The Designation and Simulation of a New Type of Electromagnetic-Clutch-By-Wire

Yunchao Yin, Chen Qi, Jinyu Qu

Abstract—This paper presents a new type of electromagnetic-clutch-by-wire (ECBW). The ECBW’s construction parameters are designed basing on the working character and working principal of the ECBW. The most important part in the designation of electromagnetic-clutch is the calculation of electromagnetic force. This paper introduces the electromagnetic force calculation method of the DC solenoid electromagnet, and establishes electromagnetic-clutch’s simulation models of the relationship among the current, magnetic flux density and electromagnetic force. The simulation result shows that the electromagnetic force satisfied the requirement of automatic transmission.

Index Terms—Electromagnetic-Clutch-By-Wire, Simulink, Construction Designation, Electromagnetic Force

I. INTRODUCTION

Nowadays, the existing electromagnetic clutches can be divided into: friction-electromagnetic clutch, Jaw-installation of electromagnetic clutch, magnetic-powder clutch, slip-type-electromagnetic clutch. When the electromagnetic coil of friction-electromagnetic clutch is engaged, the driving friction plates and the driven friction plates are pressed by electromagnetic force which generated by electromagnetic coil. So that the friction produced by the driving friction plates and the driven friction plates is used to transmit torque. When there is a large torque needs to be transmitted, the radial dimension of input disc and the driven disc must be increased, the current of the electromagnetic coil must be increased, the number of driving friction plates and the driven friction plates must be increased. Therefore, there are many disadvantages such as large size, low speed, large power consumption and so on. The Jaw-installation of electromagnetic clutch can transmit large torque. When the Jaw-installation of electromagnetic clutch is engaged, there is a low speed, however, the power consumption is huge. The response speed of the magnetic-powder clutch is very fast, and it can also achieve the precision fine adjustment. But it has a large power consumption, high cost and large slip when the temperature rises. When the slip-type-electromagnetic clutch works, there must be speed discrepancy between the driving part and the driven part, and the eddy currents in the rotor will produce heat[1-3].

The new type of electromagnetic-clutch-by-wire (ECBW) which is proposed in this paper is to overcome the shortcomings of the existing electromagnetic clutches and to provide a new structure’s electromagnetic clutch which has high speed, low power consumption and can transmit large torque[4].

II. THE CONSTRUCTION DESIGN OF ELECTROMAGNETIC COIL

A. The construction of NETIC-CLUTCH-BY-WIRE

AND THE ARRANGEMENT designation of Electromagnetic-Clutch-By-Wire

The structure of ECBW proposed in this paper is shown as Fig.1. It consists of buffer disc assembly(2), groove(2A), rubber bumper(2B), electromagnetic clutch assembly(4), electromagnetic coil(4A), electromagnet(4B), balance disc(4C), return spring(4D), fixing bolt (4E), sleeve(4H), stud-by-wire(4F), shell(4G), slip ring(4I) and balance disc(4J). When the electromagnetic valve is energized, there will be magnetic field generated around electromagnet, the balance disc will move to left with electromagnetic force overcoming the resistant force of return spring. And the stud-by-wire on balance disc will connect with driven disc to realize the smooth combination of ECBW.

When the electromagnetic valve is power off, the electromagnetic force will become the resistance force of stopping stud-by-wire to return, master-slave clutch will be departed under the function of return spring, to realize the fast depart of ECBW.

B. Arrangement of electromagnetic coil

Like the circuit, the magnetic circuit is also divided into series magnetic circuit and parallel magnetic circuit. The reluctance calculation which can represent the magnetic flux is very important for the calculation of electromagnetic force. A new type construction of electromagnet-ic-clutch-by-wire(ECBW) is proposed in this paper. In order to make full use of the structure space and keep the dynamic balance of electromagnetic clutch, four electromagnetic coils and two thrust pin guide sleeve bearing holes are arranged in symmetrical balance on the shell of electromagnetic clutch. The four electromagnetic coils are tandem. The concrete structure is shown as Fig.2.
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C. The designation of electromagnetic coil

The resistance coefficient of copper wire at different temperatures is shown as Tab. 1. Copper enamel wire is chosen to make winding, the diameter of copper wire is 0.884mm, and its sectional area is 0.5027mm².

Tab. 1 The resistance coefficient of copper wire at different temperatures

| Operating temperature (°C) | \( \rho_{20} = 0.01754 \) | \( \rho_{35} = 0.01857 \) | \( \rho_{40} = 0.01991 \) | \( \rho_{90} = 0.02236 \) | \( \rho_{105} = 0.02339 \) | \( \rho_{120} = 0.02443 \) |

Because the quality of magnetic circuit is very similar to the circuit, so we can use the analytical method of the circuit to study the magnetic circuit and do some analysis and optimization of magnetic circuit. The comparison between the magnetic circuit and the circuit is shown as Tab. 2.

Tab. 2 The comparison between the magnetic circuit and the circuit

<table>
<thead>
<tr>
<th>Type of magnetic potential</th>
<th>Voltage/ohm law</th>
<th>Resistance/reluctance</th>
<th>Kirchhoff's law</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circuit</td>
<td>( U/N )</td>
<td>( R/\Omega )</td>
<td>( I=U/R )</td>
</tr>
<tr>
<td>Magnetic circuit</td>
<td>( N/l/A )</td>
<td>( R/H^{-1} )</td>
<td>( \phi=N/l/R )</td>
</tr>
</tbody>
</table>

Therefore, the equivalent circuit of the electromagnetic coil is shown as Fig. 3.

Because the equivalent circuit of the electromagnetic coil is

\[ R = \rho l \]

(1)

The length of copper wire is:

\[ l = N \times C \]

(2)

The average perimeter of coil is:

\[ C = \frac{11 + 30}{2} \times \pi \]

(3)

The empirical formula of coil inductance (without iron core) is:

\[ L = \frac{u_0 N^2 R}{l} \left( \pi R_1 - r(0.693 + C) \right) \]

(4)

Where, \( u_0 \) is permeability of vacuum, \( N \) is coil turns and its value is 216; \( R \) is the average radius of the coil and its value is 0.01m; \( l \) is the total length of the coil and its value is 0.24m; \( k \) is the ratio of coil’s radius and length and its value is 0.74; \( t \) is the thickness of coil and its value is 0.009m; \( C \) is a coefficient determined by \( I/t \) and its value is 0.28. The value of \( L \) is calculated to be 3.537mH. The inductance with iron core is \( u_r \) times of that without iron core. And \( u_r \) is about 10 – 100, so \( L_1 \) is 0.07H.

Take the effect of electromagnetic coil’s inductance on the current change into consideration, the electromagnetic coil current change formula is:

\[ I_p = \frac{u}{R} \left( 1 - e^{-\frac{R}{L}} \right) \]

(5)

The relationship curve of electromagnetic coil’s current and power-on time is shown as Fig. 4. The changing curve of shutdown current versus time is shown as Fig. 5.
D. The designation of electromagnet

The knee-point m is chosen to be working point position as electromagnet material[6-7], according to magnetization curve and permeability curve of ferromagnetic materials. The magnetic inductive strength is strong enough in this point but cannot reach magnetic saturation. The iron-nickel alloy 1J46 is chosen to be the electromagnet material because of its high magnetic permeability, low coercivity, good durability and stable magnetism.

E. The designation of return spring

According to the design requirement, the spring specification is chosen to be: free length is 12mm, compressed length is 6mm, the diameter is 2.0mm, outer diameter is 35mm, the number of active turns N is 2.5. The mass of stud m1 is 0.102kg, the mass of suction disc m2 is 0.466kg, and the mass of thrust pin balance disc m3 is 0.373kg. So, the mathematical model of spring pressure is:

\[ F_{spring} = k \cdot s \]  \hspace{1cm} (6)

Where, \( k \) is spring constant (kgf/mm), \( s \) is effective stroke of spring pressure (mm).

\[ k = \left( \frac{G \times d^4}{(8 \times D_a^3 \times N_i)} \right) \]  \hspace{1cm} (7)

\[ D_a = D - d \]  \hspace{1cm} (8)

Where, \( G \) is material’s modulus of rigidity, \( G = 8000 \). It can be figured out that \( k \) is 0.163 kgf/mm, \( s \) (6mm) = 9.584(N).

According to the above analysis, the main design parameters of ECBW is determined as shown in Tab.3.

<table>
<thead>
<tr>
<th>parameters</th>
<th>value</th>
<th>unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>magnetic flux density /B</td>
<td>0--1.5</td>
<td>T</td>
</tr>
<tr>
<td>permeability of vacuum / ( \mu_0 )</td>
<td>4\pi10^(-6)</td>
<td>Wb/A-m</td>
</tr>
<tr>
<td>magnetic path cross-sectional area / S</td>
<td>95*10^(-6)</td>
<td>m²</td>
</tr>
<tr>
<td>number of turns / N</td>
<td>216</td>
<td>Kg</td>
</tr>
<tr>
<td>voltage / U</td>
<td>3*4</td>
<td>V</td>
</tr>
<tr>
<td>maximum current / I</td>
<td>6.16</td>
<td>A</td>
</tr>
<tr>
<td>winding resistance / R</td>
<td>0.487</td>
<td>( \Omega )</td>
</tr>
<tr>
<td>gap length / ( \delta )</td>
<td>1*10^(-3)</td>
<td>m</td>
</tr>
<tr>
<td>Wire diameter. / d</td>
<td>0.8/0.884</td>
<td>mm</td>
</tr>
<tr>
<td>magnetic leakage coefficient / ( K_l )</td>
<td>1.8</td>
<td>--</td>
</tr>
</tbody>
</table>

Tab.3 The mainly design parameters of ECBW

III. THE ESTABLISHED OF MATHEMATICAL MODEL AND SIMULATION OF ECBW

A. The mathematical model of ECBW

The electromagnetic force formula of designed DC solenoid electromagnet is[8-9]:

\[ F = \frac{\phi^2}{2\mu_0 S} = \frac{B^2}{2\mu_0} S \]  \hspace{1cm} (9)

Where, \( \phi \) is the leakage coefficient, its value ranging from 1 to 10 according to the condition of the magnetic composition, and it is generally take 1.2 to 5.0 in the design of electromagnetic valve. The selecting of the value has great empirical.

When the magnetic field is established gap length decreases, and the formula is:

\[ (\delta - 1)^2 = \frac{(NI)^2 \mu_0 S}{2K_f F} \]  \hspace{1cm} (13)

B. The simulation and analysis of ECBW

According to the mathematical equation of ECBW, the ECBW’s simulation models of the relationship among the current, magnetic flux density and electromagnetic force is established by using MATLAB/Simulink. The ECBW’s simulation model of the relationship among the current, magnetic flux density and electromagnetic force is shown as Fig.6. When the air gap length is 1mm, the relationship curve
of current and magnetic flux density is shown as Fig.7 and the relationship curve of current and electromagnetic force is shown as Fig.8. The simulation model of different air gap length and electromagnetic force is shown as Fig.9. The relationship curve of electromagnetic force and air gap length is shown as Fig.10.

Fig.6 The simulation model of the relationship among the current, magnetic flux density and electromagnetic force

Fig.7 The relationship curve of current and magnetic flux density

Fig.8 The relationship curve of current and electromagnetic force

Fig.9 The simulation model of different air gap length and electromagnetic force

IV. CONCLUSION

ECBW is one of the key components in the transmission-by-wire shifting process. The most important part in the designation of electromagnetic-clutch is the calculation of electromagnetic force. Its specific configuration parameters are designed and calculated on the basis of analyzing its operating characteristics and working principle. The established simulation model shows that: (1) When the working voltage of the electromagnetic clutch is 12V, it means that the working voltage of each electromagnetic coil is 3V, the maximum working current of the electromagnetic coil is 6.2A, the maximum power consumption is 74W, the magnetic flux density B of the electromagnet is 1.4T in the steady state, the maximum electromagnetic force of each electromagnetic coil is 32.62N, the maximum electromagnetic force of electromagnetic clutch actuator is 130N, and the maximum electromagnetic force of electromagnetic clutch actuator meets the requirement of the rapid effect of clutch engagement process. (2) After the electromagnetic clutch is engaged, the working voltage is 6V, it means that the working voltage of each electromagnetic coil is 1.5V, the continuous working current of the electromagnetic coil is 3.1A, the maximum power consumption is 37W, the magnetic flux density B of the electromagnet is 0.7T in the steady state, the maximum electromagnetic force of each electromagnetic coil is 8.26N, the maximum electromagnetic force of electromagnetic clutch actuator is 33N, and the maximum electromagnetic force of electromagnetic clutch actuator meets the requirement of low power operation after the clutch engagement.

REFERENCES


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