MODELING OF EDDY CURRENT BRAKING FOR ENERGY ABSORBING SYSTEM OF AIRCRAFT ARRESTER BARRIER SYSTEM


Abstract

Aircraft Arrester Barrier Systems (AABS) are installed near the end of runways for the purpose of arresting combat aircraft due to over shooting of runway length during aborted take-off and emergency landings. Energy Absorbing System (EAS) is one of the important subsystems of AABS. The energy absorber consists of two velocity sensitive turbine type conventional rotary hydraulic energy absorbers. There is no control in conventional EAS on energy absorption during operation of an aircraft emergency arrestment. Also, if there is any problem with conventional EAS during operation complete system fails. For different types of aircrafts different EAS needed. To overcome this problem, we may use the combination of existing conventional EAS and eddy current absorbing system. An Eddy current energy absorbing system works on the principle of Eddy currents. In proposed EAS, braking torque is high and controllable. This will help in stopping any Aircraft (like light weight, heavy weight, etc). In this paper, the proposed eddy current EAS have designed and prototype has been implemented.

Keywords: Aircraft arrester barrier system, Eddy current braking, Hydraulic energy absorber, Model development

Symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
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<tbody>
<tr>
<td>e</td>
<td>electro-motive force</td>
</tr>
<tr>
<td>Φ</td>
<td>induced flux</td>
</tr>
<tr>
<td>P</td>
<td>no. of poles</td>
</tr>
<tr>
<td>Z</td>
<td>no. of armature conductors</td>
</tr>
<tr>
<td>Ka</td>
<td>armature coefficient</td>
</tr>
<tr>
<td>I_f</td>
<td>field current</td>
</tr>
<tr>
<td>R_f</td>
<td>field resistance</td>
</tr>
<tr>
<td>Q</td>
<td>conductor charge</td>
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<tr>
<td>B</td>
<td>magnetic field vector</td>
</tr>
<tr>
<td>dx</td>
<td>differential width</td>
</tr>
<tr>
<td>F</td>
<td>Lorentz force</td>
</tr>
<tr>
<td>σ</td>
<td>conductivity of the metal</td>
</tr>
<tr>
<td>c</td>
<td>thickness of the metal plate</td>
</tr>
<tr>
<td>E_k</td>
<td>kinetic energy stored in aircraft</td>
</tr>
<tr>
<td>N</td>
<td>speed in rpm</td>
</tr>
<tr>
<td>n</td>
<td>no. of turns</td>
</tr>
<tr>
<td>A</td>
<td>no. of parallel path</td>
</tr>
<tr>
<td>T</td>
<td>torque developed in the disc</td>
</tr>
<tr>
<td>I_a</td>
<td>armature current</td>
</tr>
<tr>
<td>V</td>
<td>voltage applied</td>
</tr>
<tr>
<td>F</td>
<td>magnetic field</td>
</tr>
<tr>
<td>v</td>
<td>velocity</td>
</tr>
<tr>
<td>dA</td>
<td>differential area</td>
</tr>
<tr>
<td>L</td>
<td>vertical height of the effective magnetic field</td>
</tr>
<tr>
<td>I</td>
<td>current</td>
</tr>
<tr>
<td>L_B</td>
<td>effective length over which the currents will form</td>
</tr>
<tr>
<td>M</td>
<td>mass of aircraft</td>
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Introduction

The aircraft arrester barrier installed at the end of the run ways for the purpose of arresting combat aircrafts during aborted take-off and emergency landings. Two stanchion systems one at each end of the net are required in a system to support and to provide electrically controlled movement to the net. During deployment of the net certain forces are generated and imposed on the sub-system of the Aircraft arrester barrier system. Arrestment of an emergency landing or aborted take off of Aircraft is accomplished by engagement of the Aircraft with multiple element net assembly stretched across the runway which is lifted by two stanchion systems. There are two Energy

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absorbing systems, installed at both ends of AABS. The conventional energy absorber used in the AABS is a hydraulic energy absorber as shown in Fig.1. The existing hydraulic energy absorbing system has the following drawbacks [7, 10, 14, 21]:

- There is no control on braking torque of Existing EAS.
- The Existing EAS is highly nonlinear in nature. The initial braking torque is very high but once it starts rotating, torque reduces to a significant low value.
- For different types of aircrafts (weights) needs different EAS (i.e. different drum diameters).
- Braking torque depends upon the type of fluid in existing EAS.
- All the energy is wasted in the form of heat.

To overcome the above mentioned drawbacks of existing EAS and provide back up to it, an Eddy current EAS is proposed which works on the principle of Eddy current Brakes as shown in Fig.3. The eddy current EAS can be used in parallel or series combination of existing hydraulic energy absorber. An Eddy Current Brake (ECB) generates braking torque from the interaction between an eddy current and a magnetic flux. However, an ECB cannot generate sufficient torque at lower speeds. Also, the system heat up as it operates, causing its performance to deteriorate.

**Principle of Eddy Current Brakes**

Eddy current is a swirling current set up in a conducting medium in response to a changing magnetic field. By Lenz’s law, the current swirls in such a way as to create a magnetic field opposing the change; to do this in a conductor, electrons swirl in a plane perpendicular to the magnetic field, because of the tendency of eddy currents to oppose the cause by which it is produced and the energy is to be lost in the form of heat. More accurately, eddy currents transform kinetic energy into heat. The eddy current braking can be used in automobiles, railways, aircrafts, heavy vehicles and high speed machines [3, 11].

In the literature numerous studies have been appeared at national and international levels regarding various types of braking systems employed for various purposes. Eddy Current brakes have many advantages such as compactness in size and very effective at high speeds, no wear and tear, no noise etc. On the other hand friction braking suffers from severe limitations like loss of braking force with increasing temperature (fading phenomenon), warping of disc, wearing and tearing of pads and rotor, slow response time due to power assistance (especially in trucks, buses and trains), difficulty in controlling each wheels breaking independently, necessity of complex and costly anti-lock controls, risk of hydraulic fluid leak, risk of fluid contamination by water and subsequent loss of braking power etc [15, 18]. The concept of integrated contactless magnetic brake i.e. eddy current based magnetic brake was appeared in the research and development scenario as a remedial step to these problems. Since then many concept in designing the braking system with eddy current phenomenon have been presented in the literature [19, 20]. Various control aspects of aircraft controlling system are illustrated in [4]. The eddy current braking system has been designed for railway traction applications [12, 13, 17, 21]. All these papers cited above consider the various aspects of braking systems based on friction, hydraulic and eddy current braking and their applications mainly to railway traction system and automobiles. The important works on eddy current braking system are also available in [2, 5, 8, 9]. In this paper, an integrated approach has been for absorbing the kinetic energy of aircraft during emergency condition. It is a combination of eddy current energy absorbing system and existing hydraulic EAS. Eddy current system is designed and developed a prototype in the laboratory to show the eddy current braking system for AABS.

**Introduction to Aircraft Arrester Barrier System**

The aircraft arrester barrier system is shown in Fig.1, it consists of the following sub-systems:

- Stanchion system
- Energy absorbing system
- Engagement system
- Tape retrieval system
- Pressure roller system
- Suspension system
- Sheave assembly
- Drive tape
- Shear-off coupling
- Tape connector
- Net anchoring mechanism
- Electrical control
These subsystems perform various functions during the operation of aircraft arrester barrier system, when the aircraft is arrested in the net assembly. As the aircraft arrested in the net of AABS, then operation of EAS which are installed at both ends of the run-way and hence the braking torque is applied through net tape so that the aircraft stops it within the prescribed length of the run-way.

Energy Absorbing Systems (EAS)

Existing Energy Absorbing System

The energy absorber consists of two velocity sensitive turbine type rotary hydraulic energy absorber. Each energy absorber consists of a tape drum assembly and a vane drum assembly both splined to a vertical common shaft. They are assembled in vane fluid filled housing. The energy absorbing brake has no control system and is capable of completely automatic during an aircraft emergency arrestment. It has housing and a rotor, both consists of blades, as shown in Fig. 2. Rotor rotates in fluid and due to fluid friction brakes applied on it. The braking torque is the function of fluid viscosity, size of drum and vanes, speed of rotor etc.

Eddy Current Based Energy Absorbing System

The hydraulic energy absorber can slow down and stop the aircraft which comes in particular weight category but beyond that limit these energy absorbers are not capable to stop it. To overcome this problem, we may use the combination of existing hydraulic EAS and eddy current EAS by which, any Aircraft of any weight can be stopped effectively.

The working principle of the electric eddy current EAS is based on the creation of eddy currents within a metal disc rotating between two electromagnets, which sets up a force opposing the rotation of the disc. If the electromagnet is not energized, the rotation of the disc is free and accelerates uniformly under the action of the weight to which its shaft is connected. When the electromagnet is energized, the rotation of the disc is retarded and the energy absorbed appears as heating of the disc. If the current exciting the electromagnet is varied by a rheostat, the braking torque varies in direct proportion to the value of the current. It was the Frenchman Raoul Sarazin who made the first vehicle application of eddy current brakes [9].

Mathematical Modelling of Eddy Current EAS

For a prototype model of the system under consideration, the expression for induced EMF (E) is given as

\[ e = \frac{(Z \times N \times \Phi \times P)}{A} \text{Volts} \quad (1) \]

The torque (T) developed in the disc will be

\[ T = K_a \cdot \Phi \cdot I_a (N - m) \quad (2) \]

Flux produced is proportional to field current and the expression for field current can be given as

\[ I_f = \frac{V}{R_f} \quad (3) \]

Hence the expression for the torque may be given as

\[ T = K_a \cdot V \cdot I_a/R_f \quad (4) \]

The parameters and constants used in Equations (1-4) have their usual meanings. For eddy current modelling, when any metal plate enters into the magnetic field, it experiences a Lorentz force

\[ F = q (v \times B) \quad (5) \]

According to Faraday’s law,

\[ e = -n \frac{d}{dt} \phi (t) \quad (6) \]
To equate this electromotive force to the velocity of the plate, this involves converting the differential area to a known height times a differential width (dA = L dx), now Equation (6) will be

$$e = B L v$$  \hspace{1cm} (7)

Besides inducing the eddy currents in the metal plate, the magnet exerts a force on the currents inside its field. This is the retarding force associated with the braking.

$$F = I L * B = I L B$$  \hspace{1cm} (8)

where, I is the current and

L is the same vertical height of the effective magnetic field, the currents encounter inside the metal using the conductivity (σ) of the metal, the resistance

$$R = L_R / \sigma A = L_R / \sigma c x$$  \hspace{1cm} (9)

where L_R is the effective length over which the currents will form and c is the thickness of the metal plate. Ohm’s law lets us write a current in terms of the voltage and resistance associated with it. Using Equations (7) and (9), the magnitude of the eddy currents can be written as

$$I = e / R = (\sigma c x B L / L_R) . v$$  \hspace{1cm} (10)

This allows us to re-write the force Equation (8) in terms of an unknown (LR), measurable constants, and a varying parameter (velocity) :

$$F = (\sigma c x B^2 L^2 / L_R) . v$$  \hspace{1cm} (11)

The force developed by eddy current brakes mentioned in Equation (11) is directly proportional to the velocity of aircraft, v. The velocity of aircraft, v and its mass M decide the kinetic energy (E_K) stored in it as given in Equation (12).

$$E_K = M * v^2 / 2$$  \hspace{1cm} (12)

This kinetic energy is to be absorbed by the energy absorbing system of aircraft arrestor barrier system. Now the question arises that how much energy is absorbed by eddy current EAS and conventional hydraulic EAS? The effectiveness of eddy current EAS depends on the velocity of aircraft. At higher value of velocity, the braking torque of eddy current EAS is better. On the other hand, hydraulic EAS is good at lower velocities. Hence, the combination of both EAS is a better option. The power requirement for eddy current EAS depends upon the proportion of energy absorbed by it.

For example:

- mass of aircraft (M)= 10,000 Kg,
- velocity of aircraft v = 200 Km/h

Kinetic energy to be absorbed by the EAS can be calculated using Eqn. (12), E_K = 200 MJ

Aircraft run out distance = 270 m (max),

$$v = 200 \text{Kmph} \text{ (at time of engagement)}$$, hence, time (t) = 4.86 Sec

Hence the total electrical energy required to absorb this K.E. by EAS (if only eddy current EAS is there) = 270 kWh

Normally the kinetic energy of aircraft is in the range of mega joules, which is very high and the time for absorbing this energy is only a few seconds (which depends upon the distance travelled by the aircraft on the run way after engagement in aircraft arrester barrier system and its velocity at the time of engagement). Therefore, the power requirement is very high and single disc eddy current system cannot work. For this reason following options may be explored :

- Combination of hydraulic EAS and eddy current EAS
- Multi-disc eddy current EAS

The multi-disc eddy current system is more effective and practical solution as compared to single disc eddy current EAS. The number of discs and electro-magnets can be suitably decided in the design of eddy current EAS, to get sufficient controllable braking torque.

**Experimental Set up for Eddy Current EAS**

To investigate the feasibility of the proposed eddy current EAS, it is implemented experimentally (refer Fig.3) in the Control Lab of Electrical Engineering Dept. Jamia Millia Islamia University, New Delhi, India. The prototype model consisting of aluminium disc, single phase ac motor, two electromagnets, two rectifiers (25 A), a rpm meter and a sensor. The dimensions and motor
specifications used for the development of Lab model of EAS are given in Table-1.

**Results and Discussions**

The proposed eddy-current EAS is tested on the experimental set up in the Control lab of Electrical Engineering Dept. Jamia Millia Islamia University, New Delhi. The curves show that when voltage increases the eddy current increases, which in turn increases the torque. The torque developed is directly proportional to the eddy current. The plot between voltage and braking torque is shown in Fig.4 and Fig.5 for D.C. supply and for A.C. supply respectively. In D.C. supply, the speed of the disc mounted on a shaft of motor reduces 2700 rpm to 140 rpm but in case of A.C. supply the speed reduces 2700 rpm to 470 rpm in the same time. Hence, we can say that eddy current braking is more effective in D.C. supply and also its breaking time period is less in D.C. analysis than A.C. analysis.

The current speed characteristics are shown in Fig.6 and Fig.7 for D.C. and A.C. supply respectively. The

| Table-1 : Specification of Disc, Motor and Electromagnets for Experimental Set up |
|-----------------|-----------------|-------------------|
| Disc Diameter = 29cm | Motor Voltage = 230 V | Electromagnets Core Number = 4 |
| Thickness = 2.0mm - 3.0mm | Current = 0.3 A | Core Length = 3.5" and Width = 1.5" |

Fig.3 Experimental Set up for Eddy Current Braking

Fig.4 Voltage - Torque Characteristics for DC Analysis

Fig.5 Voltage - Torque Characteristics for ADC Analysis

Fig.6 Current Speed Curve for DC Analysis

Fig.7 Current Speed Curve for AC Analysis
speed voltage characteristics are shown in Fig. 8 and Fig. 9 for A.C. and D.C. supply respectively. In A.C. supply, three characteristics are shown for different positions of electromagnet i.e. speed is decreasing more by applying electromagnets on both side of the disc. Hence, speed is decreasing more at rated voltage by applying electromagnets on both sides because they cover more magnetic field area applying on disc. Fig. 10 shows the comparative voltage torque characteristics for A.C. and D.C. supply both together. These results show that eddy current braking is more effective in DC and better controlled.

Conclusions

The Energy Absorbing System (EAS) is a very important and critical part of aircraft arrester barrier system. If it fails, everything goes off. The existing energy absorbing systems have no control on the rate of energy absorption when the aircraft is engaged. Therefore, there is a need for development of energy absorbing system, which is capable of handling different weighted aircrafts. In this paper, a new EAS based on eddy current is proposed which provides a control over energy absorption rate. It is demonstrated that the results are in concurrence with the experimental observations. Furthermore, it is also inferred that the energy absorption is faster in eddy current absorbing system that in case of DC supply. Therefore, the combination of existing hydraulic EAS and eddy current based EAS will be more reliable and flexible. The braking system will offer high braking torque with smooth slow down to stop any weighted aircraft within prescribed runway length.

References


