Structural Analysis of an In-Wheel Motor with Integrated Magnetic Gear Designed for Automotive Applications

Claudia Violeta Pop, Daniel Fodorean and Dan-Cristian Popa *

Department of Electrical Machines and Drives, Technical University of Cluj-Napoca, 400114 Cluj-Napoca, Romania
* Correspondence: dan.cristian.popa@emd.utcluj.ro

Abstract: This paper is focused on the structural analysis of a new propulsion system defined by an in-wheel motor with an integrated magnetic gear (IWM-IMG). The IWM-IMG has two levels of torque and speed. First, the state of the art of magnetic gears (MGs) is presented. Next, the proposed structure and the main designing steps are depicted. The advantages of the proposed structure are emphasized, in terms of speed increase operation, knowing that this is achieved without it being necessary to increase the fed frequency via the inverter. Moreover, the electromagnetic characteristics are briefly introduced to prove the suitability of the proposed solution for the considered application. Next, the structural analysis is detailed, where through an analytical, numerical and experimental approach, the study is validated.

Keywords: in-wheel motor; integrated magnetic gear; EV application; design and structural analysis; speed operating extension

1. Introduction

The concerned application in our study is the electric vehicle (EV). EVs are complex systems, and their study implies the use of different strategies and methods in an interdisciplinary approach [1,2]. In general, for EVs, higher speed and increased autonomy are strongly related to the weight of the propulsion unit [3–6]. To transfer the torque speed from the electric motor to the traction wheel, a gear is generally used. A high transmission ratio from the gear can be hardly obtained when using just one gear. A solution to obtain the desired transmission ratio is to use multiple linked gears [6]. Hence, the propulsion unit will be affected by the increased weight and volume, with consequences on the power density and efficiency of the overall system. To overcome this issue, a solution can be the replacement of the mechanical gear with a magnetic one. Multiple advantages to the drive chain can be achieved with this variant, emphasized later.

A classical mechanical gear is a unit which transfers torque or speed from one shaft to another through mechanical teeth contact [7,8]. Thus, some important drawbacks occur. First, local friction and heat are produced at the teeth level, leading to losses. The physical contact between the teeth will also lead to the stress of the tooth flanges. Due to the long operation time, material friction and fatigue lead to the irreversible damage of the teeth. Moreover, because of the material friction, the metallic parts must be lubricated often, due to continuously varying temperatures at the teeth level.

All these drawbacks are eliminated in the case of magnetic gears (MGs) because the metallic teeth are replaced with magnets. The transition from a mechanical gear to a magnetic one is shown in Figure 1. There is no physical contact between the magnetic pole pieces of an MG. Hence, there is no heating, no need for lubrication and no material damage. The losses found in the active parts are represented by the iron loss component, and the mechanical one is due to bearing friction. Moreover, the levels of noise and vibration are decreased in the case of MGs.
At the beginning of the 20th century, the idea of magnetic gear emerged, and it was patented in 1901 [9]. The original topology was described as an electromagnetic gear, which unfortunately did not pique interest at that time due to its poor efficiency. Later, in 1941 [10], another topology of MGs was proposed, but still, the interest in it and its use remained low at that time. The poor performance of the magnetic materials made the idea of widely employing magnetic gears in industry almost impossible. Later, in the 1980s, ferrite magnetic material was replaced by neodymium iron boron (NdFeB) material, which exhibits better performance (i.e., power density), and this change accelerated the research interest in MGs [11–16].

For the MG shown in Figure 1, the transition from a mechanical to a magnetic gear was made by simply replacing the iron core teeth with permanent magnets (PMs) with alternating polarity. The shortcoming of this topology is the low-level utilization of PMs, because only a part of magnetic poles was in active magnetic contact, which gave an efficiency of 20–30%. The first efficient MG solution that fully exploits all the gear magneto dates to early 2000. This variant was proposed by Atallah and Howe [17] and it was a coaxial MG. The operation principle was based on modulation of the magnetic fields produced by two rotors, with PM pole pieces. Based on the idea of field modulation, numerous similar configurations with fixed transmission ratios have been proposed. The number of magnetic poles used for an MG is critical as it has a direct influence in the transmission ratio and affects the mechanical performances (i.e., the torque ripples).

Various types of MG architectures have been studied with different efficiency levels. One of them is the planetary type. Some scientific papers present the various applications for this topology [18–24], most of them being related to wind power [23,24]. The main advantages of this topology are the high speed ratio and the possibility of three terminals for input or output speed torque.

The second studied topology is the harmonic MG. The operating principle is based on the high-speed rotor moving around and creating “gear teeth” on the low-speed rotor. The high-speed rotor or the inner rotor presses on the low-speed rotor, which is “flexible”. Since in this specific case, the low-speed rotor has two fewer teeth than the stator, each revolution causes a displacement of the output with two teeth. This movement produces a time-varying sinusoidal variation of the airgap [25,26]. The main advantage of such a model is the high torque density. Additionally, a high gear ratio can be achieved. On the other hand, although it has significant functionality, this topology needs a flexible magnetic rotor, which is quite complex, constituting the main drawback of the structure. Such MG topology is suitable for applications that require positional accuracies, such as robotics or medical tools.

Another type is the axial MG topology, studied by Mezani [27]. This structure comprises two rotors, for low and high speed, covered on the inner face with PMs. The ferromagnetic pole pieces axially arranged are placed between the PMs, having the power transferring role [28–32]. Specifically, in [32], an MG with a 30:1 gear ratio was investigated. However, the performances of the axial topology were not extensively studied, since a relatively small number of papers presented their real physical integration. Due to their good power density, the axial MGs should be suitable in food and aeronautic industries.

Figure 1. Mechanical (left) and magnetic (right) gear topologies.
Next, a linear topology was studied in [33–35], having three main parts: the inner rotor, with PMs on the axial surface; the stator, composed of the modulating segments; and the outer rotor, with PMs mounted on the inner face. Very high force density can be reached by using such topology. On the other hand, a drawback is the sensitivity at the axial length of the space between the rings placed between the PMs of the rotors [35–37]. The advantages of using linear gears make them suitable for applications such as wave power generation, or other types of renewable energy [38–41].

Based on the above information, one can conclude that the radial MG shows the best results in terms of torque density. The key benefit of this configuration is the contribution of all PMs, simultaneously, in the torque transmission. The torque density of these MGs is comparable with that of the mechanical ones [42], and we considered such a variant for our proposition of a new propulsion system with an integrated magnetic gear.

Thus, our goal is to propose a two-transmission-step topology, containing an in-wheel motor with an integrated magnetic gear (IWM-IMG), capable of increasing the speed of the propulsion unit without increasing the fed frequency—and thus obtaining suitable efficiency, even at high speeds, and reducing the mechanical stress on the switching components of the power converters. With this in mind, the analysis presented here is focused on the structural analysis of our IWM-IMG, and the main elements of the design, the characteristics and performances of the propulsion system are presented.

2. The Topology under Study and the Main Steps in the Analytical Design

A. Structure Under Study, the IWM-IMG

The problem of increasing the speed in electrical machines comes from the fed frequency limit of 400 Hz for industrial applications. We propose a two-step electromagnetic geared with an option to increase speed. An in-wheel motor (IWM) is the first component of our propulsion unit. It means that the rotor is the exterior part, and next, above our rotor, a radial-type magnetic gear is placed, practically attached to the motor. Thus, the inner rotor of the MG is rotating at the same speed as the outer rotor of the IWM. Thus, we obtain an in-wheel motor with integrated magnetic gear (IWM-IMG), and its structure is depicted in Figure 2 (with magnification for a closer look on its configuration).

The stator is the interior part of the IWM. The structure chosen here has a fractional slot winding configuration. Next, one can see the first airgap. Above it, the double structure inner rotor is placed. Two rings made of PMs and steel are mirrored on the sides of one ring of non-conducting material. Next is the static part, with alternating conducting and non-conducting materials. Next is the outer rotor, with one PM layer and the iron yoke.

![Figure 2. Cross-section of the proposed IWM-IMG (with a detailed look at its structure).](image)

Our IWM-IMG was designed to develop an output power of 1500 W, operating at a rated speed of 420 r/min. The MG acts like a speed multiplier, so it can achieve 1428 r/min,
3.4 times more than the IWM, for the same fed frequency. This multiplication of the speed is achieved without increasing the iron losses in the machine and without producing supplementary heat and chopping losses within the static converter used to feed the motor. The main parameters of the IWM with an integrated MG are shown in Table 1.

**Table 1.** The main data of the analyzed structure.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of phases</td>
<td>3</td>
<td>-</td>
</tr>
<tr>
<td>Supplying voltage</td>
<td>48</td>
<td>V</td>
</tr>
<tr>
<td>Supplying frequency (IWM)</td>
<td>119</td>
<td>Hz</td>
</tr>
<tr>
<td>Demanded output power</td>
<td>1500</td>
<td>W</td>
</tr>
<tr>
<td>Number of pole pairs (IWM and for the inner rotor MG)</td>
<td>17</td>
<td>-</td>
</tr>
<tr>
<td>Number of the pole pairs of the outer rotor (MG)</td>
<td>5</td>
<td>-</td>
</tr>
<tr>
<td>Stator slots number (IWM)</td>
<td>39</td>
<td>-</td>
</tr>
<tr>
<td>Static part slot teeth number (MG)</td>
<td>22</td>
<td></td>
</tr>
<tr>
<td>Rated speed (IWM and inner rotor for MG)</td>
<td>420</td>
<td>r/min</td>
</tr>
<tr>
<td>Outer rotor speed (outer rotor speed for the MG)</td>
<td>1428</td>
<td>r/min</td>
</tr>
<tr>
<td>Rated torque</td>
<td>34</td>
<td>N-m</td>
</tr>
</tbody>
</table>

**B. Characteristics of the Used Materials**

Materials of high quality must be used to maximize the power density of the IWM-IMG and to provide high performances for the application. Hence, the PM chosen for the current application is of NdFeB type. This kind of material keeps its operational condition up to 160 °C. The main material specifications are shown in Table 2.

**Table 2.** Specifications of the used materials.

<table>
<thead>
<tr>
<th>Material</th>
<th>Property (Unit)</th>
<th>Value</th>
<th>Density (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper</td>
<td>Electric resistivity (Ω-m)</td>
<td>2.438 × 10⁻⁸</td>
<td>8954</td>
</tr>
<tr>
<td>Air</td>
<td>Magnetic permeability (m·kg/A²·s²)</td>
<td>1.2566 × 10⁻⁸</td>
<td>0.9996 (at 100 °C)</td>
</tr>
<tr>
<td>NdFeB</td>
<td>Remanent flux density (T)</td>
<td>1.11</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Magnetic field coercivity (kA/m)</td>
<td>9907</td>
<td>7400</td>
</tr>
<tr>
<td></td>
<td>Relative magnetic permeability</td>
<td>1.05</td>
<td></td>
</tr>
<tr>
<td>M530</td>
<td>Flux density saturation limit (T)</td>
<td>1.8</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Stacking coefficient of the steel sheets</td>
<td>0.95</td>
<td>7800</td>
</tr>
<tr>
<td></td>
<td>Conductivity of the steel sheets (A²·s/m²·kg)</td>
<td>4 × 10⁶</td>
<td></td>
</tr>
</tbody>
</table>

The materials used for manufacturing the MG are the same as for the IWM, having the same properties. Based on the topology of the IWM, the MG was built considering the geometrical constraints for the inner rotor diameter and length of the stack.

**C. Main Designing Steps**

The electromagnetic design process is developed for the structure with the outer rotor and the three-phase winding with fractional slots, to be integrated with the radial MG. The design process starts with the expression of the output power, from which the airgap diameter is derived [42–46]. The other parameters are obtained based on it. For in-wheel applications, the motor’s structure and materials must be carefully chosen to fulfill the performance and cost requirements. Next, the calculation of the geometrical and electro-mechanical parameters is performed, and the characteristics of the propulsion unit are obtained, as well as the mass and volume of the structure, which directly affect its efficiency [43,46].
The airgap diameter measured at the middle of the distance between the stator and rotor can be calculated starting from the rated power of the IWM, denoted with $P_N$; it is calculated as a function of the induced electromotive force (emf), $E$, the supplied current $I$, the estimated efficiency of the machine, $\eta$, and the machine’s number of phases, $n_{ph}$:

$$P_N = \eta \cdot \frac{n_{ph}}{T} \int_0^T i(t) \cdot e(t) dt = \eta \cdot n_{ph} \cdot k_p \cdot E_{max} \cdot I_{max}$$

(1)

The peak value of the emf can be expressed as:

$$E_{max} = k_e \cdot N_t \cdot B_{gap} \cdot D_{gap} \cdot L_m \cdot \frac{f_s}{pp}$$

(2)

(with the commonly known definition of frequency, as the product of the number of pole pairs, $pp$, and of the rated speed).

The diameter in the middle of the airgap is determined using the next expression, where all the other parameters are either calculated or imposed:

$$D_{gap} = \sqrt[3]{\frac{2 \cdot pp \cdot P_N}{\pi \cdot A_s \cdot k_e \cdot k_i \cdot k_p \cdot k_1 \cdot \eta \cdot B_{gap} \cdot f_s}}$$

(3)

where the coefficients $k_e$, $k_i$, $k_p$ and $k_1$ are emf, current, power and geometrical coefficients, respectively [42]. (The length of the machine is a function of the geometry coefficient $k$, based on the known expression: $L_m = D_{gap} \cdot k$.)

Considering a surface PM structure, the airgap flux density can be determined:

$$B_{gap} = \frac{B_{rmp} \cdot h_{mp}}{gap + \frac{h_{mp}}{\mu_{rmp}}}$$

(4)

where $B_{rmp}$ is the specific remanent flux density, $\mu_{rmp}$ is the magnetic permeability, $gap$ is the airgap length and $h_{mp}$ is the PM’s height.

For the sizing of the machine, other main parameters refer to the number of slots, number of coils per slot, winding turns and the geometry of the slot. For stator sizing, the geometrical aspects of the slots must be clarified.

The number of coils per phase depends on the number of slots and the number of coils per slot. Thus, the number of coils per phase can be calculated as:

$$N_c = \frac{Z_s}{2 \cdot q \cdot pp} \cdot \frac{1}{N_{cs}}$$

(5)

where $q$ is the number of slots per pole and phase, and $N_{cs}$ is the number of coils per slot.

The estimated current on a stator phase can be calculated using:

$$I_{ph} = \frac{P_N}{n_{ph} \cdot U_{ph} \cdot \cos \varphi \cdot \eta}$$

(6)

where $\cos \varphi$ and $\eta$ are the estimated power factor and efficiency, respectively.

The inner rotor contains two layers of magnets, on the inner and outer side of the rotor, separated by a layer of non-magnetic steel. The height of the PM is the same for both layers, 3.5 mm. The polar pitch, which is the length of the arc between two consecutive magnets, is expressed by:

$$\tau_p = \pi \cdot \frac{D_{pm}}{2 \cdot pp}$$

(7)

The flux of the PM for one polar pitch can be determined by using:

$$\Phi_{pm} = \tau_p \cdot a_{pm} \cdot L_m \cdot B_{gap}$$

(8)
This particularity of MG is based on the use of a ring of alternating pieces of iron and nonconductive material as a static part. On the sides of this ring in the radial direction there are two airgaps, which have the same length as the first airgap. For this part of structure, the sizing is similar to that of the stator.

The input power of the propulsion unit can be calculated by using Equation (9), where \( l_s \) and \( l_i \) are the direct and quadrature current:

\[
P_{\text{in}} = n_{ph} \cdot U_{ph} \cdot (I_q \cdot \cos(\delta) - I_d \cdot \sin(\delta))
\]  

(9)

The output power is expressed as a difference between the input electrical power of the machine and the total losses of the machine:

\[
P_{\text{out}} = P_{\text{in}} - \sum \text{Losses}
\]  

(10)

For the calculation of the mechanical power produced by the MG, the first equation is for produced speed, at its outer rotor:

\[
\Omega_{\text{out}} = -\frac{\Omega_{\text{in}}}{G_r} = -\Omega_{\text{in}} \cdot \frac{p_{\text{in}}}{p_{\text{out}}}
\]  

(11)

where \( \Omega_{\text{in}} \) is the inner speed of the MG, \( G_r \) is the gear ratio, \( p_{\text{in}} \) is the pair of poles for the inner rotor of the MG and \( p_{\text{out}} \) is the pair of poles for the outer rotor. The relation between the pair of poles and the number of steel teeth, \( N_s \), is given by:

\[
p_{\text{out}} = N_s - p_{\text{in}}
\]  

(12)

Considering that the main source of flux is that of the inner rotors of the MG, which is produced through the rotation of the outer rotor of the IWM, modulated through the static parts of the MG, the magnetomotive force produced by the outer rotor is:

\[
T_{\text{MG}} = \Phi_{\text{MG, in}} \cdot F_{\text{MG, out}}
\]  

(13)

The flux of the inductor of the MG (inner rotor part) is accordingly the product of flux density distribution and the cross-section of the surface on which the flux flows. At-talah elaborated in [17] the frequential model of the flux density by calculating it from the radial component of the field source and the modulating component, due to the static part of the MG. This flux density is given by:

\[
B_{\text{gap MG}}(\theta) = \left( \sum_{m=1,3,5} b_{rm}(Rr) \cdot \cos(m \cdot p_x \cdot (\theta - \Omega r \cdot t) + m \cdot p_x \cdot \theta_0) \right) \times \\
\sum_{j=1,3,5} \lambda_{bj}(Rs) \cdot \cos(j \cdot N_s \cdot (\theta - \Omega s \cdot t)) + \lambda_{bg}(Rs)
\]  

(14)

where \( R_r \) and \( R_s \) are the radius of the rotor and of the static part, where the flux density is computed, \( p_r \) refers to the inner or outer rotor number pair of poles, \( \Omega \) is the speed of the inner rotor of the MG, \( b_r \) and \( \lambda_g \) are the Fourier coefficients for the flux density and the modulating flux, respectively. \( \theta \) is the rotor displacement, and \( \Omega_s \) is the angular speed of the outer rotor (or of the steel teeth part, in the case of a structure for which the teeth part is mobile). Next, the determination of the magnetomotive force is based on the distributed flux and the reluctance of the circuit through which the flux flows, and is given by:

\[
F_{\text{MG, out}} = \Phi_{\text{MG, out}} \cdot R_{\text{MG, out}}
\]  

(15)

Moreover, in order to reduce, as much as possible, the torque ripples, which are images of the vibration and noise behavior of electromagnetic transmission, a specific configuration of poles and teeth of the IMG must be found. In fact, the lowest level of torque ripple is reached when the ripple coefficient \( k_r \) equals unity (the ideal case) [7]:

\[
k_r = \frac{2 \cdot P_{\text{in}} \cdot N_s}{\text{LCM}(2 \cdot P_{\text{in}} \cdot N_s)}
\]  

(16)

where LCM denotes the least common multiple between the number of poles of the inner rotor and the fixed iron teeth.
Accurate and reliable results in terms of losses are hard to obtain. The computation of losses for the studied structure can be a difficult task, because the complexity of the structure is combined with the phenomena related to different types of losses.

In electrical machines, the losses can be classified into three categories: copper losses, iron losses and mechanical losses. The first category, the copper losses or Joule losses, are dependent on the temperature and the resistance of the copper wire, because these two are related. The mathematical expression used to calculate the copper losses is:

\[ P_{co} = n_{ph} \cdot R_{ph} \cdot I_{ph}^2 \]  

(17)

The second category of losses requires special attention [42]. For determining this category of iron losses, a sum of three subcategories of losses is used: hysteresis loss, eddy current loss and excess loss:

\[ P_{a,x} = k_{hyst} \cdot B_x^2 \cdot f_s + \pi^2 \cdot \sigma_{iron} \cdot \frac{d_{lam}^2}{6} \cdot (B_x \cdot f_s)^2 + k_{exc} \cdot (B_x \cdot f_s)^3 \cdot 8.67 \]  

(18)

where the subscript \( x \) represents the analyzed part, meaning the tooth, isthmus and yoke. Other parameters are \( k_{hyst} \), \( k_{exc} \), hysteresis and excess loss coefficients, respectively; \( \sigma_{iron} \), iron conductivity; and \( d_{lam} \), thickness of the lamination sheet.

The third category of losses is based on different mechanical effects which affect the machine, such as the ventilation and aerodynamic losses [42]. Since this is a structure with an outer rotor, there is no fan mounted on the surface of the structure. Thus, the aerodynamic losses can be determined by:

\[ P_{ad} = \frac{1}{Re_n} \cdot D_{pm} \cdot L \cdot \gamma_{air} \cdot v^3 \]  

(19)

where \( Re_n \) is the Reynold’s number, \( \gamma_{air} \) is the air density for 100 °C and \( v \) is the periphery rotor speed.

The mechanical loss is the effect of the friction of the bearings, and for the rated speed, the friction bearing loss can be calculated by:

\[ P_{bf} = 2 \cdot T_{bf} \cdot 2 \cdot \pi \cdot n_N \]  

(20)

where \( T_{bf} \) is the bearing friction torque, which depends on the rotor weight and other passive elements. Thus, the total mechanical loss can be expressed as:

\[ P_{mec} = P_{ad} + P_{bf} \]  

(21)

By applying the steps of the above design procedure for the data presented in Table 1, an IWM-IMG with the geometrical parameters given in Table 3 was obtained.

**Table 3.** Main geometrical parameters of the designed IWM-IMG.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outer diameter of outer rotor</td>
<td>0.182</td>
<td>m</td>
</tr>
<tr>
<td>Height of the PM</td>
<td>0.003</td>
<td>m</td>
</tr>
<tr>
<td>Height of the static teeth of the MG</td>
<td>0.014</td>
<td>m</td>
</tr>
<tr>
<td>Outer diameter of the stator</td>
<td>0.199</td>
<td>m</td>
</tr>
<tr>
<td>Inner diameter of the stator</td>
<td>0.153</td>
<td>m</td>
</tr>
</tbody>
</table>

D. Electromechanical Characteristics

The output characteristics of the designed IWM-IMG are presented in Figure 3. The rated point of 34.1 N·m is reached at an angle of 17.64 °, which corresponds to the electric power (or input power) of 1766 W. A source current of 26 A is calculated at this angle. The output mechanical power at the shaft of the IWM, where the speed is 420 r/min, is 1603 W. On the other hand, at the output of the outer rotor of the MG, where the rated speed is 1428 r/min, the mechanical power is 1500 W. Based on the computed losses on each component of the designed IWM-IMG, the overall efficiency of the system is computed,
reaching 84.9%. The rated power factor of the designed purely electromagnetic structure is 0.9265.

![Graph showing torque axis, RATED OPERATING POINT: 34.1Nm at 17.64°](image)

**Figure 3.** The main characteristics of the designed IWM-IMG: (a) axis torque; (b) input electrical power and fed current; (c) output power (IWM only, and with IMG); (d) efficiency (IWM only, or with IMG); (e) power factor of the IWM-IMG.

To emphasize the suitability of the proposed electromagnetic propulsion unit, a comparison with other two systems was made. First, we considered the IWM connected to a separate MG (having its own housing and shaft), and secondly, the same IWM connected to a mechanical gear. The conclusions of this comparison are depicted in Table 4.
Table 4. Comparison of the proposed IWM-IMG and the IWM with a separate MG.

<table>
<thead>
<tr>
<th>Criterion</th>
<th>IWM + Separate Mechanical Gear</th>
<th>Proposed IWM-IMG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass</td>
<td>48 kg</td>
<td>32.3 kg</td>
</tr>
<tr>
<td>Strong point</td>
<td>Not expensive</td>
<td>Robustness, Efficiency</td>
</tr>
<tr>
<td>Weak point</td>
<td>Weak volume and efficiency</td>
<td>Expensive</td>
</tr>
</tbody>
</table>

In the case of the propulsion unit containing the IWM with a separate MG, we have not found specific advantages. On the other hand, its separate housing and shaft make it weak in terms of volume and mass.

The second evaluated propulsion system, the IWM with a mechanical gear, is the poorest in terms of efficiency, but the lack of magnets on the MG side should offer the best cost among the evaluated variants. Nevertheless, our proposition, the IWM-IMG, is a compact unit, with the best efficiency for a propulsion system with two levels of torque and speed.

3. Structural Analysis of the Proposed IWM-IMG

This section is dedicated to the presentation of the noise, vibration and harshness (NVH) analysis performed for the proposed IWM-IMG structure. It represents the core of this research, since it establishes the structural behavior of the propulsion unit and its suitability for the EV application. This analysis is complete, meaning that it is performed by analytical, numerical and experimental means.

A. Analytical Structural Model of the IWM-IMG

It is well known that in electrical machines, the radial forces produced by the rotor act on the stator. This phenomenon was investigated in detail in [47]. The electromagnetic forces applied on the stator influence its structure, and could have some damaging effects. One the most important effects is related to the structural deformations of the stator. These deformations are responsible for the appearance of the vibrations and noises during the operation of the system. If known, the resonant frequencies can be predicted and suppressed to mitigate the damaging effects or even avoid them completely. The deformations caused by vibrations are called modes or eigenmodes. As a function of the pressure applied on the structure, different deformations can occur, thus resulting in the modal shapes related to the number of pressure points. For example, the second modal shape has two points where the pressure is applied which “squeeze” the structure, determining an oval shape. The main modal shapes of a structure are shown in Table 5.

Table 5. Modal deformation shapes of a cylindrical structure.

<table>
<thead>
<tr>
<th>Mode Number</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modal shape</td>
<td>[ Image ]</td>
<td>[ Image ]</td>
<td>[ Image ]</td>
<td>[ Image ]</td>
<td>[ Image ]</td>
</tr>
</tbody>
</table>

The analytical prediction of the structural frequencies is difficult because of the particularities of the stator (i.e., teeth, windings) [48,49]. In [50], a method to derive an analytical model of the stator was presented, considering its cylindrical shape and integrating the teeth and windings as part of the structure. Various papers [51–54] analyzed a method that considers the investigated structure as a cylindrical shell. A new method for the determination of frequencies, implemented for cylindrical shells of finite length, was investigated in [55]. However, the most practical and simple formula used to determine the natural frequency of a structure is based on the Donnel–Mushtari theory. The natural
frequency of a cylindrical shell—the stator circumferential vibration of the \( m \)-th order, in this case—can be determined by using the general equation:

\[
f_m = \frac{1}{2\pi} \sqrt{\frac{K_m}{M_m}} \tag{22}
\]

where \( K_m \) and \( M_m \) are the lumped stiffness and lumped mass of the structure. The lumped mass parameter can be calculated with:

\[
M_m = \pi \cdot \rho \cdot D \cdot l \cdot h \tag{23}
\]

where \( \rho \) is the material density, \( D \) is the mean value of the cylindrical shell diameter, \( l \) is the cylindrical length and \( h \) is the wall thickness of the shell. The lumped mass can be determined by:

\[
K_m = \frac{4 \cdot \Omega_m^2 \cdot \pi \cdot l \cdot h \cdot E}{1 - \nu^2} \tag{24}
\]

where \( \nu \) is Poisson’s ratio and \( \Omega \) is the parameter determined by extracting the roots of second order of the motion equation. If the circumferential mode \( m \) is 1, then \( \Omega_0 = 1 \); in any other case, the parameter can be calculated by:

\[
\Omega_m = \frac{1}{2} \sqrt{(1 + m^2 + k^2 m^4) \pm \sqrt{(1 + m^2 + k^2 m^4)^2 - 4k^2 m^6}} \tag{25}
\]

where \( k \) is the thickness parameter, which can be obtained by:

\[
k^2 = \frac{h^2}{3 \cdot D^2} \tag{26}
\]

By integrating the above equations, the natural frequency of \( m \)-th order can be determined with:

\[
f_m = \frac{\Omega_m}{\pi \cdot D} \sqrt{\frac{E}{\rho \cdot (1 - \nu^2)}} \tag{27}
\]

The Donnel–Mushtari theory is more accurate than others, and in general, more reliable results can be obtained. In this paper, the structural analysis was performed for each active part of the IWM-IMG. Because the modal orders 2, 3 and 4 are the most relevant and noisy orders, they were calculated here for each part of the machine. The obtained values are presented in Table 6.

| Table 6. Circumferential natural frequencies of the IWM-IMG structure. |
|---|---|---|
| **Structure** | **Modal Order** | **Frequency (Hz)** |
| Stator | 2 | 1491 |
| | 3 | 2750 |
| | 4 | 4592 |
| Inner rotor | 2 | 802 |
| | 3 | 1137 |
| | 4 | 2949 |
| SPP | 2 | 649 |
| | 3 | 1551 |
| | 4 | 2819 |
| Outer rotor | 2 | 440 |
| | 3 | 1561 |
| | 4 | 2838 |
| MG | 2 | 1694 |
| | 3 | 3123 |
| | 4 | 5938 |
B. Numerical Structural Analysis of the Studied IWM-IMG

Based on the results obtained from the analytical approach, the numerical analysis was performed. In general, the numerical results are more precise than the analytical ones and more accurately reflect the studied phenomena. Hence, numerical analysis has been widely used in recent decades [56,57]. The analytical methods are based on several assumptions and a simplified hypothesis [58]. The numerical analysis provides reliable results in comparison with the analytical one, but it is much more time-consuming. The main advantages of numerical analysis are the flexibility offered by the software packages as well as the capability to analyze complex models with complex physical phenomena, such as material saturation and anisotropy.

The numerical analysis was performed with two software packages for electromagnetic behavior evaluation and for vibration and noise analysis. The analysis processing flowchart is shown in Figure 4. After the performances of the machine and its parameters were obtained from the electromagnetic analysis, the radial magnetic forces that act on the investigated structure were computed. The response of the structure can be observed in terms of deformations, meaning the modal structural response. Then, the vibrations and sound power level can be depicted based on the deformations of the structure.

![Flowchart of numerical analysis](image)

Figure 4. Flowchart of numerical analysis.

Depending on the application, the acoustic noise has different tonalities. For example, if the noise has a low frequency, the noise can be detected as a humming noise. On the other hand, if the noise frequency is high, it can be detected as a whining noise.

The numerical analysis was performed on the four components of the IWM-IMG (the stator and the rotor of the IWM, the inner and outer rotor of the IWM and its static part, denoted later with the SPP acronym) as well as on its whole assembled configuration. The main material characteristics used for this analysis are presented in Table 7.

<table>
<thead>
<tr>
<th>Description</th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Aluminum</td>
</tr>
<tr>
<td>Density (Kg/m³)</td>
<td>2710</td>
</tr>
<tr>
<td>Young modulus (N/m²)</td>
<td>$7 \times 10^{11}$</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>0.346</td>
</tr>
</tbody>
</table>
A frequency range must be set to perform the modal shape analysis. The analysis is considered for a preset frequency or for a set number of modes, depending on the requirements of the applications. For this analysis, a range of frequency between 0 and 8000 Hz was chosen for each structure. The forces acting on the structure create a pressure, and the response of the structure is called the force response. This is responsible for the deformation that appears and forces the structure to take on different strange shapes. These deformations represent vibration producers, which are responsible for the noise emitted in the surrounding area.

The structural response of an entity depends very much on the mechanical shape and its material. For example, a fuller shape object has increased stiffness compared to a shell-type object. Moreover, two attached objects influence one another. The influence is even bigger if the objects have different shapes and are made of different materials. Considering these facts, the structural analysis must be made separately on each component of the structure. In this way, it is possible to observe the structural and acoustic response of each part and to evaluate its impact on the behavior of the entire structure.

The main modal orders (2, 3 and 4) for each active part and for the entire structure are depicted in Table 8. The frequency of modal orders is specified for each structure.

**Table 8.** Modal orders of active parts of the studied IWM-IMG.

<table>
<thead>
<tr>
<th>Mode 2</th>
<th>Mode 3</th>
<th>Mode 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stator</td>
<td><img src="image1" alt="Mode 2 Stator" /></td>
<td><img src="image2" alt="Mode 3 Stator" /></td>
</tr>
<tr>
<td>1419 Hz</td>
<td>3068 Hz</td>
<td>4680 Hz</td>
</tr>
<tr>
<td>Inner rotor</td>
<td><img src="image4" alt="Mode 2 Inner rotor" /></td>
<td><img src="image5" alt="Mode 3 Inner rotor" /></td>
</tr>
<tr>
<td>838 Hz</td>
<td>1810 Hz</td>
<td>2906 Hz</td>
</tr>
<tr>
<td>SPP</td>
<td><img src="image7" alt="Mode 2 SPP" /></td>
<td><img src="image8" alt="Mode 3 SPP" /></td>
</tr>
<tr>
<td>788 Hz</td>
<td>1547 Hz</td>
<td>2416 Hz</td>
</tr>
</tbody>
</table>
The first results of the numerical vibro-acoustic analysis presented above represent the mode shapes of the structure. As was already mentioned, the analysis took into consideration the four main parts of the IWM-IMG. The reason for the detailed analysis is because of the complex structure of the integrated MG. It is known that the IWM is a quiet machine [59], but a deeper analysis is necessary for this structure due to the presence of a doubled rotor and other supplementary elements.

The main sources of noise in electrical motors are divided into three main categories: aerodynamic, mechanical and electromagnetic [60]. Each of these sources was analyzed in various studies [61,62]. The level of noise produced by an electromagnetic source is greatly dependent on the geometrical parameters of the machine, such as dimensions of slots and poles, airgap length [63], ratio between housing outer diameter and height of the yoke [64]. Additionally, a source of electromagnetic noise is represented by the static converters. Various papers [51,65] prove that the supply from the inverter produces harmonics, because the waveform of the voltage is not purely sinusoidal. The level of noise, in the case of the motors supplied by an inverter, is because of the superimposed resonance between the magnetic force frequency and the natural frequency.

The emitted noise was investigated, and the acoustic analysis results for each of the four parts of the structure are presented in Table 9.

**Table 9.** Acoustic level of noise on the components of the studied IWM-IMG, in dB.
The acoustic pressure is depicted at 1 m distance on the shell surface of the surrounding area. The maximum value of acoustic pressure for the stator is 73.5 dB, which corresponds to 238 Hz, which is double that of the fed frequency. These high levels of acoustic pressure were occurring at multiples of the fed frequency, which means that none of the resonance frequencies were particularly excited.

The results of the numerical analysis for the entire structure at 100 cm distance of acoustic pressure are presented in Table 8. Other scenarios are made for different distances, i.e., 70 cm and 10 cm. The values of sound power level are compared with the experimental ones in the next section, where three microphones are placed at three different distances. The purpose of setting different distances is to observe how much the acoustics are affected by the distances between the emitter and the receptor. Furthermore, different values of switching frequency were studied. The first set of simulations for a distance from 10 to 100 cm made for 8 kHz and 20 kHz are shown in Table 10.

Table 10. Values of acoustic behavior of the IWM-IMG at different measuring distances.

<table>
<thead>
<tr>
<th>Distance (cm)</th>
<th>Frequency (Hz)</th>
<th>Sound Power Level (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>8</td>
<td>82.1</td>
</tr>
<tr>
<td>70</td>
<td>8</td>
<td>87.3</td>
</tr>
<tr>
<td>10</td>
<td>8</td>
<td>91.2</td>
</tr>
</tbody>
</table>
C. Experimental Structural Analysis of the Studied IWM-IMG

Although the IWM is a quiet machine, the presence of the MG in the structure may lead to significant changes that can produce a level of noise higher than expected. Hence, to validate the numerical results, experimental measurements must be performed. Two types of experimental measurements were considered: impact tests for vibrations and run-up tests.

C.1. Impact test of the IWM-IMG

The impact test is necessary to determine the structural response of the investigated probe. The structure is placed under the influence of a force which causes the bending or deformation of the object. These modified patterns of the structure can be visualized in an analysis, performed with a software package dedicated to structural analysis.

First, the probe is suspended by a semi-elastic rope, without any constraints of movement (see Figure 5). The test for a pure structural response must be performed in free-to-free conditions, without any contact between the probe and another surface. The accuracy of the results is influenced by the additional elements, if there is at least some contact. For example, if the probe is attached to another piece, the structural response is only in one direction because the other piece is restricting the structural response in that direction. Six sensors are placed at some specific points to detect the response of the structure. To avoid increasing the mass of the probe, the use of a small number of accelerometers is recommended. The probe is excited with an impact hammer.

Based on the measurements of the impact tests, the software provides a graphical structure response. The main modal shapes for each structure and the frequency value of modal orders are shown in Table 11. The highest value of frequency of an analyzed part was reached by the stator because this is a solid shape and it has a higher damping factor due to its high material density (for example, for mode 2, this value is 1383 Hz). However, as it can be noticed, the entire structure reached an even higher frequency.

![Figure 5: Laboratory set-up for impact test (left), with suspended probes (right).](image)

C.2. Acoustic tests

The determination of the noise level was the next objective in our study. The used tools are presented in Figure 6. First, the probe was suspended by a semi-elastic rope, as in the previous tests. The difference is that now the probe is placed into a semi-anechoic chamber to avoid interference from the outer noise. A PCB accelerometer was placed on the outer surface of the probe to detect the structure’s response. Three microphones placed
in different places in the chamber were used to record the noise emitted by the investigated structure. The first microphone was placed just 10 cm from the structure to detect the noise emitted in the nearest area. The second and third microphones were placed 70 cm and 100 cm, respectively, from the structure to record the noise at greater distances (100 cm being the standard measuring distance). The measuring set-up and the main tools are presented in Figure 5, and the three microphones used are shown in Figure 6. The tests were made for each active part of the structure and separately, for the entire unit, in no-load conditions and at a rated speed. The tests were performed for two measuring scenarios: first, when the entire structure was fed from a programable power source, and second, when the batteries were the fed source (in order to avoid, as much as possible, the chopping effect produced by the programable source) via a three-phase inverter in both cases.

The first results of the tests are shown in Figure 7. The machine orders represented with oblique lines are presented here. These orders, also known as machine harmonics, are related to the rotational speed of the structure, the number of stator slots and the number of poles of the stationary part of the structure (SPP). Hence, they are multiples of slot numbers. The resonant frequencies represented with vertical lines are shown in Figure 8. The main resonant frequencies are related to the modal orders of the structure and appear as a high value of emitted noise.

The structure vibrations are strictly related to the machine performances because they can have a significant impact and they can influence the parameters of the IWM-IMG in a negative way. The vibrations are responsible for noise production, which can be annoying for the human ear.

The noise emitted by the structure was investigated for different frequencies and depicted at different distances. Figures 9–14 represent the waterfall maps for noise emitted for 8 kHz and 20 kHz. Each of the three microphones captured the noise emitted by the structure at either 10, 70 or 100 cm for each level of frequency.

Table 11. Modal orders of the investigated structures of the IWM-IMG.

<table>
<thead>
<tr>
<th>Mode 2</th>
<th>Mode 3</th>
<th>Mode 4</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Stator</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1393 Hz</td>
<td>3040 Hz</td>
<td>4668 Hz</td>
</tr>
<tr>
<td><strong>Inner rotor</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>790 Hz</td>
<td>1751 Hz</td>
<td>2676 Hz</td>
</tr>
<tr>
<td><strong>SPP</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>637 Hz</td>
<td>1197 Hz</td>
<td>2228 Hz</td>
</tr>
</tbody>
</table>
The last one, the 100 cm distance microphone, is the recommended distance for measuring the noise because this is the common distance where the noise emitted has the most significant value for a human observer, based on the standards of the automotive industry.

**Figure 6.** (a) Measuring set-up for noise detection; (b) accelerometer and microphone.

**Figure 7.** Orders of harmonic frequency.
**Figure 8.** Frequency spectrum of vibration.

**Figure 9.** Microphone at 10 cm, switching frequency of 8 kHz.

**Figure 10.** Microphone at 10 cm, switching frequency of 20 kHz.

**Figure 11.** Microphone at 70 cm, switching frequency of 8 kHz.
As one can observe, the difference between the closest and the farthest microphone is related to the switching frequency. For the 8 kHz switching frequency, the noise level difference is just 5 dB between the different microphones. For the 20 kHz frequency, the difference is 10 dB. For 100 cm, the noise emitted is the same, even if the frequency is different. The difference appears to be at the closest microphone, where there is a 10 dB difference between the switching frequency of 8 kHz and 20 kHz. A maximum level of 90 dB of emitted noise was depicted, based on the acoustic tests performed on the analyzed structure, which is not a disturbing level.

4. Discussions

A complex structure of a magnetic gear placed on top of an in-wheel motor was investigated in this article. The structure was presented in light of other existing topologies found in the scientific literature, emphasizing its originality. Such a system is to be used for electric vehicle applications, having, among others, the advantage of offering two levels of torque and speed. The main electromagnetic design elements were introduced in order to prove the suitability of the proposed propulsion system, based on the obtained
characteristics and performances. Moreover, the vibro-acoustic analysis, employed through analytical, numerical and experimental means, were presented in detail. The comparison of these results has proved the validity of the analysis, justifying the suitability of the structure for the considered application. To emphasize the achievements of the study, all the results obtained for the structural analysis are presented in Table 12. The comparison is performed separately for each active part of the studied topology, as well as for the entire structure. The mode number and the occurred frequency value for each structure are shown.

The results of the numerical analysis and experimental acoustic tests for the studied structure, for two frequency levels and for three distances, are shown in Table 13. It was proved that the obtained results validate the study, since no structure’s resonance was superimposed with the frequencies of the static inverter, and the level of produced noise is not disturbing, being in the limits of the application.

**Table 12.** Comparison of the obtained structural response values.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Analytical</th>
<th>FEM</th>
<th>Experimental Tests</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stator structural response</td>
<td>2–1491 Hz</td>
<td>2–1347 Hz</td>
<td>2–1393 Hz</td>
</tr>
<tr>
<td></td>
<td>3–2750 Hz</td>
<td>3–2934 Hz</td>
<td>3–3040 Hz</td>
</tr>
<tr>
<td></td>
<td>4–4592 Hz</td>
<td>4–4398 Hz</td>
<td>4–4668 Hz</td>
</tr>
<tr>
<td>Inner rotor structural response</td>
<td>2–802 Hz</td>
<td>2–838 Hz</td>
<td>2–790 Hz</td>
</tr>
<tr>
<td></td>
<td>3–1137 Hz</td>
<td>3–1810 Hz</td>
<td>3–1751 Hz</td>
</tr>
<tr>
<td></td>
<td>4–2949 Hz</td>
<td>4–2784 Hz</td>
<td>4–2676 Hz</td>
</tr>
<tr>
<td>SPP structural response</td>
<td>2–649 Hz</td>
<td>2–623 Hz</td>
<td>2–637 Hz</td>
</tr>
<tr>
<td></td>
<td>3–1551 Hz</td>
<td>3–1329 Hz</td>
<td>3–1197 Hz</td>
</tr>
<tr>
<td></td>
<td>4–2819 Hz</td>
<td>4–2145 Hz</td>
<td>4–2228 Hz</td>
</tr>
<tr>
<td>MG outer rotor structural response</td>
<td>2–440 Hz</td>
<td>2–429 Hz</td>
<td>2–435 Hz</td>
</tr>
<tr>
<td></td>
<td>3–1561 Hz</td>
<td>3–1182 Hz</td>
<td>3–1203 Hz</td>
</tr>
<tr>
<td></td>
<td>4–2838 Hz</td>
<td>4–2177 Hz</td>
<td>4–2236 Hz</td>
</tr>
<tr>
<td>IWM-IMG structural response</td>
<td>2–1694 Hz</td>
<td>2–1502 Hz</td>
<td>2–1542 Hz</td>
</tr>
<tr>
<td></td>
<td>3–3123 Hz</td>
<td>3–3593 Hz</td>
<td>3–3722 Hz</td>
</tr>
<tr>
<td></td>
<td>4–5938 Hz</td>
<td>4–5865 Hz</td>
<td>4–6225 Hz</td>
</tr>
</tbody>
</table>

**Table 13.** Results of the numeric analysis and experimental tests for the MG.

<table>
<thead>
<tr>
<th>Results</th>
<th>Distance of Measurement (cm)</th>
<th>Frequency (kHz)</th>
<th>Noise Level (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FEM</td>
<td>10</td>
<td>8</td>
<td>91.2</td>
</tr>
<tr>
<td></td>
<td>70</td>
<td></td>
<td>87.3</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td></td>
<td>82.1</td>
</tr>
<tr>
<td>Experimental tests</td>
<td>10</td>
<td>8</td>
<td>80</td>
</tr>
<tr>
<td></td>
<td>70</td>
<td></td>
<td>75</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td></td>
<td>70</td>
</tr>
<tr>
<td>FEM</td>
<td>10</td>
<td>20</td>
<td>94.5</td>
</tr>
<tr>
<td></td>
<td>70</td>
<td></td>
<td>101</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td></td>
<td>87.3</td>
</tr>
<tr>
<td>Experimental tests</td>
<td>10</td>
<td>20</td>
<td>90</td>
</tr>
<tr>
<td></td>
<td>70</td>
<td></td>
<td>80</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td></td>
<td>70</td>
</tr>
</tbody>
</table>
Author Contributions: Conceptualization, C.V.P. and D.F.; methodology, C.V.P., D.F. and D.-C.P.; validation, C.V.P. and D.F.; formal analysis, D.-C.P.; investigation, C.V.P.; resources, D.F.; writing—original draft preparation, C.V.P. and D.-C.P.; writing—review and editing, C.V.P., D.F. and D.-C.P.; funding acquisition, D.F. All authors have read and agreed to the published version of the manuscript.

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