Study and optimization of a small tubular linear motor with permanent magnet

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PRESENTATION TOPICS

- Company Overview: Embraco
- Introduction
- Genetic algorithm
- Constructive aspects of the motor
- Performance calculation methodology
- Optimization results
- Experimental methodology
- Experimental results
- Conclusions
Company Overview: Embraco

- Specialized in cooling solutions, Embraco is the world leader in the hermetic compressor market for refrigeration.
Company Overview: Embraco

- Founded in March 1971
- 9 thousand employees
- 30 million compressors per year
- 80 countries
- 862 patents granted in the world
- 3% of annual net revenue in research and development
- Embraco + Multibras = Whirlpool S.A.
- Independent operations
Company Overview: Embraco

1 Brazil
Plants of compressors,
Casting products,
Electronic controls,
Electric components,
Cooling system components
and assembly

2 China
Compressor plant

3 Slovakia
Compressor plant

4 United States
Sales office and
technical assistance

5 Italy
Compressor plant,
Sales office and technical assistance

6 Mexico
Sales office and technical assistance
Introduction

• Linear motors are rapidly finding applications involving short-stroke linear motion;

• The advantage includes good linearity, does not require mechanical energy conversion parts, which change rotary motion into linear motion;

• Tubular structures are very attractive compared with flat linear actuators, due to the nonexistence of end-turn effects, high thrust and self alignment;
Introduction

• This motor has a PM radially magnetized and the movement is in the axial direction;

• A genetic algorithm (GA) method with a mathematical model - Finite Element (FE) program and analytical expressions was carried out.
Genetic Algorithm

- The algorithm is based on the process of genetic replication and uses the "strategy of survival of better adapted";
- Creation of initial population, evaluation, creation of gene pool, the operation of crossover, mutation and evaluation;
- NSGA-II (Non-dominated Sorting Genetic Algorithm II);
- NSGA-II is a fast and elitist GA which works with multiobjective functions;
- People tend to avoid GA in engineering problems due to long iterations needed for best solution.
Constructive aspects of the motor

• The geometry of the motor as it was inserted in the optimization program:
  a. stator yoke
  b. bobbin depth
  c. bobbin length
  d. magnet length
  e. stator bracket
  f. magnet thickness
  g. back iron yoke
  h. stator hole

• Dimensional restrictions:
  o Fixed the radius of the stator hole (h);
  o Fixed the outer radius of the motor (a+b+f+g+h+2gap);
  o Fixed the air gap.
Constructive aspects of the motor

- Maximum current density in the windings: 35.0 A/mm²;
- Maximum length of the stator and the back iron: equal to the non optimized reference motor used for the same application;
- Maximum magnetic induction in the stator and the back iron: 1.5 T;
- Induced voltage peak in the coil (emf): 15.0 V;
- Minimum mechanical power: 10.0 W;
- The frequency, stroke and type of magnet were kept equal to the current product;
- The objective function is the efficiency.
Performance calculation methodology

- It was used an analytical model in addition to FE program (FEMM 4.2)
Performance calculation methodology

STEP 1

• The motor is mounted mathematically according to the given dimensions;
• Permanent magnet: NdFeB (Br ~ 1.0 T);
• Electrical steel: Soft Magnetic Composite;
• Winding: copper wire.
Performance calculation methodology

STEP 2

• A sinusoidal current is inserted in the winding:

\[ I(t) = \sqrt{2}I_{rms} \sin(\omega t) \quad \Rightarrow \quad I(x) = \sqrt{2}I_{rms} \sqrt{1 - \left(\frac{x}{c_r}\right)^2} \]

\( x \) is the magnet position and \( c_r \) is the displacement peak. The displacement varies from \([-c_r, +c_r]\), i.e. the total stroke is \(2c_r\).
Performance calculation methodology

**STEP 3**

- The force is calculated;
- The current density is calculated;

\[ J = \frac{4I_{rms}}{\pi d_c^2} \]

- The magnet flux induction is calculated.
Performance calculation methodology

STEP 4

- The useful power is calculated:

  \[ P_{mec} = Fv \quad \rightarrow \quad P_{mec} = 4Fc_r f \]

- The iron losses is calculated:

  \[ p_f = f \left( k_h B_m^\alpha + k_f B_m^2 \right) \rho_a Vol \]

- The copper losses is calculated.

  \[ p_c = R_c I^2 \]
Performance calculation methodology

STEP 5

• After all parameters of the performance being previously calculated, it is possible to evaluate the efficiency of the linear motor;

\[ \eta = \frac{P_{mec}}{P_{mec} + P_c + P_f} \]
\[ \eta = \frac{P_{mec} - P_f}{P_{mec} + P_c} \]

• Additionally the emf is calculated.

\[ \varepsilon(t) = -N \frac{d\phi}{dt} \]
\[ \varepsilon(x) = -N \frac{(\phi_e - \phi_s)}{(x_e - x_s)} \sqrt{c_r^2 - \left(\frac{x_e + x_s}{2}\right)^2} \]
Optimization results

- It was chosen a DOE with eight initial motors randomly created.
Optimization results

- Dimensional comparison between the reference motor and the optimized one.

<table>
<thead>
<tr>
<th>Motor Part</th>
<th>Reference (%)</th>
<th>Optimized (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stator yoke</td>
<td>100</td>
<td>85</td>
</tr>
<tr>
<td>Back iron yoke</td>
<td>100</td>
<td>118</td>
</tr>
<tr>
<td>Bobbin depth</td>
<td>100</td>
<td>95</td>
</tr>
<tr>
<td>Bobbin length</td>
<td>100</td>
<td>113</td>
</tr>
<tr>
<td>Stator bracket</td>
<td>100</td>
<td>60</td>
</tr>
<tr>
<td>Motor length</td>
<td>100</td>
<td>83</td>
</tr>
<tr>
<td>Magnet length</td>
<td>100</td>
<td>97</td>
</tr>
<tr>
<td>Magnet thickness</td>
<td>100</td>
<td>138</td>
</tr>
<tr>
<td>Magnet mass</td>
<td>100</td>
<td>125</td>
</tr>
</tbody>
</table>
Optimization results

- Performance comparison between the reference motor and the optimized one.

<table>
<thead>
<tr>
<th></th>
<th>Reference</th>
<th>Optimized</th>
<th>Difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wire diameter (mm)</td>
<td>0.25</td>
<td>0.25</td>
<td>0.00</td>
</tr>
<tr>
<td>Wire resistance (Ω)</td>
<td>1.17</td>
<td>1.22</td>
<td>4.27</td>
</tr>
<tr>
<td>Current (A)</td>
<td>1.55</td>
<td>1.45</td>
<td>-6.45</td>
</tr>
<tr>
<td>Current density (A/mm²)</td>
<td>31.57</td>
<td>29.54</td>
<td>-6.43</td>
</tr>
<tr>
<td>Mechanical power (W)</td>
<td>15.49</td>
<td>15.49</td>
<td>0.00</td>
</tr>
<tr>
<td>Copper losses (W)</td>
<td>2.81</td>
<td>2.57</td>
<td>-8.54</td>
</tr>
<tr>
<td>Iron losses (W)</td>
<td>3.01</td>
<td>2.51</td>
<td>-16.61</td>
</tr>
<tr>
<td>Turns number</td>
<td>114</td>
<td>132</td>
<td>15.79</td>
</tr>
<tr>
<td>Efficiency (%)</td>
<td>72.70</td>
<td>75.30</td>
<td>3.58</td>
</tr>
</tbody>
</table>

The efficiency was increased by 3.58%!
Experimental results

• Back-to-Back coupling concept;
• Components of the dynamometer: a) linear motor, b) linear generator, c) resonant springs and d) coupling shaft.
Experimental results

<table>
<thead>
<tr>
<th></th>
<th>Experimental</th>
<th>Theoretical</th>
<th>Difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wire diameter (mm)</td>
<td>0.25</td>
<td>0.25</td>
<td>0.0</td>
</tr>
<tr>
<td>Wire resistance (Ω)</td>
<td>1.04</td>
<td>1.04</td>
<td>0.0</td>
</tr>
<tr>
<td>Current (A)</td>
<td>2.20</td>
<td>2.20</td>
<td>0.0</td>
</tr>
<tr>
<td>Turns number</td>
<td>104</td>
<td>104</td>
<td>0.0</td>
</tr>
<tr>
<td>emf (V)</td>
<td>6.43</td>
<td>6.45</td>
<td>0.3</td>
</tr>
<tr>
<td>Copper losses (W)</td>
<td>5.00</td>
<td>5.00</td>
<td>0.0</td>
</tr>
<tr>
<td>Iron losses (W)</td>
<td>0.94</td>
<td>0.95</td>
<td>0.4</td>
</tr>
<tr>
<td>Mechanical power (W)</td>
<td>10.86</td>
<td>11.39</td>
<td>4.9</td>
</tr>
<tr>
<td>Input power (W)</td>
<td>16.96</td>
<td>17.34</td>
<td>2.3</td>
</tr>
<tr>
<td>Average force (N)</td>
<td>8.73</td>
<td>9.41</td>
<td>7.9</td>
</tr>
<tr>
<td>Efficiency (%)</td>
<td>64.03</td>
<td>65.69</td>
<td>2.6</td>
</tr>
</tbody>
</table>

- Difference of 4.9% in power and 2.6% in the efficiency;
- The difference in the force of 7.9% is greater than the error of mechanical power, since the calculation of the force does not take into account dynamic effects.
Conclusions

• The proposed methodology was carried out and the best solution was found taking into account efficiency, output power and volume;

• The new motor has many advantages related to the actual and an important gain of 3.6% in efficiency was obtained;

• GA is robust and reliable to be considered in motor design methodology, whereas the calculation methodology is fast and reliable;

• The calculation methodology was validated by comparing experimental results with simulated ones;

• In the experiments a difference of 4.9% in output power and 2.6% in the efficiency was obtained.
Thank you for your attention

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