Study on Eddy Current Braking System considering Skin Effect

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Abstract

Braking system plays a vital role in mechanical industry. Nowadays, research is in progress for development of more efficient braking systems. One of them is Eddy Current Braking System (ECBS). Principle of operation of ECBS is based on Lorentz's Force which is produced due to secondary magnetic field of induced eddy currents.
In the past, most of the mathematical models of ECBS have considered uniform distribution of induced currents and ignored the Skin Effect. Recent research shows that considering the Skin Effect, significant deviation in braking torque is obtained and hence it cannot be neglected. In this paper, we have reviewed the ECBS considering the skin effect and the parameters affecting its performance.

Keywords: *Eddy current, skin effect, skin depth, magnetic flux, braking torque.*

1. Introduction

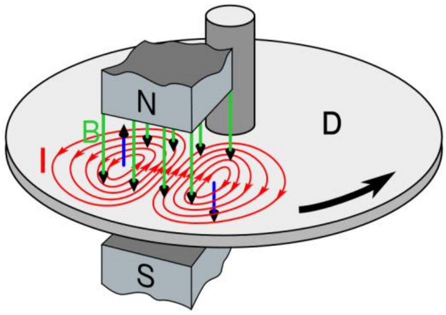
Due to rapid developments in transportation industry, eddy current brakes (ECB) are getting widely used in various areas including commercial trucks, industrial elevators, and test benches and so on. Compared to conventional braking, ECB have faster response time, longer life time and maintenance- free structures. They are composed of stationary and moving parts similar to electric machines and the principle of operation is based on the inducing eddy currents in conductive moving parts.
Usually, eddy currents (EC) are undesirable component in electromagnetic systems such as electric motors, generators, solenoids, actuators and so on. However, the aim of ECB is to obtain as much eddy current as possible in the conducting moving parts so that more braking torque can be attained.
Electromagnetic brakes are also called electro-mechanical brakes because they operate electrically, but transmit torque mechanically. These brakes have been there for over sixty years, so they have been used for a variety of applications. Its design has changed over these years, but the basic operation remains the same. Single face ECBs make up approximately 80% of all of the power applied brake applications. ECBs are being used as supplementary brakes in addition to friction brakes for heavy duty applications.
These brakes do not undergo wear, overheating, have fast and simple actuation, and has a reduced sensitivity to wheel lock. This is because these brakes do not need to make contact with the rotor; the kinetic energy is dissipated in the form of heat by the generation of induced eddy currents. ECBs are used in machinery like automobiles, locomotives, roller coasters, hydraulic and turbo machinery, machine tools, elevators, etc. The wide range applicability of these brakes strongly implies the effectiveness and ease of operation. The braking torque can be controlled by varying the coil turns or by increasing the voltage. This gives flexibility of operation of the system and makes it reliable even in changing loading patterns. A study of eddy current braking system is performed to find out the practical limit of using an electromagnetic braking system.
In this paper, with a view to enhance the braking system in automobile, we have analyzed the research carried out and explored different mathematical models of ECBS. It aims to minimize the brake failure to avoid the road accidents. It also reduces the maintenance of braking system. An advantage of this system is that it can be used on any vehicle with minor modifications to the transmission and electrical systems.

2. Working of ECBS

As per the Faraday's law, changing magnetic field across a conductor induces loops of electrical current in it. These circular currents are called Eddy currents and are generated in a plane perpendicular to the magnetic field direction. This changing magnetic field can be induced by either placing the conductor in a time varying magnetic field or by providing relative motion between magnet and the conductor. Eddy current magnitude is proportional to magnetic strength and inversely proportional to the resistivity of the material. These induced currents produce a magnetic field in an opposite sense to that of the applied magnetic field as per the Lenz's law.

Fig.1 Direction of induced eddy current

This concept includes a metal disk which will conduct eddy currents generated by magnets.Braking effect takes place due to formation of retarding torque generated by the induced magnetic field produced by the eddy currents.



3. Skin Effect

A time-invariant current in a homogeneous conductor is distributed uniformly over the conductor cross-section. Whereas a time-varying current has tendency to concentrate near the surface of conductor. If the frequency is very high, the current is restricted to a very thin layer near the conductor surfaces, practically on the surfaces themselves. Thus this phenomenon of non-uniform current distribution throughout the conductordue to time-varying magnetic field is known as the skin effect.

The cause of the skin effect is electromagnetic induction. A time-varying magnetic field is accompanied by a time-varying induced electric field, which in turn creates secondary time-varying currents and a secondary magnetic field. We know from Lenz's law that the induced currents produce the magnetic flux which is opposite to the external flux, so that the total flux is reduced. Larger the permeability and conductivity, larger the induced currents and flux reduction.

"Skin effect" is mostly used in applications involving transmission of electric currents, but the skin depth also describes the exponential decay of the magnetic flux inside a bulk material when a plane wave impinges on it at normal incidence. This happens due to the opposed magnetic field created by the induced currents with respect to the external field applied.

The skin effect exists in all conductors, but the effect is more pronounced for a ferromagnetic conductor than for a non-ferromagnetic conductor of the same conductivity. So, skin effect has a considerable practical importance in case of ECBS.

4. Skin Depth

The distance in which the current density decreases to $(1/e)$ of its surface value is called the Skin depth of the penetration given by the relation:

$$\delta = \sqrt{\frac{2\rho}{\mu\omega}} \qquad \ldots(1)$$

Where ρ is the resistivity of the conductor in ohm-meter, μ is the absolute permeability of conductor and ω is the angular velocity.

As mentioned above, the spread of current through the conductor will be non-uniform and according to the definition of skin depth is given as:

$$J = J_o e^{-t/\delta} \qquad \ldots(2)$$

Where J is the volume current density and $J_0$is the volume current density at the surface of the rotor.

5. Analysis of ECBS

When rotor of an eddy current brake rotates in the magnetic field of stator, an electrical field $E=v\times B$ is induced perpendicular to both the speed of movement v and the magnetic field B. This electrical field causes electrons to move and produce induced currents in rotor. At very low speed (relative to critical speed) the magnetic induction field due to the induced current in rotor, is negligible compared with stator main field B_0. Then it may be assumed that the resultant field also is B_0 and its direction is perpendicular to the surface of the rotor. The eddy current had been explained by many analytical methods. One of them calculated the amount of eddy current and braking torque by assuming that all the power dissipated by the eddy current is used for generating the braking torque.The other obtained the braking force by applying the Lorentz force law while using an imaginary current path lumped on the disc and resistance obtained by experiment.Almost all of the eddy current loss in eddy current brakes is used as braking force. Therefore, the braking performance can be predicted by calculating the eddy current loss occurring in the drum and coating.

The eddy current loss is given as:

$$P_e = \int \frac{J^2}{\sigma} dV \qquad \ldots(3)$$

Where P_e represents the power absorbed by the ECBS, J is the induced current density in the rotor and σ is the conductivity of the conductor (rotor) which is reciprocal of its resistivity.

The power absorbed by the brakes is integrated over its entire volume hence the equation is written in volume differential.

General case of ECBS is studied in this paper and the orientation is taken such that the applied magnetic field is along the thickness of rotor which is perpendicular to its surface. The mathematical model of ECBS is obtained using following vector decomposition:

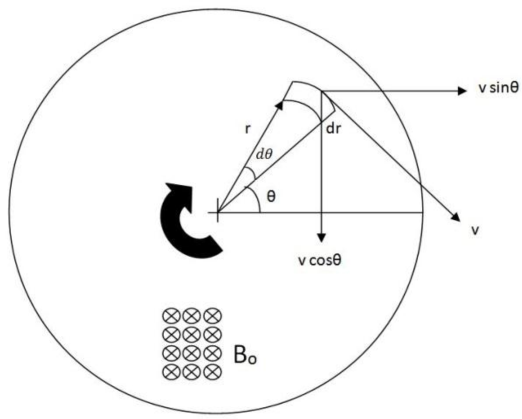


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Fig.2 Decomposition of velocity vector on rotor's surface(i.e. x-y plane)with a differential element.

An element is considered on the surface of the rotor at a radial distance r having thickness dr subtending angle $d\theta$ at the Centre. Applied field is into the plane of paper. Now the induced current density Jin the rotor disc is given as:

$$J = \frac{\vec{v}\times\vec{B}}{\rho} \qquad \ldots(4)$$

Where $\vec{v}$represents the velocity vector of assumed differential element and $\vec{B}$ is the magnetic field.
Based on above equations the braking torque is been compared for its value with skin effect and without skin effect .As the disc is placed such that applied magnetic field is into the plane of disc, the current density will vary from J_o (on its surface) to 1/e times its value on the surface along the thickness. This depth is termed as skin depth as discussed above.
Braking torque (T) is calculated using relation between power and torque given as:

$$T = \frac{P_e}{2\pi N} \qquad \ldots(5)$$

Where N is rotational speed of the rotor and P_e is the power absorbed by the rotor. Based on these above equations the losses due to skin effect are studied and its variation depending on different parameters is plotted graphically.
Based on the proposed model of Sharif the braking torque is proportional to the function given below:

$$H(R,\delta) = R^3\left(\frac{\delta}{2}\right) - 3R^2\left(\frac{\delta}{2}\right)^2 + 6R\left(\frac{\delta}{2}\right)^3 - 6\left(\frac{\delta}{2}\right)^4 + 6e^{\frac{2R}{\delta}}\left(\frac{\delta}{2}\right)^4 \qquad \ldots(6)$$

Where R is the radius of the rotor and δ is the skin depth or nominal depth of the conductor.

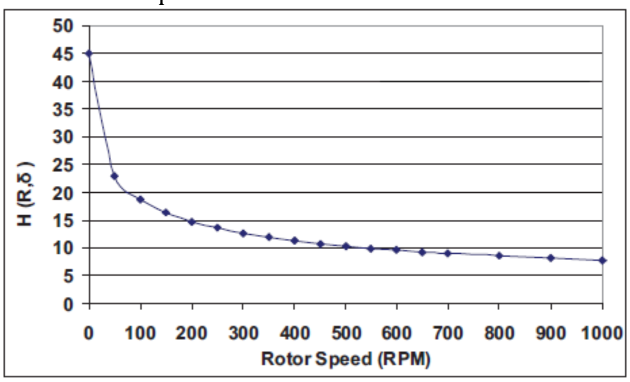

Fig.3 Torque vs rotor speed (rpm)

It shows that the skin effect is quite effective in reduction of braking torque and can't be ignored. Hence this curve predicts even in very low rotation speeds; skin effect exerts its effect noticeably, and reduces the power of brake to one half of its ideal status even at very low speed of 50 rpm.

6. Methodology

Modelling of designed experimental setup is done in Solidworks. This is the general model of ECBS considered for the study. The power transmission is carried out using belt and pulley so as to sustain the load of shaft and rotor.The whole setup is mounted on the base frame.Experiments are carried out for plotting the characteristic curve between braking torque and speed of rotor.Deducing the analytical part obtained from the mathematical model of ECBS without considering skin effect and the practical results obtained from the experiments we can get the accurate loss due to skin effect in braking torque.Alongside the dependency of design parameters on the braking torque is studied and efforts are been taken in order to minimize the losses and obtain the maximum braking torque to obtain an optimized electromagnetic braking system.

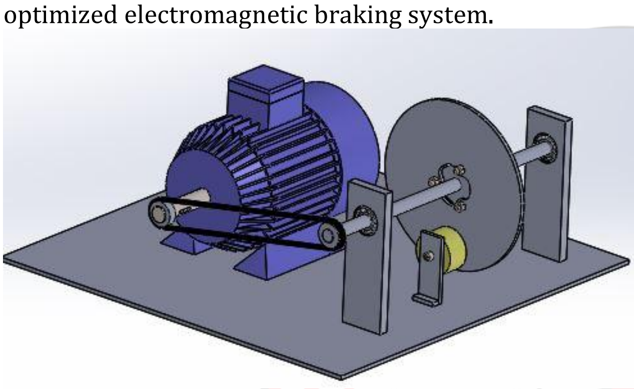

Fig.4 CAD model of ECBS

7. Design Parameters

7.1 Magnetic Source
Magnetic source for the purpose of inducing flux through the rotor can either be selected as electromagnets or permanent magnets for that purpose. But electromagnets are used as a source for eddy currents as they provide ease of power supply. Electromagnets are DC type that can be powered by battery or SMPS. Electromagnets are selected instead of permanent magnet as electrical actuation is faster than mechanical actuation with lower losses.

7.2 Orientation
Sharif has done analysis considering the cylindrical ECBS. The field is applied across the diameter. The setup has been shown below.

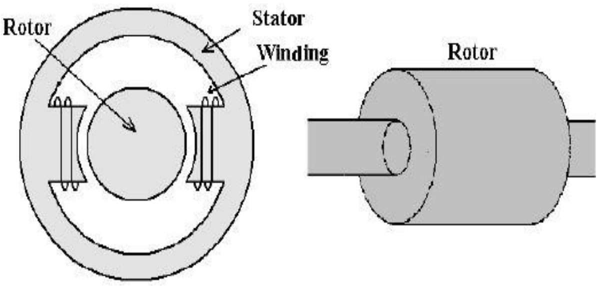

Fig.5 Referred model of ECBS and its orientation

But if the ECBS is to be used in the automotive, the space requirement becomes high. So, mostly a thin rotor is used with the magnetic flux applied perpendicular to the plane of rotation of the rotor. This orientation is ideal as it has less space requirement as well as gives higher braking torque.

7.3 Material selection
The electrical and mechanical properties of the brake disc are the key parameters in the design of an ECB. Maximum torque is obtained at low electrical resistivity and low permeability. Experiments done by G. Priyandoko shows that Aluminium 6061 is the best material to be used as a rotating element in the eddy current braking.

Table 1 Material properties

Copper		Alumin-ium	Electrical Steel
Relative permeability	1	1	5000-8000
Thermal resistivity	16.8×10^{-9}	26.5×10^{-9}	500×10^{-9}
Machinability	Easy	Easy	Hard
Cost	Cheap	Cheap	Expensive

7.4 Air Gap

The Braking Torque obtained in the equation shows that the air gap between the electromagnet and rotor has influence on the braking effect. The experiment done by Priyandoko shows that the smaller the air gap, the higher the braking torque.

7.5 Power Transmission
Power can be transmitted to the rotor shaft by using Belt and pulley arrangement, using gears, chain and sprocket, or even directly coupling the motor to the shaft. As this application demands high speed, belt and pulley is more suitable to use so as to sustain the dynamic loading. Alongside, it is also simple in design and comparatively economical.

8. Discussion

8.1 Torque-Speed characteristics

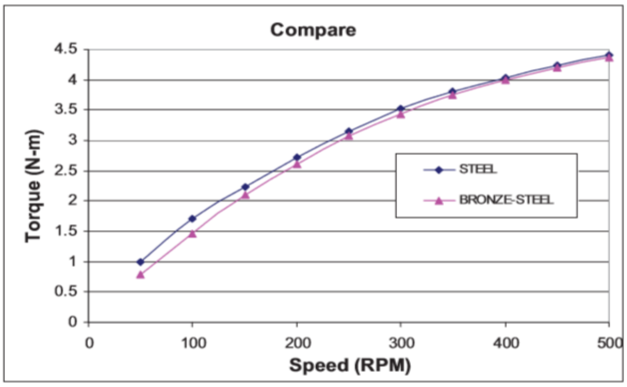

Fig.6 Comparison between Torque–speed curves of pure steel rotor and with bronze core and steel shell

It is observed that at low speed, the torque due to pure steel rotor is slightly greater; so, at higher speed rotation, the torque due to both of rotors become nearly equal. Due to high absolute permeability (μ) in iron, skin effect has exerted its effect even at speeds much lower than 50 RPM.

8.2 Torque-Current characteristics

The following graphs show how braking torque varies with air gap for Al6061.

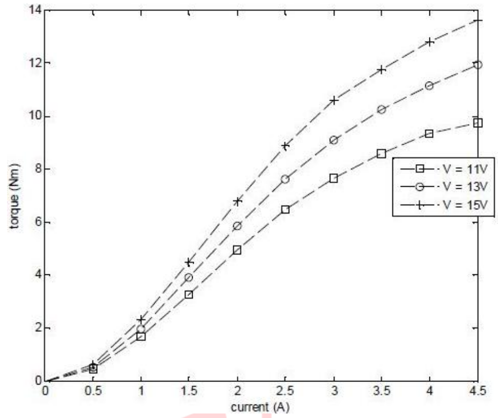

Fig.7(a) Braking Torque vs. current with 1mm air gap

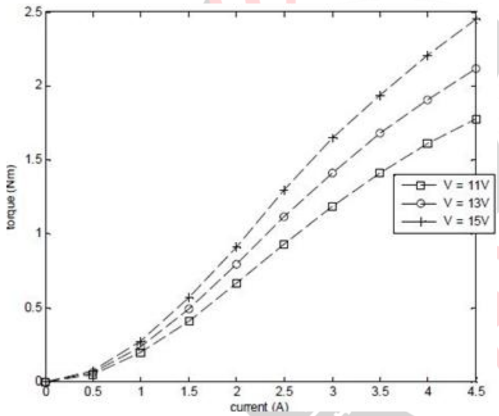

Fig.7(b) Braking Torque vs. current with 3mm air gap

From the fig. 7(a) and 7(b), the inverse relation between air gap and braking torque is observed. Also higher voltage results in higher braking effect.

9. Conclusions

The torque-speed characteristics indicate the skin effect has a significant effect over the performance of the eddy current brakes and it is not negligible. Skin effect due to high absolute permeability (μ), exerts its effect at very low speed by depleting rotor core from induced currents and reduce effective area and volume of rotor, the brake torque is reduced indisputably.

1) In reference to the table1, we can conclude the best material for ECBS is Al6061. However, more

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pronounced skin effect is observed in ferromagnetic materials.

2) ECBS gives better performance when the air-gap is small and higher braking torque is obtained.
3) As higher torque is obtained only at higher speeds, the ECBS are used only in high speed applications.
4) To avoid overheating of the rotor, holes can be made in it, which also reduces the overall weight of the brakes.

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