach attempted to use magnets or ferromagnetic materials located at the midpoint of the housing, which served to attract the moving magnet [4], as shown in Figure 3.

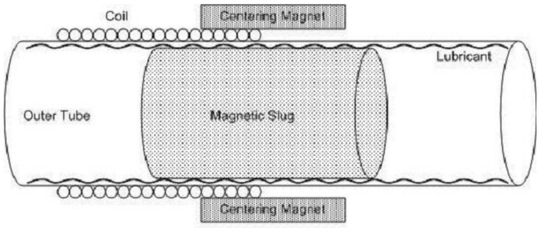

Figure 3 An Initial Design Approach

These first efforts proved less than ideal, since the inherent non-linearity of the magnetic forces as a function of distance led to signal distortion. Also, since the restoring force is rapidly diminished towards the excursion extremes, signal overload was a concern.

Figure 4 shows the schematic of a more successful design, as currently employed. This approach utilizes two small, fixed magnets, one at each end of the tube. These end magnets are both oriented so as to repel the moving magnetic element. As the repulsive forces balance, the moving slug is forced towards the center of the tube. The end magnets may be solid in the case where the motor is used as an inertial actuator, but the moving slug should then be vented through its center to allow air pressure to equalize at either end. For direct radiator applications, the end magnets may be perforated, may be rings, or may simply be small enough to allow sufficient radiation. In any case, the direct radiator uses a solid moving slug, with no need for venting.

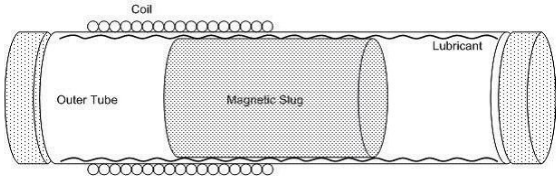

Figure 4 Improved Approach

A simplified view of this "Repulsive Mode" magnetic arrangement is shown in Figure 5. The electromagnetic coil and containment tube are not shown. The magnetic slug is free to move horizontally, constrained within the tube by rings of tightly bound magnetic fluid. The slug is suspended and centered horizontally in the absence of signal by fixed permanent magnets.

The theoretical and measured results are very satisfactory, since the push-pull configuration reduces distortion, and the increase in repulsive force towards the displacement maxima provides a natural, progressive limiting function.

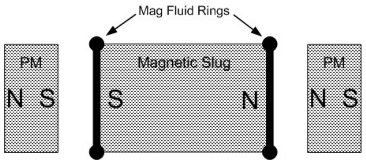

Figure 5 Repulsive Mode Magnetic Suspension

The magnetic system was modeled using a radial simplification, as shown in Figure 6. Quarter slices of the moving slug, the end magnets and the actuating coil may be readily identified.

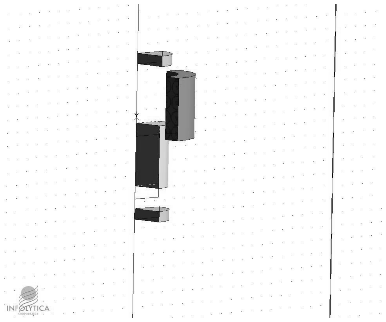

Figure 6 Magnetic System Model

Force vs. Displacement curves for this magnetic arrangement is shown in Figure 7. For comparison, Force vs. Displacement for the mechanical suspension of a representative 4.5 inch woofer in shown in Figure 8. This woofer provides a generally similar maximum volume displacement as the magnetic suspension transducer under consideration.

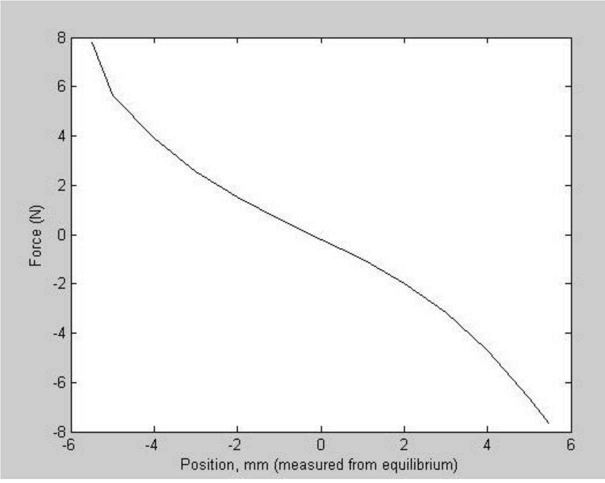

Figure 7 Force vs. Displacement For Magnetic Repulsive Suspension

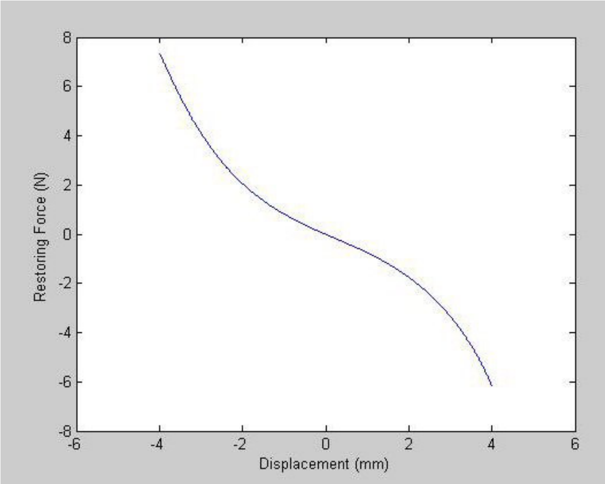

Figure 8 Force vs. Displacement For Mechanical Suspension

While the correspondence between the mechanical and magnetic systems is not exact, it does serve to show that the desired linearity and limiting functions have been achieved in both cases. If anything, the magnetic system can be seen to have slightly better linearity and over a somewhat greater excursion.

5. APPLICATION

As noted above, the transducer described has been designed into commercially available audio headphones. The device is here operated as an inertial transducer in which the outer tube radiates sound directly to the listener's ear. The inertial transducer, of course, requires its own suspension. However, because it comprises a system that is predominantly mass-controlled, the suspension design is simplified. Figure 9 shows example frequency responses from two different capsules taken using a KEMAR manikin. Both low- and high-frequency rolloff effects can be seen arising from the KEMAR and compliant headband mounting, but the method remains preferable to most alternatives for characterizing headphone transducers.

A psychoacoustic or listener preference analysis of the magnetically suspended driver used in a headphone is beyond the scope of this paper. There are many variables that can influence the performance and perception of headphone sound. All listeners, however, noted that the moving mass system, with its very low resonant frequency and strong bass output, yielded a listening experience that was unusually visceral for headphone reproduction.

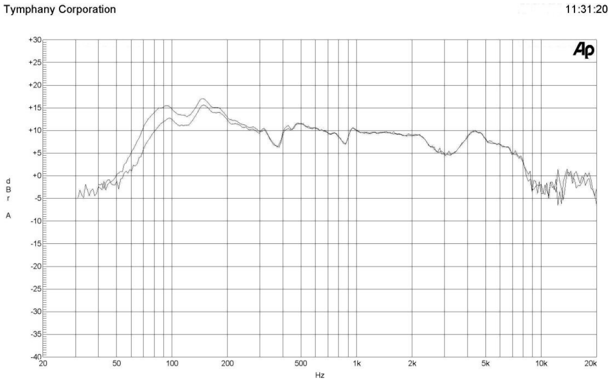

Figure 9 Headphone Frequency Response

6. EQUATIONS OF MOTION

In determining the generalized equations of motion for the magnetic slug and its containing tube, the principle of momentum conservation applies: any change in the momentum of the moving magnet will be accompanied by an equal and opposite change in the momentum of the housing:

$$\frac{d}{dt}\left(m_c\dot{x}_c + m_s\dot{x}_s\right) = m_c\ddot{x}_c + m_s\ddot{x}_s = 0 \qquad (1)$$

This can also be thought of as an application of the well-known “action-reaction” principle: the forces applied by the electromagnetic coil and the end magnets onto the moving slug are also applied by the moving slug to the coil and the end magnets. Since the coil and end magnets are firmly attached to the housing of the transducer, these reactive forces are transmitted to the housing. In the case of an inertial transducer, the resulting vibration is transmitted to the air surrounding the housing and becomes the primary sound generation mechanism. In the case of a direct radiator, the housing vibration is minimized, and sound is produced via the motion of the magnet.

The equations of motion for the housing and the magnetic slug are given by:

$$m_c\ddot{x}_c + b\cdot(\dot{x}_c - \dot{x}_s) + k(x_c - x_s) = BL\cdot i \qquad (2)$$

$$m_s\ddot{x}_s + b\cdot(\dot{x}_s - \dot{x}_c) + k(x_s - x_c) = -BL\cdot i \qquad (3)$$

It is simple to verify the conservation of momentum (1) by adding together equations (2) and (3). The above equations, use the following notation:

x_c is the position of the housing relative to an inertial frame, $\dot{x}_c$ is its velocity, and $\ddot{x}_c$ is its acceleration;

m_c is the mass of the housing, which includes the shell, the coil, the restoring end magnets, and the effective mass of any attached structure;

x_s is the position of the slug relative to an inertial frame, $\dot{x}_s$ is its velocity, and $\ddot{x}_s$ is its acceleration;

m_s is the mass of the slug and the surrounding ferromagnetic liquid;

b is the mechanical damping between the slug and the housing;

$k = g(x_s - x_c)$ is the stiffness and is a nonlinear function of the relative position of the slug and the housing. The resulting force is depicted in Figure 7. It is the result of the interaction between the magnetic slug and the end magnets.

BL is the force factor, which is also a nonlinear function of the relative position of the slug and housing, i.e., $BL = f(x_s - x_c)$.

7. CONCLUSION AND SUMMARY

The transducer described in this paper replaces the mechanical soft parts traditionally used in diaphragm suspension with purely magnetic forces; this results in several differences compared to existing transducers:

- Tubular form factor allows efficient new product design possibilities.
- Resonant frequency is significantly lower than in conventional transducers of similar size, and can be tuned for specific applications through the appropriate choice of magnet size and strength.
- Linearity is improved over longer excursions, as illustrated in Figures 7 and 8.
- Life expectancy can be improved due to reduced wear and tear.
- Environmental robustness can be increased given the possibility of a completely sealed system.

- Manufacturing becomes simpler and more consistent due to reduced parts count and a self-aligning assembly.
- Efficiency is somewhat lower than most electrodynamic motors.
- Some stray magnetic field.

Prototype Specifications:

- Size: 15 mm (D) X 32 mm (L)
- Weight: 12 g
- Impedance: 16 Ω, minimum
- Operating Range: 5 Hz to 18 kHz, nominal
- Efficiency: 83 dB/mW, (in-ear)
- Max Output: 115 dB (in-ear)
- Distortion: <0.2% typical
- Linear Excursion: 10 mm p-p

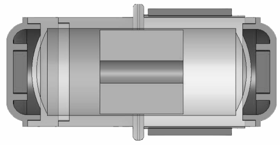

Figure 10 Cross-Section of Compact Magnetically Suspended Transducer

In summary, a Compact Magnetically Suspended Transducer has been designed, optimized and characterized. It fully eliminates flexing mechanical parts to provide certain advantages hard to achieve with conventional technology. We hope not only to bring benefits to certain product applications, but also to prove the practicality of magnetic suspensions and stimulate research in this area of speaker design.

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