Ironless loudspeakers

Guy Lemarquand

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G. Lemarquand

Abstract

We note the drawbacks of classical loudspeaker motors: the inductance varies with the coil's position, there is a reluctant effect and Eddy currents appear because of the iron in the motor. We then present ironless structures of loudspeaker motors to eliminate these drawbacks. These structures are studied with the use of Coulomb's model of permanent magnets, which affords analytical calculations. Thus the design can be optimized to create a uniform, high level induction in the space where the coil moves.

I. Classical iron structures

Classical loudspeakers have a well-known structure: the coil moves in front of the iron pole pieces of a magnetic circuit which is excited by a permanent magnet. This structure has three major drawbacks [1]. The magnetic field in the airgap is non-uniform. The inductance of the coil varies with the coil's position. Both effects create a distortion that increases with the displacement of the coil i.e. with the sound level. Eddy currents in the pole pieces create a force that ejects the coil out of the airgap and lessens the stability of the loudspeaker. The suppression of the nonlinearities has been the permanent challenge of moving coil loudspeaker designers [2].

A. Electrical model

The simple descriptions of the electrodynamic loudspeakers use equivalent electrical circuits. The voice coil is considered an impedance that is resistive and inductive, where the coil gives rise to a back electromotive force (EMF) proportional to the cone velocity. The acoustomechanical aspects of the cone motion are reflected in the impedance, and the loudspeaker output can be predicted from the electrical input in the range of frequencies for which the cone moves as a rigid assembly [3] [4] [5].

B. Inductance effects

Several parameters make the inductance vary and we describe here all these effects.

The iron pole pieces increase the inductance of the moving coil. The corresponding impedance increases with the frequency. The loudspeaker is fed by a voltage amplifier, and the force exerted by the coil on the diaphragm is proportional to the current [6]. So the force decreases with the frequency, and this force is not in phase with the voltage. The phase shiftings of the harmonics of the electrical signal are not maintained. This frequency-dependent impedance variation causes a variation in the applied force. In the classical structure, a short circuiting coil is added on the stator to reduce the inductance of the moving coil and thus the distortion of the speaker's output.

Another effect of the iron pole pieces is the following. The coil behaves like a moving iron yoke coil, the yoke in this case is around the coil. When the coil moves, the position of the yoke changes and as a consequence the reluctance of the magnetic circuit of the coil varies. For a displacement from the centered position of the yoke with regard to the coil, the reluctance increases and this leads to the creation of a force on the coil in a direction that decreases the reluctance. A centering effect is thus observed. This force is proportional to the current in the coil. Both described effects are in fact position dependent. When a high frequency signal is superimposed to a low frequency signal, the answer of the loudspeaker is not the same as for the high frequency signal alone, because the mean position of the coil in the airgap is not the same. As a result, intermodulation is observed.

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The author is with the Laboratoire d'Acoustique de l'Universite du Maine UMR CNRS 6613, Avenue Olivier Messiaen, 72085 Le Mans Cedex 9, France

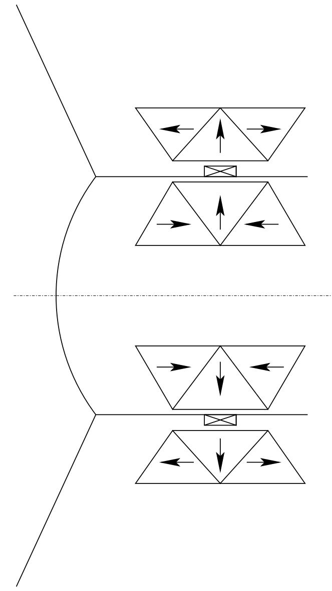

Fig. 1. Ironless loudspeaker structure.

C. Eddy currents effects

Many authors have noted that Eddy currents flowing in the solid iron pole structure modify the electrical impedance. The voice coil motors have a normal inductive behavior at low frequencies. At high frequencies, the Eddy currents hinder the magnetic flux from penetrating the iron. A first consequence is the decrease of the effective permeability of the iron and so, a decrease of the inductance of the coil: this decrease is a proof for the existence of the Eddy currents. The measurement of the inductance is the easiest way to determine the frequency at which Eddy currents appear. Vanderkooy describes this as a semi-inductive behavior of the loudspeaker [7].

The Eddy currents appear to suppress that which creates them. The Eddy currents flow circularly in the iron pole pieces around the coil's axis. They create a magnetic moment that has the same direction as the one created by the current in the coil. Thus they create a magnetic field in the coil that is opposed to its own field. The moving coil becomes axially unstable (and radially stable). As soon as the coil moves, the action of the Eddy currents is to create axial forces that tend to eject the coil from the airgap. The system behaves like an Eddy current magnetic bearing. This axial force is another cause of distortion.

To reduce Eddy currents Yamamuro [8] and Bank [9] propose to use laminated pole pieces.

II. IRONLESS MOTOR

We present an ironless structure, made totally out of permanent magnets. The first advantage is that the inductance of the coil is very low and constant. The second advantage is the absence of the reluctance effects and a great decrease of the Eddy currents, depending on the electrical conductivity of the permanent magnets' material. As a consequence, some sources of distortion are suppressed. The third advantage is the increase of the magnetic field and the decrease of the magnetic leakage, leading to good efficiency of the loudspeaker [10].

Our major goal is to create a very uniform induction in the space of the moving coil to cancel the harmonic distortion. The induction level must be increased to improve the efficiency of the loudspeaker.

The maximum excursion of the coil is limited in the presented structure by the inversion of the magnetic field in the areas outside the nominal displacement. This constitutes a good protection for the suspensions elements, spider and outer peripheral edge when a peak of power is applied to the voice coil motor. It is noticeable that these structures are not very difficult to realize with the use of plastic bonded magnets.

A. Geometry of the device

The motor comprises two concentric sets of permanent magnets rings (Fig.1). The rings have a triangular section. Each set is a stack of three rings. The ring in the middle has a radial magnetization. The two other rings are axially

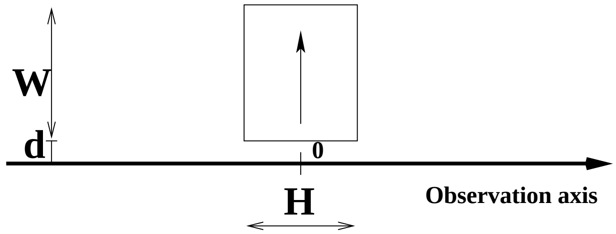

Fig. 2. Single rectangular magnet structure.

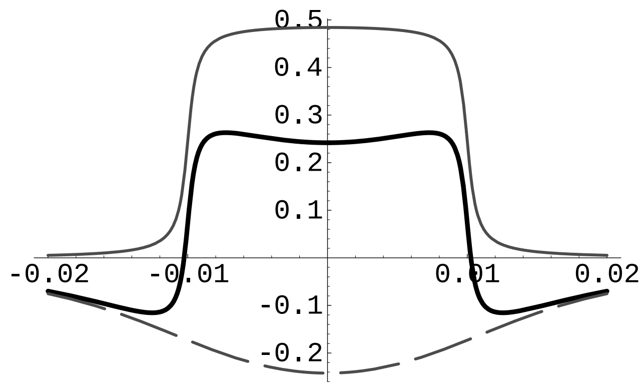

Fig. 3. Radial magnetic induction, B_r (T), created by one magnet, along the observation axis. Induction created by the near face, by the far face (dashed line) and resultant induction (bold line).

magnetized. The radial space between the sets defines a cylindrical airgap in which the whole coil is located.

At standstill, the sets are centered and the centers of the central ring of each set are in the same perpendicular to the axis plane. The radial component of the magnetic field in the airgap goes from the inner set to the outer set. We consider this direction as the positive one.

B. Analytical study of the structure

We consider a magnetic polar model for all the permanent magnets. We assume that the magnetization of the magnets is uniform, so we have to consider only surface pole densities. For a general purpose, we consider that the magnetization of each magnet is equal to 1 tesla. We consider a structure of infinite radius (length) in order to show results that are independent of the radius of the device. We give the result for one set of rings.

We use Coulomb's theorem to calculate the field created in the free space by a charged plane and apply it to all the planes. For the whole structure, the total field is calculated by multiplying the previous result by two (for the two sets) and by the real value of the magnetization of the magnets. The curvature must be taken into account too.

1) Field created by one magnet: We calculate the field created by a single rectangular magnet (height, h, of $2cm$, width, w, of $1cm$, infinite length) in the air at a distance, d, of $0.5mm$ of the magnet (Fig.2). This analytical calculation uses the well-known formulas of the field created by two charged planes [11].

Fig.3 shows the component, B_r, of the magnetic induction along the observation axis. The field created by the near face (the face at the lower distance from the observation axis) is almost uniform in front of the magnet. The field created by the far face (the face at the greater distance from the observation axis) has the opposite sign and varies over the front of the magnet. We notice that for a thin magnet (the width is the half of the height) the resultant field is lowered and distorted by the influence of the far face. For a position on the observation axis no longer in front of the magnet the sign of the radial component, B_r, of the induction changes.

Fig.4 shows the influence of the width of the magnet.The dashed line shows the induction created by the near face alone. Of course, when the width increases the resultant induction approaches the induction created by the near face. When the width decreases, the induction is both decreased and distorted.

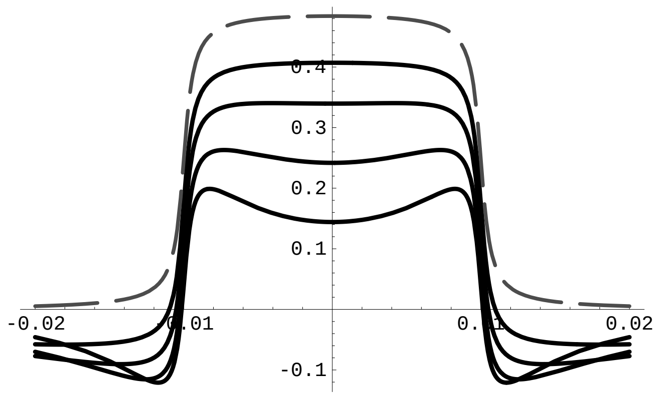

Fig. 4. Radial magnetic induction, B_r (T), along the observation axis, created by the near face (dashed) and by one magnet for various values of the width, from bottom to top, $w = 0.5cm, 1cm, 2cm$ and $4cm$.

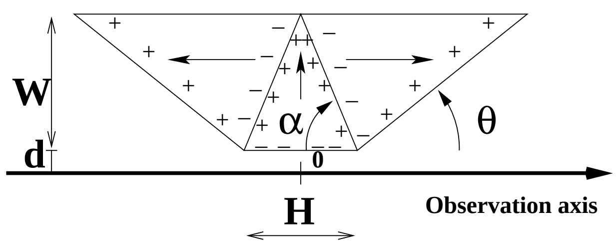

Fig. 5. Three magnets structure.

2) Three prismatic magnets structure: We consider now our new device with the stacked structure of the magnets illustrated by Fig.5.

We first compare the induction created by this structure with the one created by a single square magnet (w is $2cm$, h is $2cm$). The central magnet is $2cm$ high and $2cm$ wide. The angle θ defining the dimensions of the side magnets is varied. When θ equals 90^o the whole structure has a square section, identical to the single magnet one. Fig.6 shows that the induction in front of the central magnet increases nevertheless by 22%. We observe that when θ decreases, the induction in front of the central magnet increases. As an example, this increase reaches 76% for a value of θ of 30^o. We also notice that an optimal value of θ exists that makes the radial induction, B_r, quite uniform in front of the central magnet. These structures increase the induction value on the side of the observation axis (front) because they diminish the flux on the other side of the structure (rear). Indeed, the rear flux appears as a leakage for the loudspeaker.

An optimum is found when θ equals 45^o (Fig.7). Both first and second derivatives of the induction are null in front of the central magnet ($x = 0$), so, the induction is almost a constant for small displacements of the coil. The value of the induction is $0.57T$, which represents 164% of the value obtained whith a single square magnet.

As a remark, the magnetic pole density, σ_c^*, of the central magnet on the inclined plane is:

$$\sigma_c^* = Jcos\alpha \quad (1)$$

where J is the magnet polarization and α the magnet's angle defined on Fig.5. The magnetic pole density, σ_l^*, of the lower (resp. upper) magnet on the same inclined plane is:

$$\sigma_l^* = -Jcos(90 - \alpha) \quad (2)$$

When the width, w, is greater than the half height, $h/2$, the angle α is greater than 45^o. So, σ_c^* is greater than σ_l^* and the resulting magnetic pole density on the inclined separating plane of the magnets is negative. Of course, there is no magnetic pole density on the lateral sides of the upper and lower magnets (rear of the structure). When the width, w, equals the half height, $h/2$, the angle α is 45^o and there is no magnetic pole density on the separating plane of the magnets.

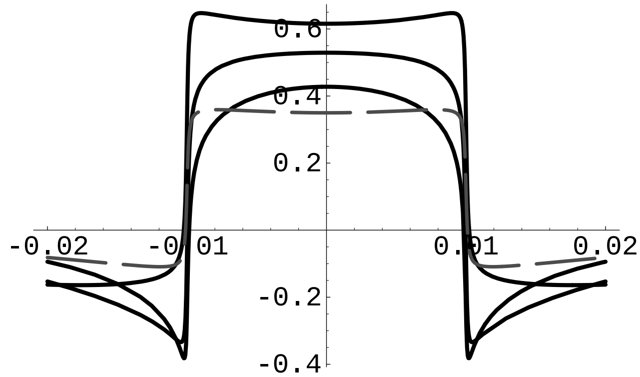

Fig. 6. Radial magnetic induction, B_r (T), along the observation axis. Comparison between the single magnet structure (dashed) and the three magnets structure when θ equals $30^o, 60^o$ and 90^o (from bottom to top) and $w = 2cm, h = 2cm$.

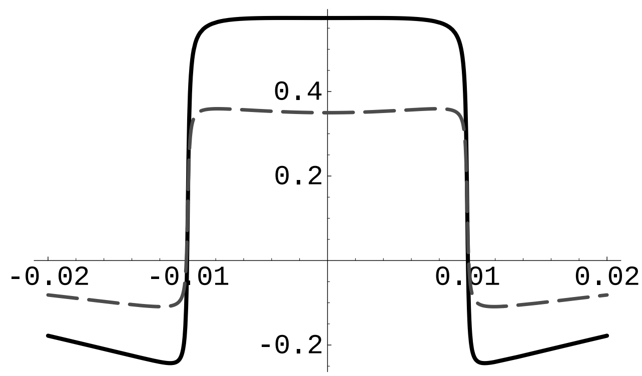

Fig. 7. Radial magnetic induction, B_r (T), along the observation axis, created by the optimal structure: $\theta = 45^o$ and $w = 2cm, h = 2cm$. Dashed line: single magnet.

When the width, w, is smaller than the height, h, the value of the induction in front of the central magnet is still greater than for the single magnet, but the second derivative of the induction can no longer be cancelled (Fig.8). The radial induction varies greatly in front of the central magnet. In this case also, variations of θ only modify the induction in the area which is not in front of the central magnet.

3) Improved thin structure: Fig.9 shows the three magnets structure where the central magnet is no longer triangular, but has been truncated to a trapezoid. The angle α can now be varied independently from the width, w, of the structure. This allows the optimization of the shape of the induction in front of the central magnet (Fig.10, Fig.11). Of course, the induction created by a thin structure is lower than for a wide one. For a $7mm$ (resp.$5mm$) width, w, the radial induction created by a single magnet is $0.19T$ (resp.$0.14T$). But the three magnets structure still gives higher induction levels than the single magnet. The optimal structure with regard to the uniformity of the induction reaches a value of the induction 188% (resp.195%) higher than the single magnet one.

III. Conclusion

The principal aim in the design of a loudspeaker motor structure is to achieve the greatest possible magnetic field strength and uniformity in the space where the coil moves. We note that in classical structures, the iron of the motor makes the inductance of the coil vary with the position of the coil, thereby creating a reluctant effect. These solid iron pole pieces also allow Eddy currents to appear. The consequence is a distortion of the sound of the loudspeaker. We propose ironless structures of motors: the inductance is small and constant, there is neither reluctant effect, nor Eddy currents. The analytical calculations of the induction in these structures, using Coulomb's model of a magnet, afford optimization of the dimensions of the structures with regard to the induction uniformity.

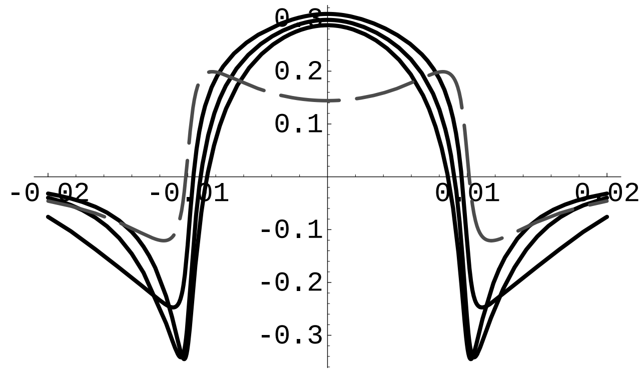

Fig. 8. Radial magnetic induction, B_r (T), along the observation axis, created by thin three magnets structures. From bottom to top: w=2cm, h=5mm, d=0.5mm, $\theta = 30^o, 60^o, 90^o$. Dashed line: single magnet.

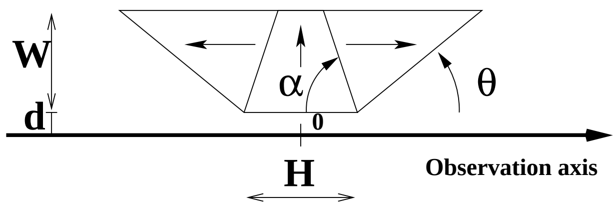

Fig. 9. Three magnets structure with a central trapezoid magnet.

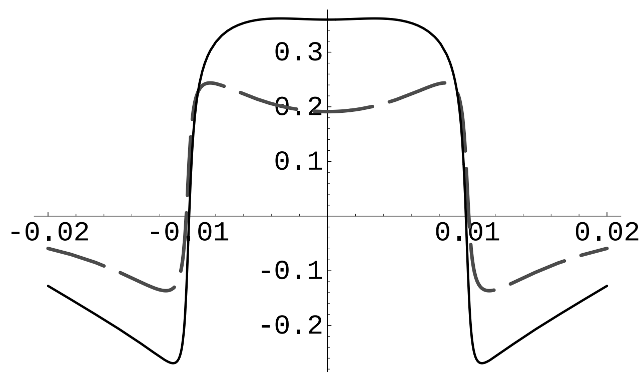

Fig. 10. Radial magnetic induction, B_r (T), along the observation axis, in the optimal truncated three magnets structure. $w = 7mm$, $\theta = 30^o$, $\alpha = 40^o$, $h = 2cm$, $d = 0.3mm$. Dashed line: single magnet.

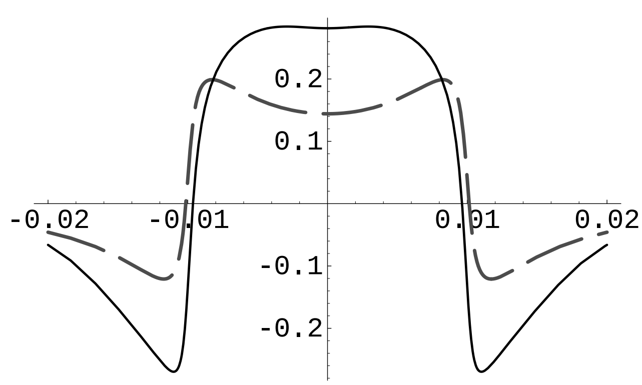

Fig. 11. Radial magnetic induction, B_r (T), along the observation axis, in the optimal truncated three magnets structure. $w = 5mm$, $\theta = 35^o$, $\alpha = 31.5^o$, $h = 2cm$, $d = 0.5mm$. Dashed line: single magnet.

Stacked structures of magnets afford high induction values. These ironless structures seem to be an interesting alternative to the classical structures of loudspeaker motors.

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