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IRONLESS LOUDSPEAKERS WITH FERROFLUID SEALS

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This paper describes the drawbacks related to the iron in the classical electrodynamic loudspeaker structure. Then it describes loudspeaker motors without any iron, which are only made of permanent magnets. They are associated to a piston like moving part which glides on ferrofluid seals. Furthermore, the coil is short and the suspension is wholly pneumatic. Several types of magnet assemblies are described and discussed. Indeed, their properties regarding the force factor and the ferrofluid seal shape depend on their structure. Eventually, the capacity of the seals is evaluated.

Keywords: electrodynamic loudspeaker, permanent magnet, ironless structure, ferrofluid seal.

1. The classical electrodynamic loudspeaker

1.1. Structure and drawbacks

The structure of electrodynamic loudspeakers is well-known: it consists of a coil which moves in front of the iron pole pieces of a magnetic circuit excited by a permanent magnet. It is to be noted that three major drawbacks have been highlighted [1, 2]. First, the magnetic field in the air gap is non-uniform. Second, the inductance of the coil 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 challenge of the electrodynamic loudspeaker designers has always been to suppress the nonlinearities.

1.2. Electrical modeling

The electrodynamic loudspeakers can be represented by equivalent electrical circuits. Thereby, the voice coil is modeled by an impedance which is both resistive and inductive. Moreover, a back electromotive force (EMF) proportional to the cone velocity appears in the coil. Therefore, the impedance variations are tightly related to the acoustomechanical aspects of the cone. As a consequence, the loudspeaker output signal can be predicted from the electrical input in the frequency range in which the moving part can be considered as a rigid assembly [3, 4].

1.3. The coil inductance has a prominent part

The coil inductance plays a prominent part in both the functioning and the quality of the loudspeaker. This section describes in which way.

First, the iron pole pieces increase the inductance of the moving coil. Consequently, the impedance increases with the frequency. Moreover, the loudspeaker is commonly fed by an open loop voltage amplifier while the force exerted by the coil on the moving part is proportional to the current [5]. As a result, the force decreases when the frequency increases. Furthermore, the voltage and the force are out of phase. The effect is to be seen on the phase shiftings of the electrical signal harmonics which are modified. In the classical electrodynamic loudspeaker, a short circuiting coil is sometimes added on the stator in order to reduce the moving coil inductance and thus the distortion of the output signal.

Second, the coil 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. Indeed, a coil displacement from the centered position of the yoke with regard to the coil implies a reluctance increase. 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. Moreover, this force is proportional to the square of the current in the coil.

Therefore, 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. Indeed, the coil mean position in the air gap is not the same in both cases. As a result, intermodulation is then observed.

1.4. The eddy currents create distorsion

It has been proved that the electrical impedance is modified by eddy currents flowing in the solid iron poles. So, at low frequencies, voice coil motors have a normal inductive behavior whereas, 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 which implies a decrease of the coil inductance, thus proving the existence of the eddy currents. Moreover, measuring the inductance is the easiest way to determine the frequency at which eddy currents appear. Furthermore, eddy currents appear to suppress what creates them. Indeed, they flow circularly in the iron pole pieces around the coil axis. Thus, they create a magnetic moment whose direction is the same as the one of the magnetic moment created by the current in the coil. Consequently, they generate in the coil a magnetic field which is opposed to the coil own field. Their action is to create axial forces that tend to eject the coil out of the air gap. Finally, the moving coil becomes axially unstable (and radially stable): The system behaves like an eddy current magnetic bearing. This axial force is another cause of distortion. Some authors [6] propose to use laminated pole pieces to avoid eddy currents.

The remainder of this paper describes another option which consists in totally suppressing the iron.

2. The ironless structure

2.1. Principle

This paper presents loudspeakers whose motors are made totally of permanent magnets. Indeed, the basic motor consists of two outer stacked ring permanent magnets which are radially magnetized in opposed directions. Moreover, the moving part is an inner piston made of non magnetic material which is radially centered with the rings. One of its extremities is the emissive surface and was chosen to be a plane. Furthermore, a short coil is wound around the piston so that it is entirely in the rather uniform magnetic field. 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.

It is to be noted that the inductance of the coil in this structure is very low and constant as the coil yoke has now the behavior of the air. In addition, the reluctance effects disappear. Furthermore, a great decrease of the eddy currents is observed as the permanent magnets have a small electric conductivity. Plasto-magnets are well-adapted to the motor realization and are electrically insulating. Consequently, some of the sources of distortion are suppressed. Moreover, the magnetic field can be increased, its uniformity improved and the magnetic leakage decreased, thus leading to a good efficiency of the loudspeaker [7, 8].

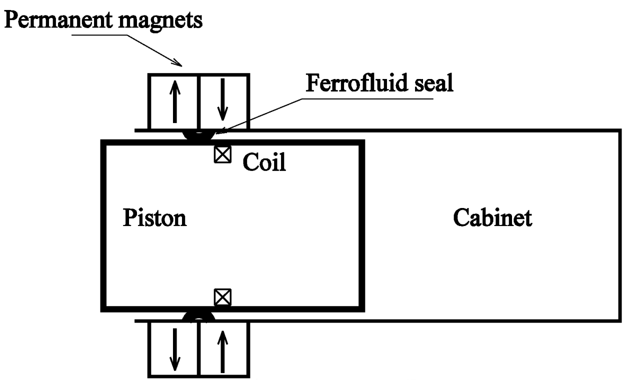

Fig. 1. Loudspeaker principle.

The concept of such structures offers various possibilities. Indeed, the devices can be simple and use only two ring magnets (or even a single one) but they can be more complicated, with three or more ring magnets. 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.

2.2. Tools for the study

It is emphasized here that all the calculations related to the presented structures are carried out analytically [9]. Indeed, a coulombian model is used for the magnets which allows the calculation of the magnetic field they create. Each ring magnet is represented by two charged surfaces which are the ring faces perpendicular to their magnetization direction. For radially magnetized rings, the charges or magnetic poles are located on both curved surfaces of the ring and their surface density is written $\sigma^* = J$, where J is the magnet polarization, in Tesla (T).

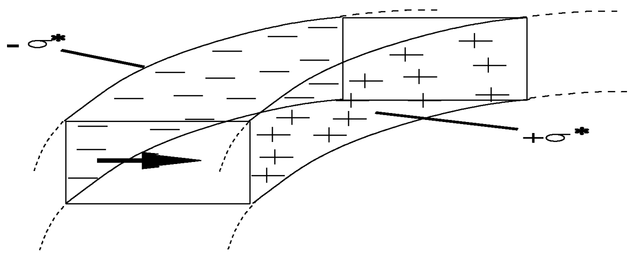

Fig. 2. Magnet coulombian model.

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 its uniformity. 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. Moreover, the magnetic pressure, $p_m(r, z) = \mu_0 MH$, in the ferrofluid and the ferrofluid potential energy, $E_m(r, z)$ are also calculated. where H is the magnetic field created by the magnets, $(\mu_0 M)$ is the magnetization volume density of the ferrofluid and μ_0 is the vacuum magnetic permeability. Besides, color plots of the magnetic pressure show its repartition in the air gap: the red zones correspond to the highest values, the blue ones to the smallest. They help determine the seal shape. Indeed, the seal contour is a magnetic iso-pressure.

Eventually, these expressions also allow the determination of the seal capacity.

2.3. Comparing structures

A simple structure contains two ring magnets. Figure 3a shows the radial component of the magnetic field and the magnetic pressure in the ferrofluid in front of the magnet. It is to be noted that the magnetic field is quite uniform in front of each magnet. Consequently, this structure is well adapted for two coil loudspeakers. Indeed, as each short coil remains always in a uniform field the force factor is great. Moreover, for small quantities of ferrofluid, a seal is formed in front of the magnet interface. For larger ferrofluid quantities, two smaller seals appear at the motor extremities. For even larger quantities the three seals join to form a single large one.

Figure 3b shows another magnet assembly for the motor which is constituted by three stacked ring magnets. The middle ring is radially magnetized while the top and bottom rings are axially magnetized with opposed magnetizations. Such configurations with a magnetization progressive rotation are related to Halbach cylinders. On one hand the magnetic field is rather intense and uniform in front of the middle ring magnet over a range which corresponds to this magnet height. On the other hand they present two field gradients in front of the magnet interfaces where very energetic ferrofluid seals can form. So, these structures are interesting because they can be optimized from both points of view. The magnet dimensions as well as their magnetization are the parameters that can be varied for this purpose.

Figure 3c shows another option for the magnet assembly. Indeed, the ring magnets have a triangular cross-section instead of a square one. As a result, the magnetic field is uniform in front of the radial magnet, the ferrofluid seals are fixed at the assembly extremities and the structure has no magnetic leakage. This structure can be optimized as well.

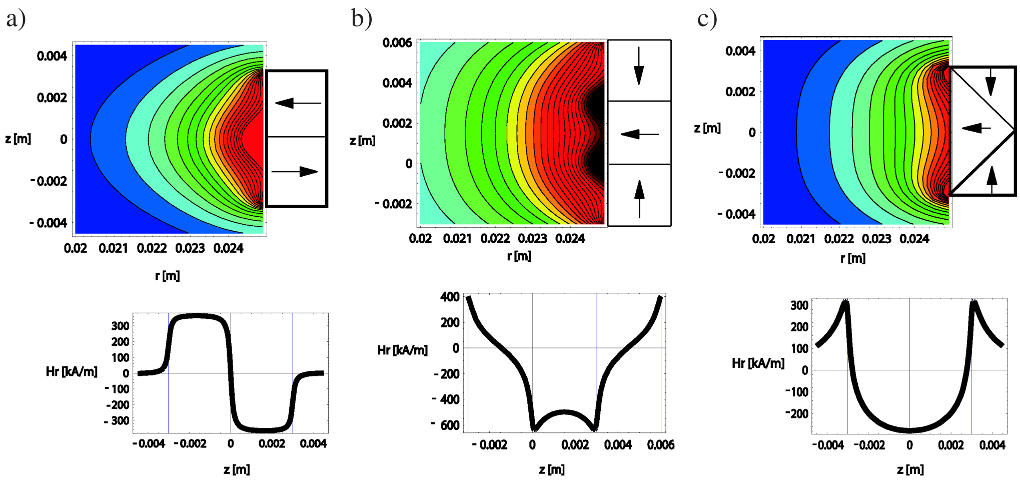

Fig. 3. Various magnet assemblies: a) two magnets, b) three magnets: rectangle, c) three magnets: triangle.

It is important to note that the ferrofluid seals fulfil in fact several functions. Of course, they insure the watertightness between the loudspeaker front and rear faces. Moreover, the moving part glides on them with no limitation in the displacement. The seals exert on the moving part a slight pull-back force which only bring it back towards its rest position when the atmospheric pressure varies but doesn't impede its movements.

Besides, they exert radial forces which center the moving part. Therefore, they act as radial bearings. Furthermore, they also have a heat transfer role.

3. Conclusion

Thus, this paper describes a concept of ironless loudspeakers with ferrofluid seals and a pneumatic suspension. Moreover, it shows how the concept gives rise to various structures which have different properties and can be optimized according several criteria. It is emphasized that such structures suppress all the distortions related to the iron and to classical suspensions and offer an improved force factor. Therefore, they prove to be useful.

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