A Novel Claw Pole Eddy Current Load for Testing a DC Counter Rotating Motor Part I: Construction

Khalil Kanzi *, Abolfazl Dehafarin *, Sam Roozbehani*, Majid Kanzi*and Qasem Vasheghani*

Abstract – Providing variable load for testing a motor in high speed conditions is usually a difficult task. The eddy current brake can be used in application of load testing of motors. This paper deals with construction of a novel claw pole eddy current brake which is employed as a load for a DC counter rotating motor (CRM). These kinds of motors have two inner and outer shafts that rotate in opposite directions simultaneously, which are particularly suitable for under water propulsion systems. The prototype 45KW eddy current brake consists of two parts. One of them is installed on the inner shaft of the 60KW DC CRM and the other one is installed on its outer shaft. The simulation and experimental results with prototype brakes are also analyzed by using MATLAB/Simulink and the operational characteristic of the brake is demonstrated as a function of the motor speed and current of the magnetic poles.

Keywords: Counter rotating motor, Claw pole eddy current brake, Load testing, Eddy current loss

1. Introduction

To improve economy of fuel used in ships, many devices have been designed to have the energy lost in a propeller recovered. One of the best answers yet found to recover energy from the rotational propeller is to have a second propeller rotating in the opposite direction. Such an additional propeller is called a counter rotating propeller (CRP). A counter rotating motor (CRM) is suitable for the implementation of a CPR. CRMs draw interest in being applied in the underwater marine environment increasingly because of their considerable advantages, such as high efficiency [1]-[2]. Providing a load test condition of a CRM is difficult because of its counter rotating property. In order to solve this problem, employing an eddy current brake seems appropriate.

Eddy current brakes are electromechanical devices used in two types of application. Many papers reported the application of eddy current brake in vehicles using a finit element method in order to do 2D or 3D analysis [3]-[5]. The second application of eddy current brakes is for load testing of a motor in high speed conditions [6]. In this paper the novel eddy current brake is employed as a variable load for testing the CRM motor.

The principle behind the operation of an eddy current brake relates to basic electromagnetic induction theory. This theory is based on Faraday's induction law, i.e. when a conducting element moves through a constant magnetic field; a current is induced. This current reacts with the magnetic field to produce a force which opposes the motion of the element [7]. This retarding force (torque) can be employed as a load for an electrical machine.

The main property of the presented eddy current brake is due to its claw pole structure which has not been reported in any paper before. The schematic of this brake is shown in Fig.1. The stator of this brake consists of only one excitation coil placed between some claw pole pairs. These claw poles produce a magnetic field with a high number of pole pairs.

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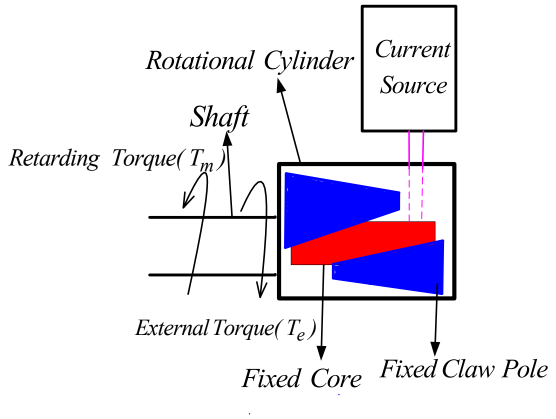


Fig.1. Schematic of the proposed eddy current load

In Fig.1, only one pair of claw poles is shown. If the windings are excited by a direct current and the cylinder is rotated by external torque (Te), relative motion between the cylinder and the magnetic field generated by the core, induces an eddy current within the iron cylinder body. Interaction between the magnetic field and the induced eddy currents produces a retarding torque (Tm) which is a function of the dc excitation current, cylinder speed, and electromagnetic properties of the solid iron. If the rotational cylinder in Fig.1 is coupled to the motor and rotated by it, this method of loading is especially applicable for testing motors with a high-speed range. Therefore, such a device can be used as a brake for determining the torque-speed curves of electric motors.

This paper deals with construction of novel claw pole eddy current brakes which are employed as loads for dc counter rotating motors and part II deals with design and modeling of eddy current loss which is applicable for designing the eddy current brakes. In addition, the magnetic analysis of the claw pole eddy brake will be described in part II.

2. Overview of the Experimental System

The schematic of the whole system is shown in Fig.2. The counter rotating motor has two inner and outer shafts that rotate in opposite directions. Two claw pole eddy current brakes are used for load testing of the motor. Each of these breaks is connected to a shaft. Two current sources are used for exciting the coils of the eddy brake. The description of each part of the system is as follows:

2.1 Structure of Counter Rotating Motor

In order to recover energy from the rotational flow of a propeller in ships, a second propeller that rotates in the opposite direction is needed. For solving this problem, the CRM has been employed as a resolution. The cross sectional view of prototype 60KW DC CRM is shown in Fig. 3, whereas Table 1 demonstrates the machine's overall characteristics. These types of motors have inner and outer shafts. For DC CRM, an electromagnetic torque is applied on the stator (outer rotor) and rotor (inner rotors) with the same magnitude, but in opposite directions. As the inertia of the two rotors is different, their speeds aren't the same in the steady state.

2.2 Structure of Claw Pole Eddy Current Brake

The rotary type eddy current brake and cross section of it are shown in Fig.4 and Table 2 is tabulated with its measured mechanical dimensions. The main parts of the prototype eddy current brake, including excitation coil, claw pole, and rotative cylinder are shown in Fig (5) and (6). It has been supposed that the cylinder is rotated by the motor shaft. As the current source is connected to the excitation coil, a magnetic field is generated in the core and the claw poles produce a magnetic field with a high number of

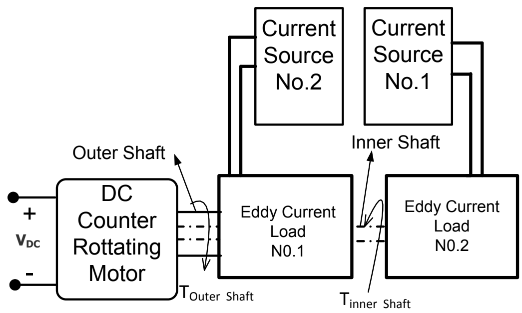


Fig. 2. Overview of experimental system

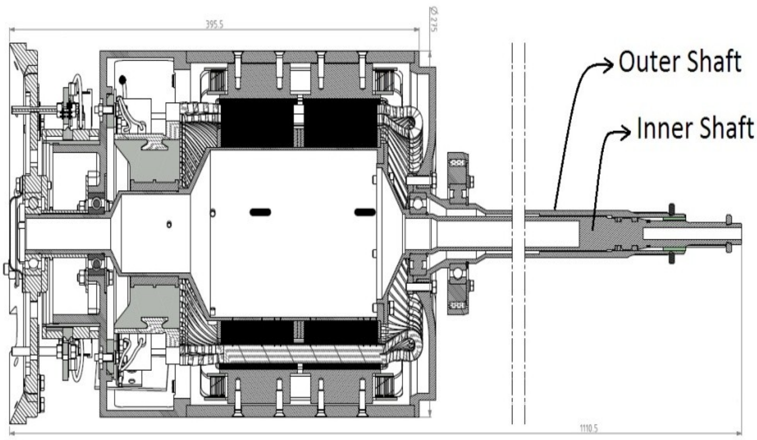


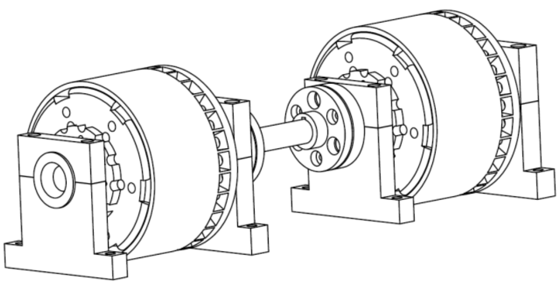
Fig. 3. Cross sectional view of DC counter rotating moto

Table 1. The caption must be followed by the table

Dc Counter Rotating Motor Parameter	Value
Rated Power	60KW
Motor Type	Seri
Rated Voltage	200V
Rated Current	300A
Diameter of Motor	275mm
Length of Motor	310mm
Insulation Class	H
Relaytive speed of Armature and field	3500-4000 rpm
Armature rated Speed	1750-2000 rpm
Poles and Yoke rated speed	1750-2000rpm

Table 2. Mechanical dimension of eddy brake

Brake Parameter	Value
Total rated Power	2*22.5KW
Rated Excitation Current	30A
Cylinder Outer Diameter	361.40mm
Cylinder Inner Diameter	340.40mm
Cylinder Thickness	10.5mm
Small Rule of Claw Pole	41.98mm
Big Rule of Claw Pole	120.53mm
Small Rule of Claw Pole	41.98mm
Height of Claw Pole	138mm
Core, Claw pole and Cylinder Material	Fe-st32



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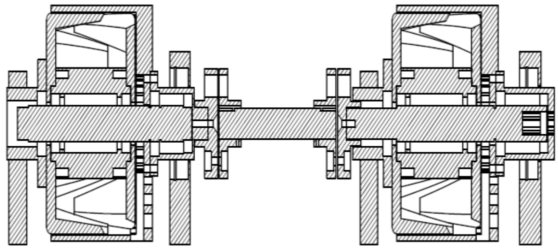

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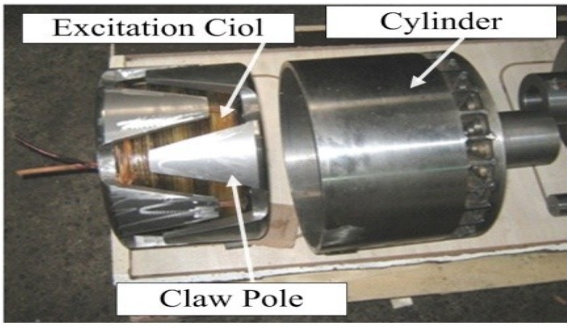

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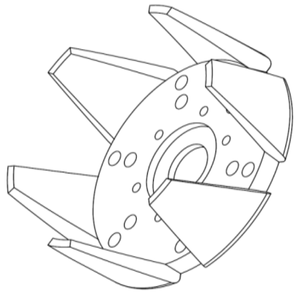
Fig. 4. Eddy Brake, a: overview, b: cross, c: main p



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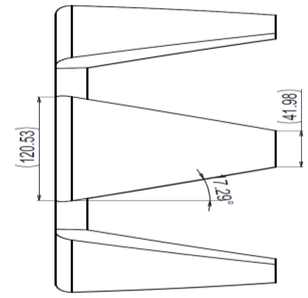

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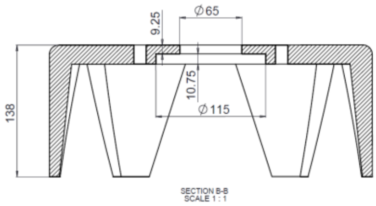

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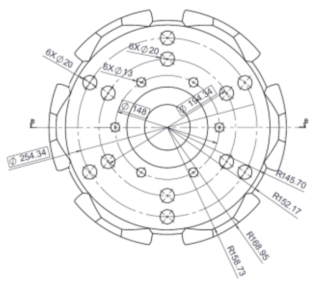

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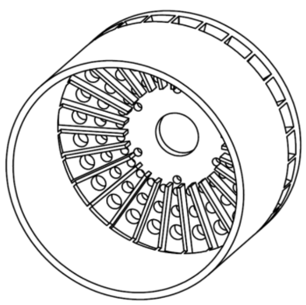
Fig. 5. Claw pole of eddy brake, a, b, c: right vision, d:front vision



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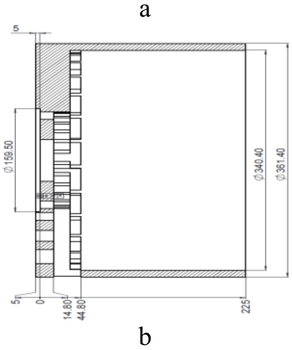

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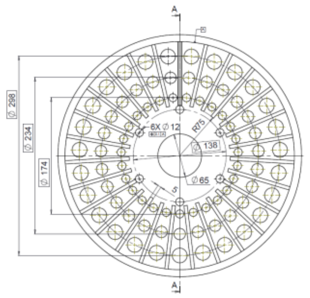

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Fig. 6.Cylinder of Eddy Brake, a: front vision, b: right vision, c: rear vision

pole pairs. In this state, as the cylinder is rotated by DC CRM, eddy current is induced within. Therefore mutual interaction of the eddy current and the magnetic field generates retarding torque. Finally the disagreement between the retarding torque and the main torque (motor torque) causes heat loss in the cylinder. In this paper the eddy current brake is coupled to the motor. As mentioned in section 2.1, the CRM rotates in two directions simultaneously; so two eddy brakes are employed as load in this system. Each brake is connected to either shaft of CRM.

2.3 Current Source

In this system, two current sources are used. The role of the current sources is generating the magnetic field in excitation coils. The nominal current of each is 30A. As the current source is connected to excitation coils, the magnetic field is generated in the core.

3. Experimental Results

Eddy current loss in a conductive material occurs when it is subjected to a time varying magnetic flux. In fact, the disagreement of the retarding torque and main torque (motor torque) leads to heat loss in the cylinder.

As the eddy current causes heat, this type of loss is called eddy current loss. Exact prediction of the eddy current loss is difficult in electrical machines. On the other hand, the value of the eddy current loss is an important issue both in the designing and analysis of eddy current brakes. In this section approximate values of eddy current loss in eddy brakes at different speeds and for specified excitation currents are calculated. The experimental system is shown in Fig.7. The counter rotating motor is coupled to both eddy brakes. One of them is coupled to the inner and the other to the outer shaft of the motor. Also, both eddy current brakes are connected to the current sources. The nominal current of these sources is 30A. Since the two rotors of the CRM rotate in two opposite directions at the same time, the two eddy brakes do likewise. Hence, testing of the motor is divided to two states; in each, one of the brakes is blocked.

3.1 Blocked Eddy Current No.2

In this state the second eddy brake is blocked. The motor is tested in a no load condition for which the excitation currents of the eddy brakes are set to zero. In this condition the no loading loss of the system which includes mechanical loss of the motor, eddy current loss of the motor and mechanical loss of the eddy brake are as follows:

$$P_{No-loading\,loss} = P_{Mechanichal\,loss\,of\,motor} + P_{Eddy\,current\,loss\,of\,motor} + P_{Mechanichal\,loss\,of\,eddy\,brake} = V_m.I_m - R_m.I_m^2 = A \quad (1)$$

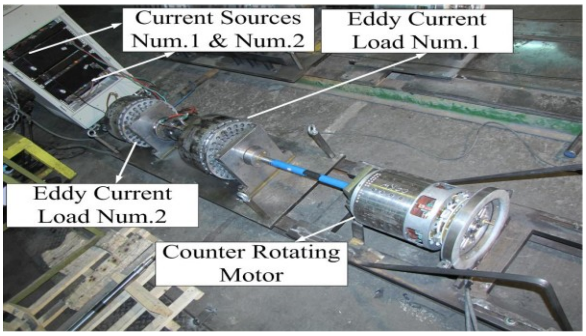

Fig.7. The experimental system

Table 3. Test results of counter rotating motor in no loading condition, and also second eddy brake is blocked

Vm(v)	Im(A)	Nr(RPM)	Ns(RPM)	Current Source No.1(A)	Current Source No.2(A)	No Loading Loss of system(KW)
10	67	269	0	0	0	.4379
15	67	500	0	0	0	.7729
20	67	715	0	0	0	1.107
25	68	865	0	0	0	1.460
30	70	1029	0	0	0	1.8467
35	71	1202	0	0	0	2.224
40	72	1351	0	0	0	2.6120
45	74	1536	0	0	0	3.046
50	79	1648	0	0	0	3.627

Where V_m is motor voltage; I_m is motor current and R_m is motor resistance. The results of experimental test of the system for different values of voltage and speed are tabulated in Table 3. According to these results and by interpolation method, the curve of no loading loss of the system is shown as a function of the motor speed in Fig.8.In the next step, while the second eddy brake is blocked, the excitation current of the eddy current brake no.1 is set to a non-zero value. In this condition, the loading loss of the system includes the mechanical loss of the motor, eddy current loss of the motor, mechanical loss of the eddy brake and eddy current loss of the eddy brake is as follows:

$$P_{loading\,loss} = P_{Mechanichal\,loss\,of\,motor} + P_{Eddy\,current\,loss\,of\,motor} + P_{Mechanichal\,loss\,of\,eddy\,brake} + P_{eddy\,current\,loss\,of\,eddy\,brake} = A + B \quad (2)$$

Considering (1), the loading loss in this condition is:

$$P_{loading\,loss} = V_m^{'}.I_m^{'} - R_m.I_m^{'2} = A + B \quad (3)$$

For example, the experimental test results of the motor for different values of voltage and speed by setting the first current source to 15A are tabulated in Table 4.

For specified values of the current source, performing the same test and calculating the loading loss in each step is done and the curve of loading loss of the system as a function of motor speed is shown in Fig.9.

Assuming that the sum of mechanical loss of the motor, mechanical loss of the eddy brake and the eddy current loss of the motor is equal in loading and no loading tests in same speed conditions, the eddy current loss of eddy brake is the result of subtracting equations (1) and (3). According to this and by interpolation method, the eddy current loss

of the eddy brake as a function of motor speed (cylinder speed) for specified values of excitation current is shown in Fig.10.

For each excitation current, the value of flux in air gap of the eddy brake can be determined. Measuring this flux will be explained in part II of this paper. Finally the eddy current loss of the eddy brake is shown as a 2dimensional function of the excitation current and speed in Fig .11.

Table 4. Test results of counter rotating motor in loading condition, second eddy current brake is blocked.

Vm(V)	Im(A)	Nr(RPM)	Ns(RPM)	Current Source No.1 (A)	Current Source No.2 (A)	Loading Loss of system (KW)	Eddy Current Loss of eddy brake (KW)
10	97	178	0	15	0	.4835	0.0456
15	111	291	0	15	0	1.028	0.2551
20	125	387	0	15	0	1.6922	0.5852
25	136	483	0	15	0	2.4438	0.9838
30	145	572	0	15	0	3.2630	1.4163
35	153	675	0	15	0	4.1448	1.9208
40	159	765	0	15	0	5.0530	2.441
45	162	861	0	15	0	5.9332	2.8872
50	162	972	0	15	0	6.7432	3.1162

Table 5. Test results of counter rotating motor in no loading condition; First eddy current brake is blocked.

Vm(V)	Im(A)	Nr(RPM)	Ns(RPM)	Current Source No.1(A)	Current Source No.2(A)	No Loading Loss of system (KW)
10	67	0	256	0	0	.4591
15	67	0	457	0	0	.8484
20	67	0	609	0	0	1.233
25	68	0	796	0	0	1.618
30	70	0	976	0	0	1.959
35	71	0	1181	0	0	2.224
40	72	0	1423	0	0	2.546
45	74	0	1658	0	0	2.782
50	79	0	1854	0	0	3.117

Table 6. Test results of counter rotating motor in loading condition, first eddy current brake is blocked.

Vm(V)	Im(A)	Nr(RPM)	Ns(RPM)	Current Source No.1 (A)	Current Source No.2 (A)	Loading Loss of system (KW)	Eddy Current Loss of eddy brake (KW)
10	100	0	157	0	15	.483	.0239
15	117	0	268	0	15	1.0473	.1989
20	128	0	356	0	15	1.7129	.4799
25	139	0	457	0	15	2.4761	.8581
30	144	0	548	0	15	3.247	1.288
35	148	0	653	0	15	4.0476	1.8236
40	149	0	751	0	15	4.8122	2.2662
45	154	0	865	0	15	5.7039	2.9219
50	157	0	956	0	15	6.5756	3.4586

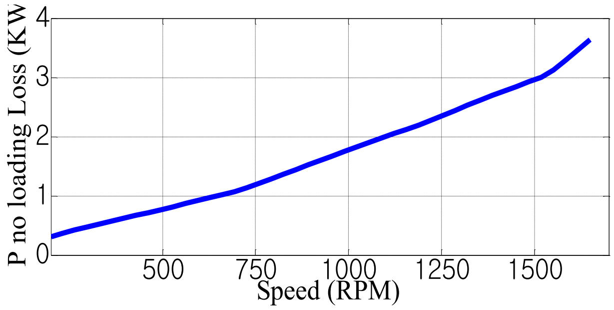

Fig.8. No loading loss of system which includes mechanical loss of motor, eddy current loss of motor and mechanical loss of eddy brake in state 1.

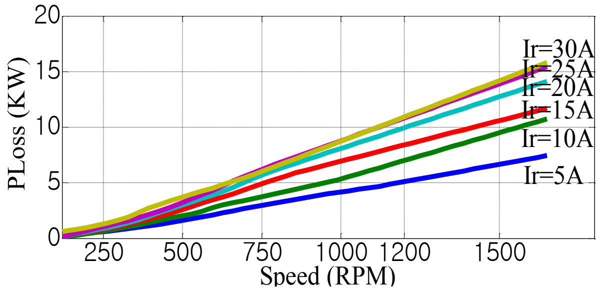

Fig.9. The loading loss of system includes the mechanical loss of motor, mechanical loss of brake and eddy current loss of motor and eddy current loss of brake in state 1 (Ir is the value of first current source).

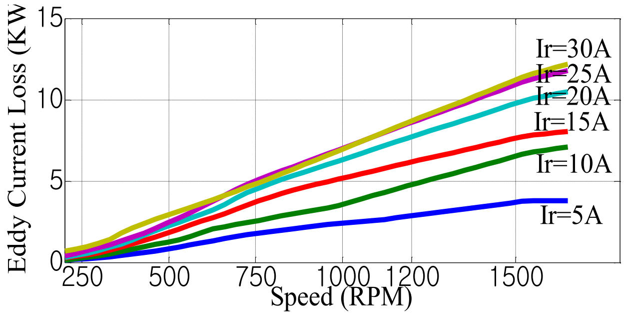

Fig. 10. Eddy current losses of the eddy brake in state 1. (Ir is the value of first current source).

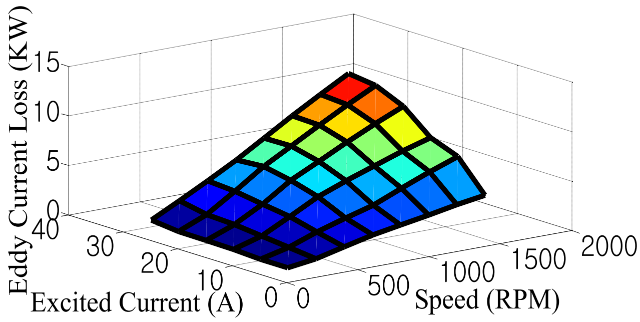

Fig.11. Eddy Current Losses of eddy brake as a function of speed and excited current in state 1.

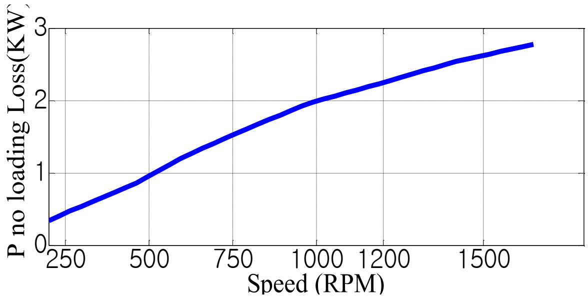

Fig.12. No loading loss of system which includes mechanical loss of motor, eddy current loss of motor and mechanical loss of eddy brake in state 2.

3.2 Blocked Eddy Current No.1

In this state the first eddy brake is blocked and the stages mentioned in section 3.1 were repeated. Regarding this point, the results of testing the motor in this condition are presented in Table 5 and 6. Also the plots of a no loading loss curve of the system, the loading loss curve of the system and the eddy current loss of the eddy brake as functions of motor speed (cylinder speed) are shown in Fig.12, 13 and 14 respectively. Furthermore, the eddy current losses as a 2dimensional function of the excitation current and speed are shown in Fig.15.

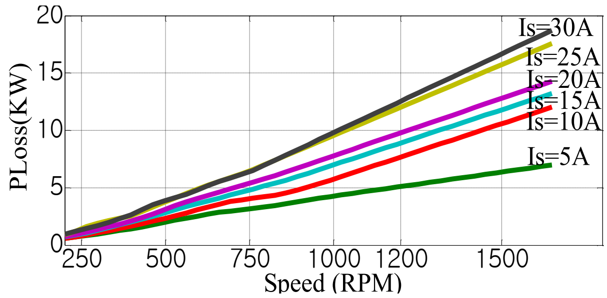

Fig.13. The loading loss of system includes the mechanical loss of motor, mechanical loss of brake, eddy current loss of motor and eddy current loss of brake in state 2 (Is is the value of second current source).

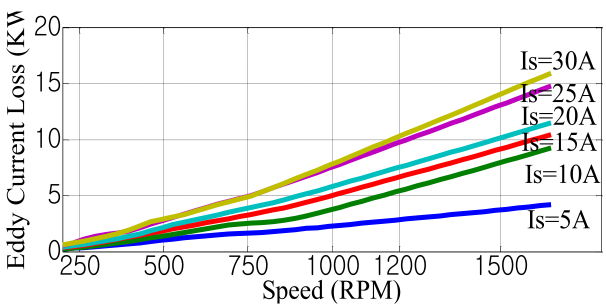

Fig.14. Eddy current losses of the eddy brake in state 2. (Is is the value of second current source)

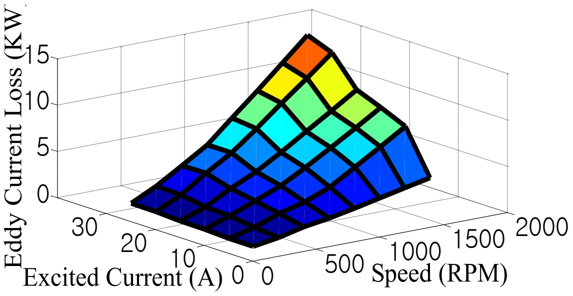

Fig.15. Eddy Current Losses of eddy brake as a function of speed and excited current in state 2.

4. Conclusion

Counter rotating motors are used in ship applications. Since providing variable loads for testing counter rotating motors is difficult, this paper deals with the construction of novel claw pole eddy current brakes. The main property of the prototype eddy brake is the claw pole structure of it. This kind of structure creates multiple pole pairs. The behavior of two novel eddy current brakes is well described by their characteristics curves, demonstrating the eddy current power loss curves as functions of the rotational speed and excitation current. This approach for load testing has the advantage of simplicity in structure. In part II of this paper we will propose the modeling of eddy current brake losses as a function of excitation current and rotational speed which is useful for designing the claw pole eddy current brake.

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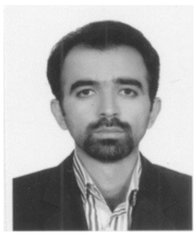

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