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, Electromagn-etic 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 ELECTROMAG OF ELECTROMAGNETIC COIL

A.The construction d NETIC-CLUTCH-BY-WIRE ANDTHE ARRANGEMENT *esignation 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 cultch will be departed under the function of return spring, to realize the fast depart of ECBW.

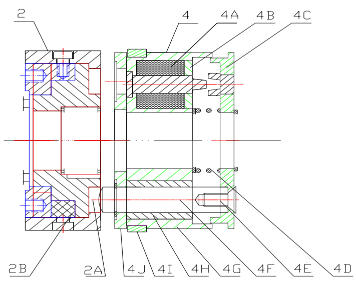

Fig.1 The construction of ECBW

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.

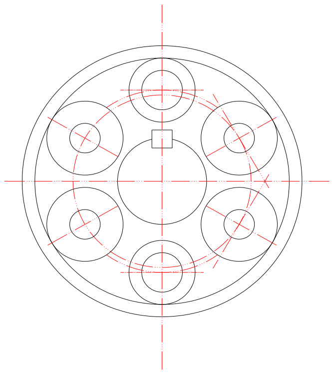

Fig.2 The shell of ECBW

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 0.5027mm^2.

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

operating temperature (℃)	resistance coefficient $\Omega \cdot mm^2 / m$	operating temperature (℃)	resistance coefficient $\Omega \cdot mm^2 / m$
20	ρ_{20} =0.01754	90	ρ_{90} =0.02236
35	ρ_{35} =0.01857	105	ρ_{105} =0.02339
40	ρ_{40} =0.01991	120	ρ_{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.2The comparison between the magnetic circuit and the circuit

type	voltage/magnetic potential	resistance/reluctance	ohm law	Kirchhoff's law
circuit	U/V	R/Ω	$I=U/R$	$\sum I=0$
magnetic circuit	$N \cdot I$/A	R/H^{-1}	$Ø=N \cdot I/R$	$\sum Ø=0$

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

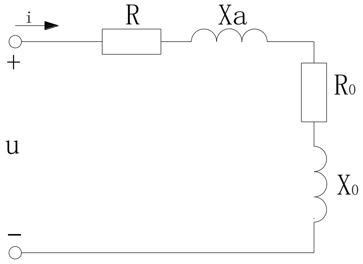

Fig.3The equivalent circuit of electromagnetic coil

The formula for the copper wire resistance of the electromagnetic coil is[5]:

$$R = \frac{\rho l}{S} \qquad (1)$$

The length of copper wire is:

$$l = N \times C \qquad (2)$$

The average perimeter of coil is:

$$C = \frac{11+30}{2} \times \pi \qquad (3)$$

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

$$L = \frac{u_0 . N^2 . R}{l}[\pi Rk - t(0.693 + C)] \qquad (4)$$

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 is0.74; t is the thickness of coil and its value is 0.009m; C is a coefficient determined by $1/t$ 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 in to consideration, the electromagnetic coil current change formula is:

$$I_p = \frac{u}{R}(1 - e^{-\frac{R}{L}t}) \qquad (5)$$

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.

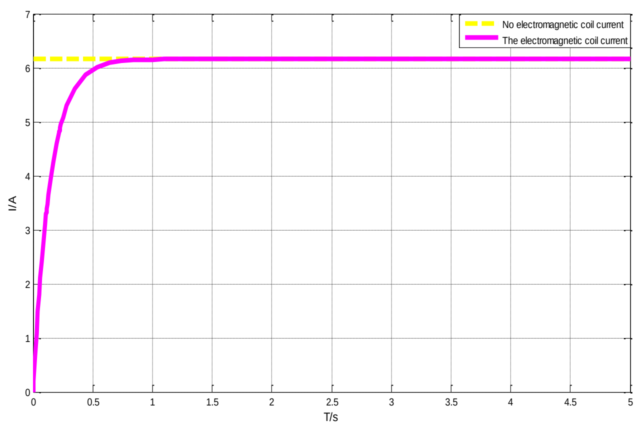

Fig.4 The relationship curve of electromagnetic coil's current and power-on time

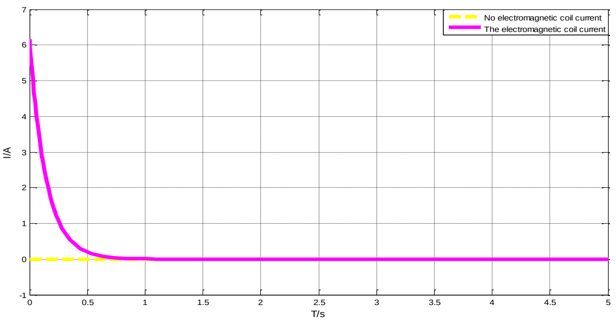

Fig.5 The changing curve of shutdown current versus time

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 coercively, 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_c is 2.5. The mass of stud m_1 is 0.102kg, the mass of suction disc m_2 is 0.466kg, and the mass of thrust pin balance disc m_3 is 0.373kg. So, the mathematical model of spring pressure is:

$$F_{spring} = k.s \qquad (6)$$

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

$$k = (G \times d^4)/(8 \times D_m^3 \times N_c) \qquad (7)$$

$$D_m = D - d \qquad (8)$$

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

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

Tab.3The mainly design parameters of ECBW

parameters	value	unit
magnetic flux density /B	0--1.5	T
permeability of vacuum / μ_0	4π*10^(-7)	Wb/A·m
magnetic path cross-sectional area /*S*	95*10^(-6)	m^2
number of turns/N	216	Kg
voltage/U	3*4	V
maximum current /I	6.16	A
winding resistance /R	0.487	Ω
gap length / δ	1*10^(-3)	m
Wire diameter. /d	0.8/0.884	mm
magnetic leakage coefficient /K_f	1.8	--

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]:

$$F = \frac{\phi^2}{2\mu_0 S} = \frac{B^2}{2\mu_0} S \qquad (9)$$

Where, φ is working air gap flux, *Wb*; B is working air gap magnetic induction, T. μ_0 is permeability of vacuum, and its value is 4π×10^{-7}Wb/A•m; S is magnetic path cross-sectional area, m^2.

In the preliminary design of the electromagnet, if the magnetic flux leakage and the air gap of connection part are ignored, considering only the core stroke gap to be the main air gap, the magnetic induction strength B of the iron core stroke (the main air gap) is:

$$B = \frac{N \cdot U}{R\delta} \mu_0 = \frac{NI}{\delta} S \qquad (10)$$

Where, N is the number of turns; I is selected as current intensity, A; U is the supply voltage, Ω; R is winding resistance,; δ is the length of the air gap, m. Usually the magnetic flux density reaches magnetic saturation when its value is15000 ~ 20000 Gs.

Take Eq.10 into Eq. 9, the following formula can be obtained:

$$F = \frac{(NI)^2 \mu_0}{2\delta^2} S \qquad (11)$$

Only part of the coil magnetic potential acted on working air gap, after considering the magnetic flux leakage, formula 11 can be written as:

$$F = \frac{(NI)^2 \mu_0}{2K_f{}^2 \delta^2} S \qquad (12)$$

Where, K_f is the leakage coefficient, its value is ranging from1 to 10according 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:

$$(\delta - 1)^2 = \frac{(NI)^2 \mu_0}{2K_f{}^2 F} S \qquad (13)$$

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.

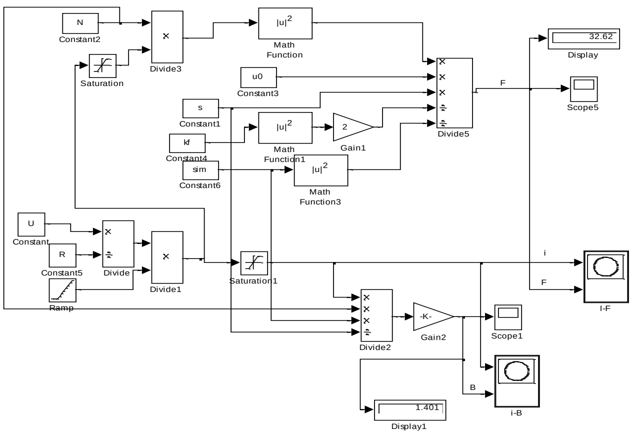

Fig.6 The simulation model of the relationship among the current, magnetic flux density and electromagnetic force

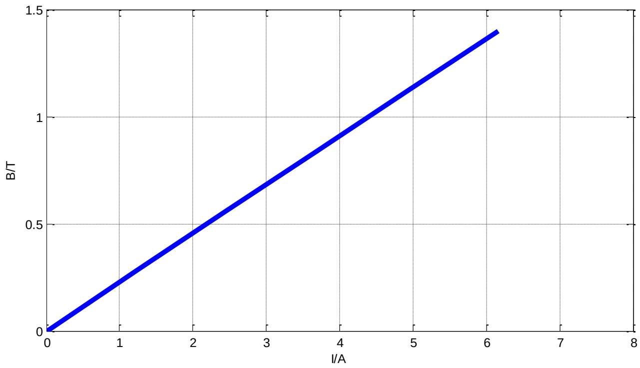

Fig.7 The relationship curve of current and magnetic flux density

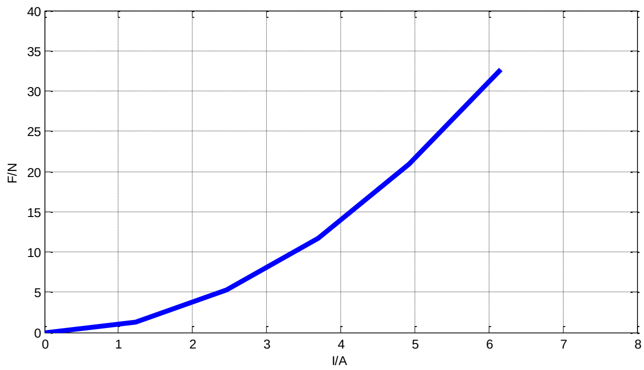

Fig.8 The relationship curve of current and electromagnetic force

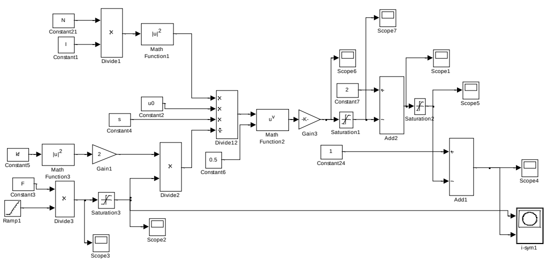

Fig.9 The simulation model of different air gap length and electromagnetic force

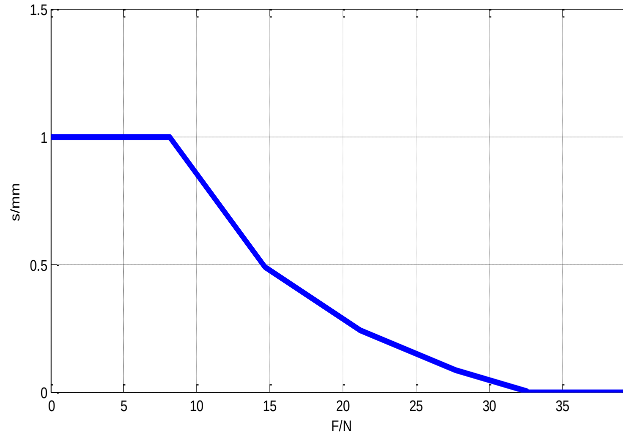

Fig.10 The relationship curve of electromagnetic force and air gap length

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.

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