A novel twin rotor permanent magnet dc motor was designed and developed for a mirror actuator. The rotors of each motor can be controlled and operated independently. The design objective was to reduce the cost of actuator manufacture by replacing its two single dc motors with the twin rotor motor. The paper describes the operation principles, main design considerations, alternative topologies, analysis, and experimental data for the manufactured motors.

Keywords: Permanent magnet dc motor, Twin rotor dc motor, FEA model, Multiple-rotor, Twin rotor

Introduction

In some applications, two or more motors are required in close proximity to each other to provide different independent drives within a system. Examples of such applications are sewing machines and automobile power seats [1,2]. There are a considerable number of such innovative designs of different types of multiple-rotor motors in the literature. However, they tend to be very complex and hence too expensive to manufacture. To resolve this issue, it is desirable to reduce the number of components and consequently the total cost of the assembly.

This paper is based on an existing automotive mirror actuator, which was redesigned to replace its two permanent magnet dc motors with an equivalent twin-rotor (armature) dc motor. In order to comply with the design objectives, the twin-rotor motor had to satisfy the following cost and manufacturing criteria:

- the same housing thickness as in single motors,
- the same armature as single rotor dc motor,
- lower cost than two single rotor dc motors,
- the same magnet material as in the single motor,
- easy assembly and manufacture.

The twin rotor motor designs, analysis, possible performance improvements and experimental data will be presented in the following sections.

Design

Recently, due to the needs of an automotive mirror manufacturer, arising from their cost and manufacturing objectives, a novel, simple and effective permanent magnet twin rotor dc motor was designed and developed. The manufactured “Bow-Tie” design prototype is shown in Fig. 1. The cross-sectional and load condition field distribution of the twin rotor dc motor for two alternative topologies are given in Fig. 2. Fig. 2 (a) illustrates the motor topology where the magnet is isolated from casing by means of non-magnetic material spacings, whereas in Fig. 2 (b) the magnet is attached to the casing. The former design is the preferred topology to reduce flux leakage between the magnet and casing. In both designs the magnet is magnetised so as to produce magnetic flux extending in a direction from the left rotor to the right rotor.

Fig. 1: Prototype of the twin rotor dc motor

Fig. 2: Field distribution of “Bow Tie” design twin rotor dc motor (only right armature is energised)
(a) Magnet is separated from casing
(b) Magnet is attached to the casing

A number of other magnetic field inducing assemblies have also been investigated. These assemblies may comprise of one or more magnets. For instance, two magnets separated by a ferromagnetic pole piece may be used. The magnetisation direction of the magnet or magnets...
may also be varied. However, the preferred designs are the magnetic field inducing assemblies comprising of a single magnet in view of cost and simplicity of manufacturing.

The single rotor permanent magnet dc motor, which was used in the mirror actuator, was the basis of the twin rotor dc motor design. Some of the performance (at maximum efficiency) and topological data of the single rotor dc motor are given in Table 1. The cross sectional topology and field distribution of the motor is shown in Fig.3.

Table 1: Single rotor dc motor data

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Torque, mNm</td>
<td>1.025</td>
</tr>
<tr>
<td>Current, mA</td>
<td>125</td>
</tr>
<tr>
<td>Speed, rpm</td>
<td>5909</td>
</tr>
<tr>
<td>Magnet type</td>
<td>Ferrite</td>
</tr>
<tr>
<td>Armature length, mm</td>
<td>10.55</td>
</tr>
<tr>
<td>Number of turns per coil</td>
<td>490</td>
</tr>
<tr>
<td>Magnet axial length, mm</td>
<td>14</td>
</tr>
</tbody>
</table>

Fig. 3: Field distribution of the single rotor dc motor at full load

The advantages, which can be offered by twin rotor dc motors as compared with single rotor dc motor, can be summarised as follows:

- less number of parts required in comparison to its single rotor counterpart,
- fewer magnets – less magnet volume, and
- more compact design.

Some negative-effects such as higher vibration and lower starting torque were realised, when the prototype was analysed and tested in comparison with its single rotor counterpart. However, these problems can be rectified if some of the design constraints such as magnet material, casing thickness and armature design are relaxed. It should be noted that in the designs published here, no effort has been made to optimise the performance or geometry of the prototype, which could reduce or eliminate the afore-mentioned problems.

Field Analysis

A two-dimensional (2-D) finite element method (FEM) with magnetic vector potential formulation has been adopted for field and performance analysis. In this formulation the magnetic flux density vector, \( \mathbf{B} \), is defined as

\[
\mathbf{B} = \nabla \times \mathbf{A} \tag{1}
\]

where \( \mathbf{A} \) is the magnetic potential vector. The magnetic flux intensity vector, \( \mathbf{H} \), is calculated from

\[
\mathbf{H} = \mu^{-1} \mathbf{B} \tag{2}
\]

where \( \mu \) is the magnetic permeability tensor.

The total developed torque, \( T_e \), acting on bodies contained in a particular volume is computed from

\[
T_e = \frac{1}{2} \mu (\mathbf{B} \cdot \mathbf{s_a}) + (\mathbf{\Gamma} \times \mathbf{B})(s_a \cdot \mathbf{s_s}) - (\mathbf{\Gamma} \times \mathbf{\hat{s_s}})(\mathbf{\hat{H}} \cdot \mathbf{\hat{B}}) \] \( \mathbf{ds} \)

where \( \mathbf{\Gamma} \) is the vector of radius with respect to the centre of rotation, \( \mathbf{s_a} \) and \( \mathbf{s_s} \) denote the normal unit vector and vector of differential surfaces respectively. The flux is calculated from

\[
\Phi = \frac{1}{2} \mathbf{A} \cdot \mathbf{d} \mathbf{\ell} \tag{4}
\]

where \( \mathbf{d} \mathbf{\ell} \) is the vector of differential lines.

In this paper steady-state behaviour of the machines were studied using magnetostatic analysis. The models investigated here fully account for magnetic material non-linearities within the machine core. The 2-D model field results were used in conjunction with an electrical circuit to enhance performance prediction accuracy.

The armature angular speed can be derived from

\[
n = \frac{(V - V_B - I_a R_a) T_e}{2\pi} \tag{5}
\]

where \( V \) and \( V_B \) are the source and brush voltage drops, and \( I_a \) and \( R_a \) are armature current and resistance respectively [3].

Performance Analysis

A finite element analysis (FEA) has been conducted to evaluate the torque and flux for both the single and twin rotor motors. As detailed information on the magnetic material properties of the original single rotor dc motor was not available for conducting the simulations, the similar material characteristics listed in Table 2 were used. The axial length of the magnets and armature core, given in Table 1, are used for the simulations of the single and twin rotor dc motors.

Table 2: Material properties used for simulations

<table>
<thead>
<tr>
<th>Material type</th>
<th>Strontium ferrite</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnet coercive force, A/m</td>
<td>248000</td>
</tr>
<tr>
<td>Magnet remanence, T</td>
<td>0.34</td>
</tr>
<tr>
<td>Casing and core materials</td>
<td>Steel 1411</td>
</tr>
</tbody>
</table>

These material properties were used for FEA throughout the simulations, which may have led to discrepancies between simulated and experimental results. However, the use of the above materials allows direct comparison between the performances of the single and twin rotor motor designs. The
magnet overhang is another factor that profoundly affects the machine performance. In order to investigate this effect a full 3-D analysis is required. The magnet overhang effect can be taken into account by including a factor (1.15-1.2) in the flux and torque calculation in the 2-D model.

The overall geometries, such as magnet overhang, magnet thickness, casing and armature axial length of the designed twin rotor machines have been kept equal to the existing single rotor armature permanent magnet dc motor to facilitate performance comparisons.

The Maxwell torques exerted on the whole armature body, which includes windings and armature core, are calculated from finite element analysis using Equation (3). The fluxes are computed from Equation (4).

For magnetostatic analysis, knowledge of instantaneous winding currents is essential for successful FE analysis. These currents can be calculated from the total average armature currents and the commutator positions.

The currents in the winding change every 30 mechanical degrees depending on the relative position of commutators and brushes. Two of these situations are illustrated in Fig. 4 and their corresponding circuit diagrams are shown in Fig. 5.

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Simulation Results

The procedure implemented in the previous section was used for torque calculations arising from FE simulation. Due to the commutation and design of the armature, the analysis was carried out for the chosen current for steps of 30° of the armature angular displacements. Fig. 6 (a) and (b) are the calculated torques and fluxes per pole at four different armature angular positions, with 125 mA armature current, namely 0°, 30°, 60°, and 90°. These calculated values are repeated sequentially for other angular positions of the rotor, eg 120°, 150°, 180° and 210°. The analysis reveals the torque fluctuations for the considered motors.

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In order to construct the external performance characteristics (torque-speed) of the motors, a series of FEA has been carried out for different armature current loadings and considering the four positions of the rotor for each loading. Each torque point of the performance characteristics is calculated by averaging of the computed four torque values at a particular current. The speed corresponding to the calculated average torque point is calculated from Equation (5). Figs. 7 and 8 depicts the performance characteristics of the single and twin rotor motors respectively. In the figures, the line of best fit has been run through the points for obtaining continuous graphs.
Experimental Results

The single and twin rotor motors were tested on a micro-dynamometer built specifically for testing these types of motors. The rotor was connected to a metal disc via a flexible coupling and an Eddy-current magnetic brake was used to apply a torque load to the motor. The speed and torque were measured from the dynamometer using an optical speed encoder and a load cell respectively. The interpolated performance curves from the motors are shown in Figs. 9 and 10.

The differences between the experimental and simulated are due to differences in the magnetic material characteristics used in the construction of the single and twin rotor motors. Another reason is that mechanical losses were not considered in the performance simulated calculations. However, the simulation results provide reasonable performance comparisons of the motors.

Conclusion

A new twin rotor motor design was developed and analysed. The design is simple with lesser number of parts in comparison with two single rotor motors. Therefore, if it is mass-produced the cost will be less than its two single rotor motor counterpart. It also has potential for other applications rather than automotive accessories, which require a number of motors with stringent weight and cost constraints.

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References