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► **To cite this version:**

Guy Lemarquand, Romain Ravaud, Valérie Lemarquand, Claude L. Depollier. Mechanical Properties of Ferrofluids in Loudspeakers.. 125 th Convention, Oct 2008, San Francisco, United States. pp.7533. hal-00413291

HAL Id: hal-00413291

<https://hal.science/hal-00413291>

Submitted on 3 Sep 2009

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Mechanical Properties of Ferrofluids in Loudspeakers.

Guy Lemarquand, Romain Ravaud, Valerie Lemarquand and Claude Depollier

Abstract

This paper describes the mechanical properties of ferrofluid seals in ironless electrodynamic loudspeakers. The motor is constituted of several outer stacked ring permanent magnets. The inner moving part is a piston. In addition, two ferrofluid seals are used which replace the classical suspension. Indeed, these seals fulfill several functions. First, they ensure the airtightness between the loudspeaker faces. Second, they act as bearings and center the moving part. Finally, the ferrofluid seals also exert a pull back force on the moving piston. Both radial and axial forces exerted on the piston are calculated thanks to analytical formulations. Furthermore, the shape of the seal is discussed as well as the optimal quantity of ferrofluid. The seal capacity is also calculated.

I. INTRODUCTION

Electrodynamic loudspeakers have a well-known structure: a coil moves in front of the iron pole pieces of a magnetic circuit polarized by a permanent magnet. Moreover, it is also well-known that classical electrodynamic loudspeakers have drawbacks whose consequences are nonlinearities. Many authors highlighted these nonlinearities and proposed solutions to reduce or suppress them [1][2][3]. The three major drawbacks are the following. First, the magnetic field in the air gap is non-uniform. Second, the inductance of the coil, which exert a non linear pull back force on the moving part [4], varies with the coil position. Both effects are sources of a distortion which increases with the coil displacement and the current intensity, so with the sound level. Third, Eddy currents in the pole pieces create a force which ejects the moving part and the coil out of the air gap, thus lessening the stability of the loudspeaker. The analysis of these drawbacks lead us to a peculiar design of loudspeaker motors, namely to ironless motors with ferrofluid seals. Furthermore, as these structures suppress some of the nonlinearities sources, such as the iron and the classical suspension, they have an improved behavior. Besides, the absence of iron enables analytical formulations to calculate their properties and authorizes multi-criteria optimization as well. This paper first reminds the drawbacks related to the iron. Then, it presents the proposed ironless structures with ferrofluid seals. Finally, it shows how the mechanical properties can be calculated.

II. THE ELECTRODYNAMIC LOUDSPEAKER

A. Drawbacks of the Classical Iron Structures

It has to be noted that equivalent electric circuits are used to describe the electrodynamic loudspeakers. Thereby, the voice coil is modeled by an impedance which is both resistive and inductive. Moreover, the coil gives rise to a back electromotive force (EMF) which is proportional to the cone velocity. So, both acoustic and mechanic behaviors of the cone are to be found in the impedance variations. As a consequence, the loudspeaker output signal can be predicted from the electric input of the equivalent circuit. As long as the moving part can be considered as a rigid assembly, the model is valid in the corresponding frequency range.

1) *The Inductance:* As a matter of fact, the iron pole pieces increase the inductance of the moving coil. Consequently, the impedance increases with the frequency. On one hand, the loudspeaker is generally fed by an open loop voltage amplifier. On the other hand, the force exerted by the coil on the moving part is proportional to the current. So, the current decreases when the frequency increases and the force decreases too. Furthermore, the voltage and the force are out of phase. Consequently, the phase shiftings of the electric signal harmonics are modified. It can be noted that a short circuiting coil is sometimes added on the stator of the classical electrodynamic loudspeaker, in order to reduce the moving coil inductance and thus the distortion of the output signal. It is to be noted that another effect is related to the coil. Indeed, the latter behaves like a moving iron yoke coil for which the yoke is around the coil. So, when the coil moves, the yoke position changes and the reluctance of the magnetic circuit varies. Moreover, when the coil moves from the centered position of the yoke with regard to the coil the reluctance increases. Consequently, a force is created on the coil in such a direction that makes the coil move to decrease the reluctance. This results in an axial centering effect. Furthermore, the exerted force is proportional to the square of the current in the coil. So, this pull back force is non linear.

2) *The Eddy Currents:* It has been proved that the electrical impedance is modified by Eddy currents flowing in the solid iron poles. As a consequence, voice coil motors have a normal inductive behavior at low frequencies whereas the Eddy currents hinder the magnetic flux from penetrating the iron at high frequencies. Thereby, the result is the decrease of the effective permeability of the iron. This implies a decrease of the coil inductance, thus proving the existence of the Eddy currents. It can be noted that measuring the inductance is the easiest way to determine the frequency at which Eddy currents appear. Moreover, Eddy currents always appear to counteract their own causes. In the present case, they create a magnetic moment in the iron pole pieces, whose direction is the same as the one of the magnetic moment created by the current in the coil. The resulting system behaves like an Eddy current magnetic bearing. Unfortunately, the moving coil becomes axially unstable (but remains radially stable according to Earnshaw theorem). Indeed, the interaction of both magnetic moments creates axial forces that tend to eject the coil out of the air gap. These axial forces are another cause of distortion. Laminated pole pieces are a solution to avoid Eddy currents flowing circularly in the iron pole pieces around the coil axis.

III. THE IRONLESS STRUCTURE

A. Description

We propose loudspeaker motors totally made out of permanent magnets. Indeed, figure.1 presents a motor structure which consists of three outer stacked ring permanent magnets which are radially magnetized. It has to be noted that the middle ring magnetization has a direction opposed to the one of both extremity rings. Moreover, the moving part is an inner piston out of non magnetic material which is radially centered with the rings. One of its extremities is the emissive surface which is convex here, but could also be either plane or concave depending on the intended acoustic properties. Furthermore, a short coil is wound around the piston so that it is entirely in the region of uniform magnetic field, even when it moves. Besides, ferrofluid seals are located in the air gap between the inner piston and the outer ring magnets. As a consequence, the classical suspension disappears. The air in the rear cavity constitutes the loudspeaker pneumatic suspension. Therefore the suspension behavior is linear.

B. Properties

1) *The absence of iron:* As a matter of fact, the absence of iron suppresses the reluctance effect and its related non linearities. Moreover, the coil self inductance is dramatically decreased which is interesting for the loudspeaker impedance at high frequencies. Furthermore, as the permanent magnets have a small

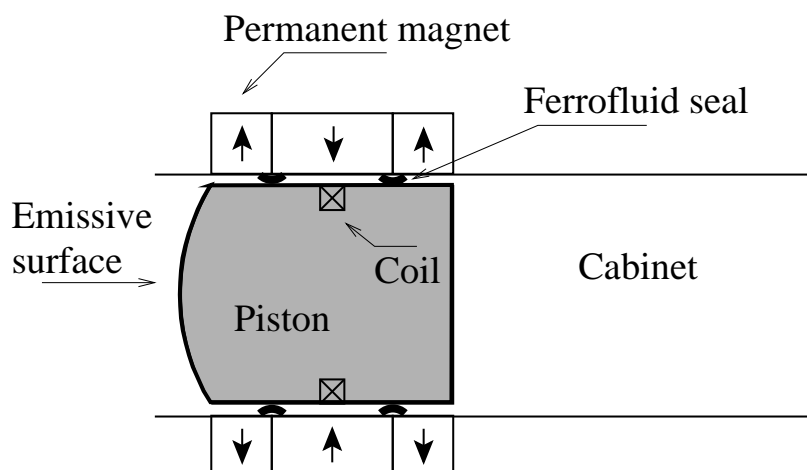


Fig. 1. Structure of an ironless loudspeaker.

electric conductivity the Eddy currents in the pole pieces disappear too. It is emphasized that plasto-magnets are well adapted for the realization of such motors and are electrically insulating. The iron suppression solves the saturation problem too, which was becoming a technical limit with the new rare earth permanent magnets. Consequently, some of the sources of distortion are removed. Furthermore, the design of the magnet assembly allows the use of a short coil entirely located in a region of uniform magnetic field. So, the force factor is significantly increased. For example, the device middle magnet of Fig.1 is twice as long as the extremity magnets. Thus, the region of uniform field corresponds to the middle ring magnet length. Besides, ironless motors enable to control the magnetic leakage and even to design devices with no leakage at all [5]. Indeed, the ironless concept offers various design possibilities. In fact, the devices can be simple and use only two ring magnets (or even a single one) or they can be more complicated, with three or more ring magnets of various section shape. Furthermore, they have the great interest of being analytically tractable, a fact that enables their optimization. Besides, their optimization can be made with several criteria, such as the magnetic field uniformity, its intensity level but also the mechanical properties of the ferrofluid seals.

2) *The moving part:* The inner moving part is a piston with plane extremities. Besides, the classical suspension disappears. Instead, two ferrofluid seals are used which fulfill several functions. First, they ensure the airtightness between the loudspeaker faces. Second, they allow the heat transfer from the moving coil to the stator. Such a use is common in loudspeakers. But the ferrofluid seals also act as bearings and center the moving part by exerting a radial force on the moving part. Moreover, they exert a pull back force on the moving piston too. Consequently, they play the same part as the suspension and the spider. These functions are more innovative. It is to be noted that the suspension is due to the compression properties of the air in the rear cavity. In order to avoid the rest position offset when the atmospheric pressure varies, the latter is provided with a capillary tube whose extremity is at the external pressure. The ferrofluid seal exerts a light pull back force towards the stable equilibrium rest position. Moreover, this pull back force is ten thousand times smaller than the air compression force. Thus, the loudspeaker compliance is only related to the air compressibility which is perfectly linear. It is pointed out that the sliding of the piston on a ferrofluid allows very large displacements of the moving part. From

this point of view, the piston length has to be chosen so that the ferrofluid seals remain confined between the piston and the stator over the whole displacement range. The structure of Fig.1 is long because it is intended for large displacements. The only movement limitation is linked to the displacement speed. Indeed, it has been proven that intermodulation appears for high speeds (a few meters per second) and for a large bandwidth use of such ferrofluid suspended loudspeakers [6]. This phenomenon is due to the non linearity of the sound propagation in air.

C. Study and Calculations

An important point is the fact that the structure having no iron, we are able to calculate analytically the magnetic field, H , created by the magnets. Indeed, a coulombian model of the magnets, which represents each magnet by two charged surfaces, allows the calculation of all the components of the magnetic field they create [7]. On one hand, the calculation of the radial component of the magnetic field is useful to characterize a structure with the field intensity as well as the field uniformity. The analytical formulation enables to optimize the design of the magnets according to criteria such as high field intensity and uniformity over a given displacement range of the coil, which will enhance the force factor. Moreover, the design and the optimization can take the magnetic leakage into account, depending if it is tolerated or not for the device. On the other hand, the same calculation is useful to characterize the field gradients too. Indeed, the ferrofluid seals form where the field gradients are high. Furthermore, the magnetic pressure in the ferrofluid, pm , can be calculated too, as

$$pm(r, z) = \mu_0 MH,$$

where $(\mu_0 M)$ is the magnetization volume density of the ferrofluid and μ_0 is the vacuum magnetic permeability. The ferrofluid seals shape can thus be determined as the seal contour is a magnetic isopressure. Of course, the shape also depends on the ferrofluid quantity used. Besides, the mechanical properties of the ferrofluid seal can be calculated. Indeed, they come from the ferrofluid seal potential energy which is defined by:

$$E_m = - \int \int_{(\Omega)} pm(r, z) dV$$

where (Ω) is the ferrofluid seal volume. The radial centering force exerted on the moving part by the seal is expressed by:

$$F_r = \Delta E_m / \Delta r,$$

where Δr is the radial distance in length for which the piston is moved away and ΔE_m the corresponding potential energy variation. Therefore, the radial stiffness can be calculated as well. Moreover, the same reasoning for axial displacements leads to the axial force and stiffness. The capacity of the seal can be evaluated too. It must be emphasized here that the analytical formulation enables a great flexibility in the optimization of the seals characteristics. Indeed, a multicriteria optimization gives the possibility of optimizing the whole device, from the force factor and the magnetic leakage to the seal shape and the ferrofluid quantity, as well as the radial and axial stiffnesses and the seal capacity.

IV. CONCLUSION

This paper shows that significant improvements are still possible for such well-known devices as electrodynamic loudspeakers. Indeed, ironless loudspeakers with ferrofluid seals prove to have a very good linearity, as they suppress the source of many nonlinearities. Furthermore, their structure allows the analytical formulation of their magnetic and mechanic properties. In consequence, their optimization according to multiple criteria is not only possible but also very flexible. Eventually, it is to be noted that a first prototype was presented at the 120th AES Convention in Paris and that the improvements made since are quite satisfying.

REFERENCES

- [1] A. Dobrucki, "Nontypical effects in an electrodynamic loudspeaker with a nonhomogeneous magnetic field in the air gap and nonlinear suspension," *J. Audio Eng. Soc.*, vol. 42, pp. 565–576, 1994.
- [2] W. Klippel, "Loudspeaker nonlinearities - cause, parameters, symptoms," *J. Audio Eng. Soc.*, vol. 54, pp. 907–939, 2006.
- [3] M. R. Gander, "Dynamic linearity and power compression in moving-coil loudspeaker," *J. Audio Eng. Soc.*, pp. 627–646, September 1986.
- [4] G. Lemarquand, "New structure of loudspeaker," presented at the AES 120th convention, Paris, France, 2006.
- [5] M. Berkouk et al., "Analytical calculation of ironless loudspeaker motors," *IEEE Trans. Magn.*, vol. 37, pp. 1011–1014, March 2001.
- [6] G. Lemarquand and M. Bruneau, "Large bandwidth loudspeaker emitting coherent acoustic waves: nonlinear inter-modulation effects," *J. Audio Eng. Soc.*, vol. 56, pp. 36–44, January 2007.
- [7] R. Ravaut et al., "Analytical calculation of permanent magnet rings," *IEEE Trans. Mag.*, vol. 44, June 2008.