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INFLUENCE OF COIL WINDING MATERIAL ON THE PERFORMANCE OF ELECTRODYNAMIC LOUDSPEAKERS

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ABSTRACT

This work presents an analytical method to determine which material -copper or aluminum- is more suitable for coil winding, based on the initial specifications of the transducer. The proposed approach compares the coil mass to the total moving mass and establishes a threshold value that defines the suitability of each material for achieving maximum efficiency.

Initial method relies on minimal variables, primarily derived from the original loudspeaker model. These variables include the total moving mass (M_{MS}), encompassing all moving parts, such as the air load on both sides of the diaphragm, and the material used for the coil conductor.

The role of the voice coil, however, differs from some perspectives presented in the literature, particularly those equating the coil mass to the total moving mass, a simplification that is not realistic for a transducer characterized by inherently low efficiency.

Additionally, the analysis accounts for variations in the Bl force factor caused by the physical differences between copper and aluminum for the same electrical resistance, due to the alterations in the air gap volume.

Keywords: *Electrodynamic loudspeaker, voice coil, moving mass, transducer efficiency.*

1. INTRODUCTION

This article proposes a novel approach in the development of the electrodynamic loudspeaker, focusing on the optimization of the voice coil. The objective is to achieve results comparable to those obtained through conventional methods but with lower time and costs, as well as a significant reduction in the carbon footprint during the manufacturing process.

To this end, a comprehensive study of the voice coil is presented, analyzing various improvement criteria and refining its performance to achieve an optimal balance between performance and cost. The importance of optimizing the coil mass in relation to the moving masses is discussed, and a solution based on the limit value theory is proposed. This approach allows for performance maximization through changes in the material of the winding wire as well as in the geometry of its cross-section.

As mentioned, equating the coil mass to the remaining moving masses would require a significant increase in the size of the magnetic circuit, which is economically unfeasible [1]. On the other hand, some authors propose reducing the coil size to match the total moving mass [1, 2], but this would introduce technical challenges that are difficult to resolve. Therefore, the approach should focus on maximizing efficiency while retaining the original components, with some modifications in the properties of the voice coil conductor.

For certain types of loudspeakers, copper is traditionally preferred for voice coil construction due to its excellent conductivity and mechanical strength. Consequently, it is the most widely used material in low and mid-frequency direct-radiation models. Conversely, aluminum is recommended in high-frequency loudspeakers and compression drivers, mainly due to its low density [3].

Although this criterion may involve some subjectivity, it is the most applied approach in loudspeaker manufacturing. This study challenges this practice and proposes a method to determine the suitability of one material over another to

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achieve maximum loudspeaker performance if that is the objective or to optimize the magnetic circuit for a given performance level.

2. APPROACH

In loudspeaker design, it is not usual to conduct a preliminary study to determine the optimal coil mass to maximize system performance. Typically, the dimensions and construction characteristics of the voice coil -such as diameter, conductor material, winding width, among others- are dictated by parameters such as electrical resistance, power capacity, maximum linear displacement, or peak displacement, etc. However, this study aims to justify the need to refine the coil based on additional criteria that enable maximum performance. This includes improving the *Bl* product with an optimized moving mass and dissipation while also achieving the desired power and efficiency characteristics through magnetic circuit optimization. The latter is a critical component in terms of weight and cost, highlighting its relevance in the overall design and efficiency of the system.

2.1 Voice coil mass versus efficiency

The efficiency of the loudspeaker in the mid-frequency range can be expressed using the following equation:

$$\eta = K \frac{S_D{}^2 B^2 l^2}{R_E M_{MS}^2} \quad (1)$$

Where the terms affected by the change in the coil are the wire length l of the coil and the moving mass M_{MS}.

This expression can be expanded by substituting the electrical resistance R_E in terms of the resistivity of the material ρ, as well as the length l and cross-sectional area s of the conductor. Additionally, M_{MS} can be replaced by the sum of the individual masses that comprise it.

$$\eta = K \frac{S_D{}^2 B^2 l^2}{\rho \frac{l}{S} (2M_A + M_{MD} + M_{MVC})^2} = K \frac{S_D{}^2 B^2 l S}{\rho (2M_A + M_{MD} + M_{MVC})^2} \quad (2)$$

With M_A being the mass of the air load on the membrane, M_{MD} the mass of the membrane, spider, and dust cap, and M_{MVC} the mass of the coil.

In the numerator, the product of l and S appears, representing the volume of the winding. By mathematical adjustment, the coil mass M_{MVC} is obtained.

$$\eta = K' \frac{S_D{}^2 B^2 M_{MVC}}{(2M_A + M_{MD} + M_{MVC})^2} \quad (3)$$

By taking the derivative of Equation (3) with respect to M_{MVC} and equating it to zero, the condition for maximizing efficiency is found.

$$M_{MVC} = 2M_A + M_{MD} \quad (4)$$

This condition suggests that the coil mass M_{MVC} must equal the mass of the remaining moving components (Fig. 1, solid line).
However, this solution is unrealistic. Compelling the coil mass to match the total moving mass would require an extremely powerful magnetic circuit to maintain a constant *Bl* product, resulting in prohibitively high costs. Nevertheless, even with a variable *Bl* product, there is an optimal value for the coil mass relative to the total moving mass that maximizes efficiency (Fig. 1, dashed line).

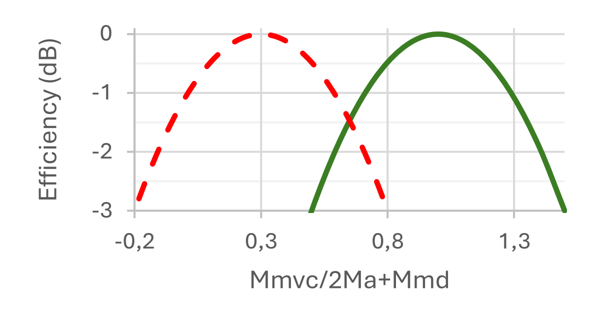

Figure 1. Efficiency versus voice coil mass

2.2 Influence of the conductor material on efficiency

This study aims to determine which of the two analyzed materials (copper or aluminum) is more suitable for voice coil construction to optimize loudspeaker efficiency. To achieve this, the expression for efficiency in Equation (1) is considered, depending on the *Bl* product and the moving mass.
Since efficiency is directly proportional to the first term and inversely proportional to the second- both terms squared- it can be stated that this relationship serves as the determining criterion, as the other terms in the equation remain constant regardless of the material used for the winding.

2.3 Determination of variables affecting efficiency

From the expression for the electrical resistance of the loudspeaker coil:

$$R_E = \rho \frac{l}{S} \tag{5}$$

The ratio of the aluminum wire diameter, w_{DAl}, to the copper wire diameter, w_{DCu}, is obtained:

$$w_{DAl} = 1{,}17 w_{DCu} \tag{6}$$

Using these values and taking μ as the material density, the coil mass M_{MVC} can be calculated as:

$$M_{MVC} = \mu l S \tag{7}$$

From this, it follows that the mass of the aluminum coil M_{MVCAl} relative to the copper coil mass M_{MVCCu} is:

$$M_{MVCAl} = 0{,}355 M_{VCCu} \tag{8}$$

This indicates that, for a coil with the same electrical resistance R_E, voice coil diameter V_{CD}, and winding width w_L, the aluminum wire diameter must be 17% larger than that of copper. Furthermore, based on this relationship, the aluminum coil mass is approximately one-third that of the copper coil.

2.4 Variation of the *Bl* product due to the change in the voice coil material

For magnetic systems such as the one illustrated in Fig. 2, empirical studies have shown that the magnetic flux Φg in the air gap can be calculated using the following expression [4]:

$$\Phi_g = \frac{L_m B_R / 1.07\mu_0}{(L_g/\mu_0 A_g)(27.5\mu_0 L_m R_m + 1.55) + L_m / 1.07\mu_0 A_m} \tag{9}$$

Where

B_R Residual induction
R_m Magnet reluctance
A_m Magnet cross section area

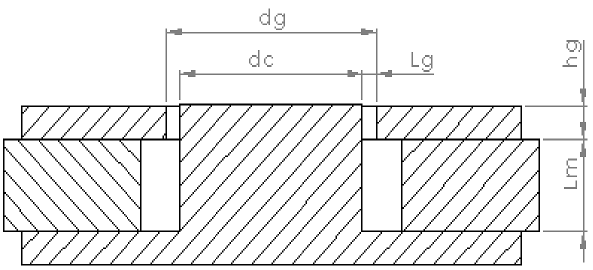

Figure 2. Section of the loudspeaker magnet system

By applying these results, it is possible to determine the variation in the air gap size and, using Eq. (10) and (11), calculate the difference in magnetic induction B between the two coils:

$$B = \frac{\Phi_g}{A_g} \tag{10}$$

Where the air gap area Ag is given by:

$$A_g = \pi\left(d_c + L_g\right) h_g \tag{11}$$

Initial calculations performed with the air gap dimensions for the copper coil, and subsequently adjusted for the aluminum coil, reveal a 3.5% reduction in magnetic induction B when switching from copper to aluminum.
On the other hand, the reduction in the second term, l, is due to the increase in the wire diameter when using aluminum, which leads to a decrease in the number of turns and, consequently, in the total wire length, according to the following relationship:

$$l_{Al} = 0.854 l_{Cu} \tag{12}$$

Based on these variations, the ratio of the Bl product for the aluminum coil to that of the copper coil can be expressed as:

$$Bl_{Al} = 0.824 Bl_{Cu} \tag{13}$$

3. CONCEPT OF THE LIMIT VALUE BASED ON THE COIL MATERIAL

As discussed earlier, this study aims to select the voice coil wire material based on criteria for either maximizing efficiency or optimizing the magnetic motor. Without requiring prior analysis of the magnetic circuit, the choice between copper and aluminum can be deduced using the criteria outlined below.

3.1 Initial considerations

In the early loudspeaker design, constraints related to the moving mass (e.g., membrane, suspensions, and other moving parts) are established. Similarly, the geometric dimensions of the coil are defined based on power handling, electrical resistance, linear displacement, etc. With these values and Equation (1), the efficiency equivalence for both materials can be expressed as:

$$K \frac{(Bl)^2_{Cu}}{R_{ECu}(M_{MS})^2_{Cu}} = K \frac{(Bl)^2_{Al}}{R_{EAl}(M_{MS})^2_{Al}} \tag{14}$$

Since the electrical resistance is the same (R_{ECu}= R_{EAl}), it cancels out along with other constants. On the other hand:

$$2M_A + M_{MD} = M_X \qquad (15)$$

Substituting M_{MS} according to Equations (1) and (15), and simplifying, yields:

$$\frac{Bl_{Cu}}{M_{MX}+M_{MVC\,Cu}} = \frac{Bl_{Al}}{M_{MX}+M_{MVC\,Al}} \qquad (16)$$

Reordering terms:

$$\frac{Bl_{Cu}}{Bl_{Al}} = \frac{M_{MX}+M_{MVC\,Cu}}{M_{MX}+M_{MVC\,Al}} \qquad (17)$$

Substituting and solving using Equations (8) and (13),

$$\frac{M_{MX}}{M_{MVC\,Cu}} = 2.66 \qquad (18)$$

This implies that when the ratio of M_{MX} to the copper coil mass equals 2.66, both materials yield equivalent performance. For ratios below 2.66, aluminum is better, whereas ratios above 2.66 favor copper (Fig. 3).
It is easy to deduce that, when the ratio in Equation (18) exceeds the indicated value, the weight of the moving parts other than the voice coil becomes predominant. As a result, the coil mass is not as critical, and a higher *Bl* product is preferable.

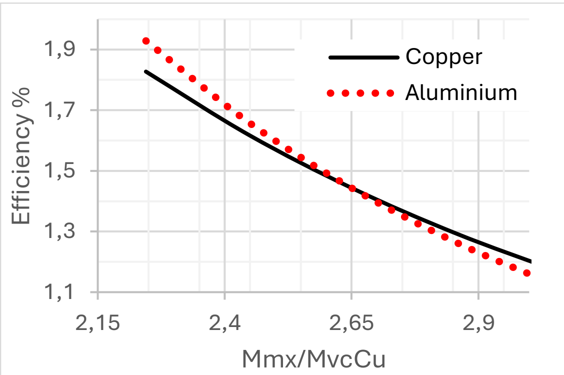

Figure 3. Variation of the efficiency

According to Equation (13), this is achieved with a copper coil. On the other hand, if the value is below 2.66, the coil mass becomes dominant. In this case, the lightest possible coil is desirable, which is achieved with aluminum, despite having a lower *Bl* product.

3.2 Example

A loudspeaker is selected from a well-known manufacturer that provides the following data: Loudspeaker size: 18” (46 cm), with 100 mm voice coil diameter, made of 0.50 mm diameter copper wire. The M_{MX}/M_{MV} value is 1,32, so less than 2.66. According to this, the efficiency will be higher with an aluminum coil. A 30% increase in efficiency has been confirmed by changing the coil wire material, according to the procedure seen above (Tab. 1).

Table 1

Coil Material	M_{MVC} Kg	M_{MS} Kg	M_{MX} Kg	Bl N/A	η %
Copper	0,099	0,23	0,131	29	2,7
Aluminun	0,035	0,166	0,131	23,9	3,5

4. PERFORMANCE VARIATION DUE TO WIRE CROSS-SECTION GEOMETRY

The conventional geometry for the voice coil conductor is circular, from which the packing factor can be obtained. This factor represents the ratio between the actual volume of the wire and the total volume of the winding (Fig. 4a). In this case, the packing factor is 78.5%. It is also possible to use rectangular cross-section wire, which achieves a 100% packing factor (Fig. 4b).

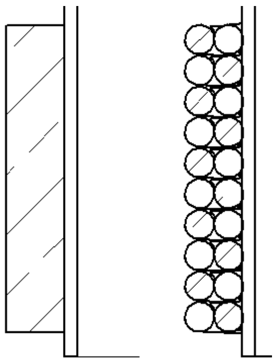

Figure 4a. Difference between voice coil volume (left) and wire volume (right)

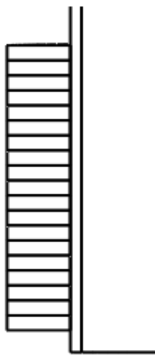

Figure 4b. Voice coil with edge wound rectangular wire

This allows the wire length and cross-sectional area to be increased while maintaining the electrical resistance. Obviously, this configuration enhances the Bl product.

4.1 Calculation of rectangular cross-section voice coil parameters

When switching from one geometry to the other, certain dimensions are preserved, such as the winding length (w_L) and the inner and outer diameters of the winding, which avoids modifications to the air gap dimensions.
Additionally, while the round-wire coil uses two layers in the winding, the rectangular-wire coil only uses one. Consequently, the height of the rectangular-section wire (*h*) will be equal to $2w_D$.

$$l = \frac{2w_L V c_D \pi}{w_D} \tag{20}$$

By substituting (considering the number of layers *n* is equal to 1, and the wire thickness denoted as *t*.

$$l = \frac{w_L V c_D \pi}{t} \tag{21}$$

4.2 Rectangular vs. Circular Cross-Section Conductor

Due to its higher packing factor, the rectangular cross-section coil will have a greater number of turns, thereby increasing the Bl product.
Expressing the electrical resistance based on the rectangular wire cross-section geometry:

$$R_{E_{FLAT}} = \rho \frac{w_L V c_D \pi}{h t^2} \tag{22}$$

4.2.1 Calculation of wire thickness

As previously defined, $h = 2w_D$. The thickness can be obtained from the following expression:

$$R_E = \rho \frac{2w_L V c_D \pi}{\frac{{w_D}^2 \pi}{4}} = \rho \frac{w_L V c_D \pi}{h t^2} \tag{23}$$

Solving for *t*:

$$t = 0{,}44 w_D \tag{24}$$

4.2.2 Determination of rectangular wire coil mass

The mass is expressed as:

$$M_{MVC_{Round}} = lS\mu = \frac{2w_L V c_D \pi^2 w_D^2}{4w_D}\mu \tag{25}$$

$$M_{MVC_{FLAT}} = lS\mu = \frac{w_L V c_D \pi}{t} h t \mu \tag{26}$$

Resulting in:

$$M_{MVC_{FLAT}} = 1{,}273 M_{MVC_{Round}} \tag{27}$$

Since the air gap volume remains unchanged, the new value of *l* is derived using equations (25) and (26):

$$l_{Rect} = 1{,}136 l_{Round} \tag{28}$$

Thus

$$Bl_{FLAT} = 1{,}136 Bl_{ROUND} \tag{29}$$

4.3 Critical value between round and rectangular wire coils

Following the methodology in Section 4.1, equation (16) is adapted by substituting materials with the cross-sections:

$$\frac{Bl_{ROUND}}{M_{MX} + M_{MVC_{ROUND}}} = \frac{Bl_{FLAT}}{M_{MX} + M_{MVC_{FLAT}}} \tag{30}$$

From this, it results:

$$\frac{M_{MX}}{M_{MVC_{ROUND}}} \approx 1 \tag{31}$$

This solution demonstrates that no critical value exists to equalize the performance of voice coils with circular versus rectangular cross-section geometries. In practice, since the rectangular wire coil mass M_{MVC} is significantly smaller than other moving masses, the improvement in *Bl* product will enhance overall performance. This improvement depends on the ratio M_{MX}/M_{MVC}, with greater benefits as this ratio increases.

5. CONCLUSION

It has been possible to establish the advantages of analyzing the loudspeaker coil to achieve a balance between the mass of moving parts, excluding the voice coil and the voice coil mass itself.
While the optimal solution -equating both masses- is economically unviable or practically unattainable, it has been demonstrated that selecting the appropriate conductor material, copper or aluminum, allows for

either maximizing efficiency or optimizing the magnetic circuit. This approach offers both economic and technical advantages.

Additionally, the feasibility of using alternative wire cross-section geometries to increase the packing factor and consequently, the Bl product, has been outlined. This improvement is universally beneficial, particularly in bigger diameter models. In such cases, the higher manufacturing cost of flat wire voice coil (compared to more economical round wire voice coil) is compensated by the potential to reduce the magnetic circuit volume.

6. ACKNOWLEDGMENTS

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