HIGH FORCE DENSITY EDDY CURRENT DRIVEN ACTUATOR

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Abstract: Intense pulsed magnetic fields can be developed by closing a switch and discharging a bank of capacitors through a pancake coil. Eddy currents which flow in an adjacent conducting part constrain the magnetic fields to a thin gap resulting in intense magnetic pressure. New apparatus which employ this mechanism have recently been developed which display exceptional force density and fast rise time. A recoilless 7kg robotic high force actuator developed with a grant from the National Science Foundation can generate a 65 kN force pulse while returning just 600N recoil force to the robot arm. The resulting gap induction is in excess of 5 Tesla. The system impedance characteristics have been adjusted to take advantage of low voltage. A similar low voltage system has been proposed for the de-icing of aircraft. In this system the pancake coil is held adjacent to the wing leading edge. The discharge of capacitors through the coil raps the leading edge, dislodging accumulated ice. The proposed system is undergoing evaluation by the FAA and several aerospace companies.

Introduction

Eddy current driven actuators powered by capacitor discharge circuits have been used in metal forming for around twenty years [1-2]. NASA has investigated the use of eddy current repulsion for dislodging accumulated ice from engine inlets and the leading edges of aircraft wings. A conductor plate is placed slightly in front of a coil. A high current pulse is unleashed through the coil which generates an intense magnetic field. The conductor resists penetration of the magnetic field generated by the coil causing a buildup of magnetic pressure in the gap. Through this process high repulsive forces between the coil and the conductor are generated.

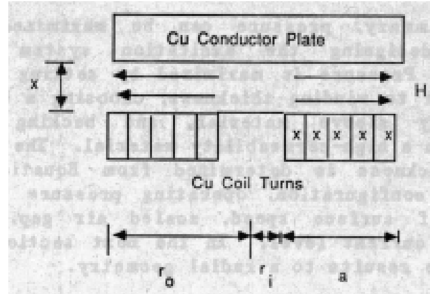
Previous systems that took advantage of this phenomenon required the use of extremely high voltage (~10 kV) to achieve the desired force magnitudes (up to 133 kN). The use of high voltage resulted in systems, which are dangerous to operate and prone to failure. These drawbacks have retarded the widespread implementation of this technology. Recent developments have demonstrated that the same high forces are achievable using discharge voltages of less than 500 V. This has led to a new class of compact "low voltage" actuators which are more reliable, less expensive and safer to operate than the previous high voltage models. These include generic robotic and handheld devices, as well as actuators used to dislodge accumulated ice from aircraft structures.

Electroimpact robotic end effectors have the capability of delivering up to 133 kN with a capacitor discharge voltage of under 500 V. As a result of the narrow force pulse, the reaction force which must be absorbed by the robot is two orders of magnitude less than the output force. Such characteristics give these actuators the potential to significantly broaden the functional range of robots. The handheld actuators for example can deliver over 50 kN of output force. This puts unprecedented power in the hands of the operator. Both these units can be powered by typical 110 VAC line voltage.

Prototype "low voltage" deicing modules have been constructed and are under evaluation by a number of aircraft companies. These modules are mounted directly behind the wing leading edge. The wing skin serves as the conductor. When the cod is pulsed, the skin is magnetically flexed and the ice is dislodged.

Theoretical Analysis

Integral to these actuators is a pancake coil which is held in close proximity to a conducting plate. The device is "fired" by triggering a thyristor switch which discharges a bank of capacitors through the coil. The resulting large current pulse generates a magnetic field which induces eddy currents in the adjacent plate. The magnetic field lines are confined to the gap by the conductor plate as shown in Figure 1. This is characterized by a repulsive force between the coil and the plate. The force is inherently transient since as the field permeates through the conductor the force disappears. The electrical discharge frequency of the system is tailored to the specified application by adjustment of the coil parameters. Ribbon thickness and width have been optimized to match the mechanical and electrical frequencies of the particular systems.



μ_o = permeability of space   x = gap thickness
N = number of turns   n = coil turn density = N/a

Figure 1 Cross Sectional View of Eddy Current Device

The capacitor discharge circuit which drives the system can be modeled as shown in Figure 2.

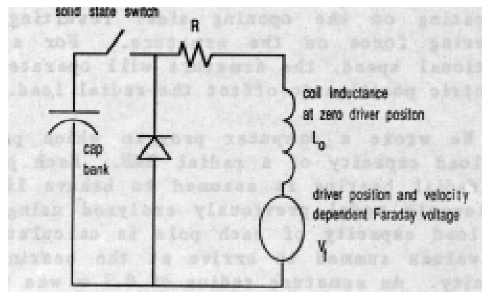


Figure 2 Capacitor Discharge Circuit

The term V_f is Faraday voltage as determined from the total magnetic flux linkage, λ of the system given by:

$$\lambda = \int_{r_i}^{r_o} \psi \, dN = \int_{r_i}^{r_o} (B)(S)dN = \int_{r_i}^{r_o} (\mu_o n I)(2\pi r x)\, n dr = \mu_o n^2 I x A \quad (1)$$

where $A = \pi(r_o^2 - r_i^2)$ (2)

and $V_f = d\lambda/dt = u_o n^2 A \, (I'x + Ix')$ (3)

where x and x' are the distance and velocity of the conductor plate relative to the coil. The velocity term separates the system analysis from regular electrical circuits. After applying Kirchoff's laws to the circuit and substituting Eq. 3 two equations result:

$$I = C \, dV_c / dt \quad (4)$$

$$V_c = IR + L_0 I' + V_f = IR + (L_0 + u_0 n^2 A x) I' + u_0 n^2 A I x' \quad (5)$$

where L_0 = Coil Inductance at x = 0

Eq. 5 illustrates the direct coupling between the electrical and mechanical systems of these devices. The motion of the plate is caused by the magnetic repulsion force. For two closely coupled current sheets a simple relationship exists between current and transverse magnetic field:

$$H = nI \quad (6)$$

It the follows that the Maxwell stress tensor is given by

$$F_m = 1/2 \, (u_o n^2 I^2 A) \quad (7)$$

The above equations can then be linked to the particular mechanical system equations resulting in a series of ODE's. However, in order to optimize the system design a more involve analysis was performed under NSF sponsorship. This is briefly described below.

Assuming that the current flow in the coil is primarily in the circumferential direction, it can be modeled as a mesh of current loops and the spatial magnetic fields can be determined by summing the contributions from all loops. Loops can be characterized with lumped parameters and can be linked to other loops with appropriate equations. Currents are induced in the adjacent conductor plate which image those in the coil, i.e. these currents are also assumed circumferential. The conductor plate can then be modeled as an array of closed turns arranged axially and radially. The axial loops represent parallel connections and the radially arranged loops represent series connections. Each loop is inductively coupled to every other loop both within as well as between the coil and plate. The force between coil and plate elements can be shown to be:

$$F = \sum_{ij} I_i I_j \, dM_{ij} / dx \qquad 8$$

I_i...coil current
I_j... .plate current
M_{ij}...coil/plate mutual inductance

A unique magnetodynamic computer simulation which employs this technique was written by one of the authors in conjunction the development of the "low voltage" concept. A generalized magnetic field solution for coupled cylindrical axially concentric elements is employed. In the absence of magnetic materials the magnetic field from axisymmetric current loops can be determined from the Biot-Savart law. A generalized solution incorporating elliptical integrals is derived for the mutual inductance of axially concentric current loops. A more in depth explanation of this analytical approach is presented by Zieve [7]

Robotic and Handheld High Force Actuators:

Robots provide the flexibility to perform operations on many complex geometries but are relatively limited in payload, size and weight. As a result robots have heretofore been limited to low force tasks. Pneumatic handheld force actuators are extremely noisy and over time the constant vibration has been shown to result in permanent physical injury to the wrist of the worker. The low recoil "one shot" electromagnetic actuators described in this paper offer solutions for both of these applications. These are generic high force actuators that have been used for a number of applications including riveting, driving interference pins, punching holes, shearing and dimpling of metal and composites.

Robot End Effector:

By exploding the principal of conservation of momentum the Electroimpact Robot End Effector (EREE) is able to transfer two orders of magnitude more force to the workpiece than is felt by the robot arm. Considerable force is obtained with the low system voltage due to the use of several unique features. For one, a thick copper driver plate is employed. This thick plate extends the magnetic diffusion time to several milliseconds. Plate 1 shows a prototype model of the EREE. A hardened steel driver is attached to the copper plate and the plate is brought in contact with the coil. When the capacitors are discharged a force impulse is transferred to the workpiece. By Newton's Third Law, an equal and opposite impulse is imparted to the recoil mass of the actuator, which being larger, moves at a slower rate. The energy of the narrow high force impulse can therefore be dissipated by a much lower force over a longer time. It is this force which must be absorbed by the robot arm. Figure 3 shows typical force and current traces for a metal forming operation.

In the robotic system, two 7 kg actuators are mounted on opposing robots and controlled by a single power supply. Each actuator is connected to a capacitor bank. The capacitance of the bank is approximately 28,800 µF with an energy rating of 2.9 kJ.

The use of relatively low voltage and high capacitance is a unique feature of the Electroimpact design. The two capacitor banks ***are*** discharged simultaneously, resulting in the transfer of equal and opposite force pulses to the workpiece. Therefore, the impact felt by the workpiece is easily confined to a small area.

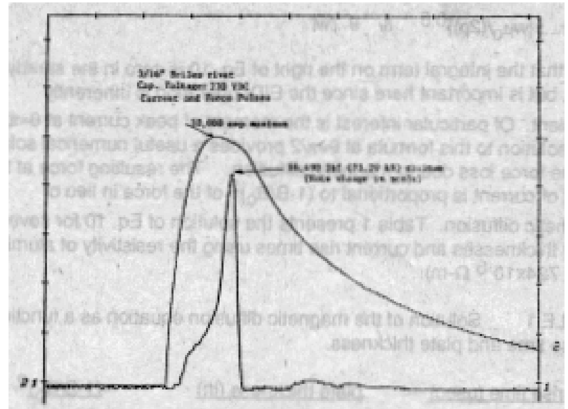


Figure 3 Force and Current Traces for the EREE

Handheld Actuator:

The handheld electromagnetic impactor is a further extension of the EREE. It weighs about 7kg and is capable of outputting forces in excess of 10,000 lbs. Plate 2 show two prototypes of this device. Unlike the EREE, the capacitors are mounted directly behind the coil. This not only makes the unit more portable, it also adds a sufficient amount of mass which lessens the recoil acceleration making it comfortable to operate. The actuators can be used separately or can be synchronized using a single power supply. They can perform most operations in a single shot eliminating the noise and excessive vibration of pneumatic handheld actuators.

Electro-Impulse De-icing (EIDI):

Presently, de-icing of aircraft wings and engine inlets is accomplished using hot bleed air from the aircraft engines. With the advent of high bypass aircraft engines such as the proposed unducted fan engine, the quantity of bleed air necessary for de-icing will no longer be readily available. As a result a number of alternative methods have been proposed. A promising technique is to mechanically dislodge the ice using eddy current actuators. Coils are mounted directly behind the leading edge in the wing box. Capacitors are discharged through the coil inducing eddy currents in the aluminum wing skin. The repulsive magnetic force causes the skin to flex and dislodges the accumulated ice.

Until recently all these proposed electromagnetic systems operated at voltages around 2 kV or higher. All coils were operated from a single high voltage capacitor bank. Using the concepts employed in the development of the above described actuators, Electroimpact has developed an independent "low voltage" electromagnetic deicing module (LVEIDI). Plate 3 shows an example of a prototype. The use of low voltage is considerably less expensive, more reliable and safer than high voltage. The new system uses low voltage electrolytic capacitors mounted directly on the coil, and therefore obviates the need for the bulky transmission cables used in high voltage distributed systems.

Of primary interest is the force mechanism. Note that the leading edge plate serves to squash down the magnetic field lines and thereby hold down the coil inductance as described above. An important issue for the use of an eddy current based system is magnetic diffusion. The field pattern observed in Figure 1 will only be maintained for a short period of time. In the robotic and handheld actuators, this period was extended by the use of a thick copper plate. In the deicing application, the diffusion time is limited by the thickness of the wingskin. Solutions to the diffusion equation are characterized by the diffusion depth [3]:

$$d = (2/(w\mu_0 s))^{0.5} \qquad 9$$

w...electrical frequency & s...aluminum conductivity

This formula although commonly employed is derived for sinusoidal steady state excitation. Misleading results are obtained if the formula is applied to the transient conditions of EIDI. A useful formulator this case is the solution of the diffusion equation for a sinusoidal flux imposed on the surface of a semi-infinite solid beginning at t = 0:

$$B/B_0 = \exp(-z)\sin(\theta - z) + (2/\pi)\int_0^t \frac{\exp(-v^2\theta)\,\sin(vz\sqrt{2})\,v\,dv}{(1+v^4)} \qquad 10$$

$$z \ldots x(w\mu_o/(2\rho))^{0.5} \quad \& \quad \theta \ldots wt$$

Note that the integral term on the right of Eq. 10 is zero in the steady state, but is important here since the EIDI operation is inherently transient. Of particular interest is the moment of peak current at $O = \Pi/2$. The solution to this formula at $O = \Pi/2$ provides a useful numerical solution for the force loss due to magnetic diffusion. The resulting force at the peak of current is proportional to $(1\text{-}B/B_0)^2$ of the force in lieu of magnetic diffusion. Table 1 presents the solution of Eq. 10 for several plate thicknesses and current rise times using the resistivity of aluminum ($\rho = 1.724 \times 10^{-8}\ \Omega$-m).

TABLE 1 Solution of the magnetic diffusion equation as a function of rise time and plate thickness.

Rise time (μsec)	plate thickness (in)	$(1\text{-}B/B_0)^2$
100	.063	.62
200	.063	.40
100	.118	.94
200	.118	.79

Note for a sheet thickness of .063" that considerable loss of force occurs for rise times in excess of 100 μsec. This effect can be somewhat reduced in the deicing system with the addition of a thin doubler plate opposite the coil, bringing the total thickness to .118". Research performed at Wichita State suggests that a current rise time of 200 μsec will provide good ice removal Note from the table for this slow rise time that the use of a doubler plate is nearly mandatory. For the 125 μsec rise time of the "low voltage" EIDI (97 msec to 90%) a doubler plate would be helpful but isn't mandatory.

The impact force of the Electroimpact prototypes can be estimated from Eq. 6 assuming system operating parameters of n=1358 turns/m, I=1800A, A= 5.1x10-3m2 and a leakage flux of 50%. A peak force of 1100 lbf is predicted. Boeing has suggested that the peak operating force should be about 1000 lbf. The Electroimpact modules use an oval coil since this configuration has been shown to extend the fatigue life of the skin in relation to round coils by spreading the force over a larger area. The capacitors on the LVEIDI module are rated for a peak charge voltage of 525 VDC. The pulse current and voltage traces for a discharge cycle are shown in Figure 4.

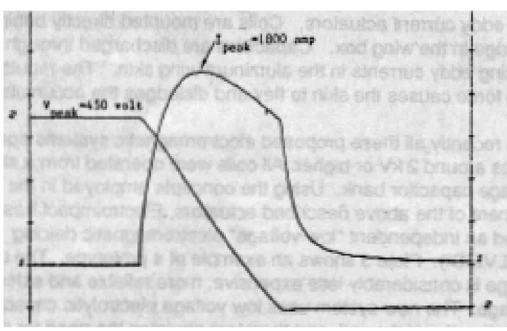


Figure 4 Voltage and Current Pulses for the LVEIDI Module

Conclusion

Actuators powered by capacitor discharge and operating at relatively low voltages have been demonstrated to be able to deliver forces in excess of 130 kN. The high forces result from magnetic pressure due to the restriction of a magnetic field between a pulsed pancake coil and a conducting plate. Fast rise times result in favorable characteristics such as low momentum transfer to the mounting structure. These actuators have been shown to be able to perform a number of functions from recoilless robotic riveting to the deicing of aircraft wings. The innovative use of low voltage makes these systems safe and reliable, and has resulted in renewed commercial interest in capacitor discharge systems.

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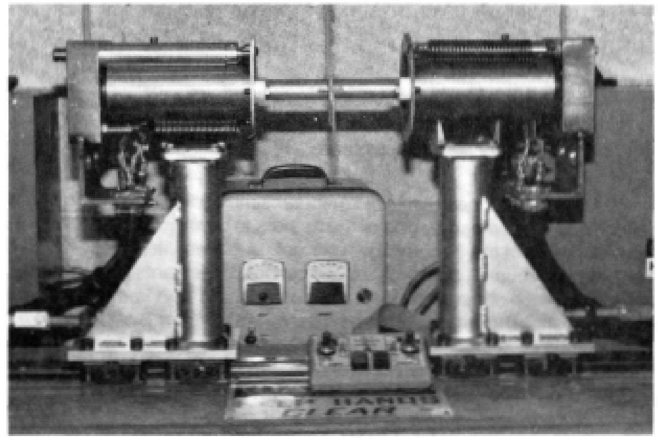

Plate 1: Prototype Model of the Robotic Actuator

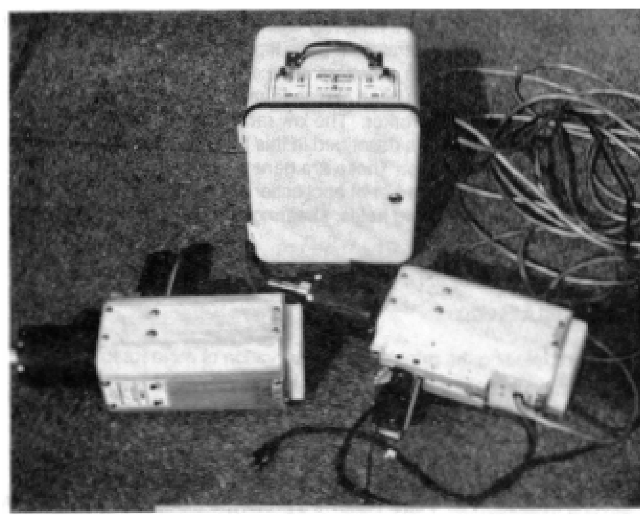

Plate 2: Handheld Actuator

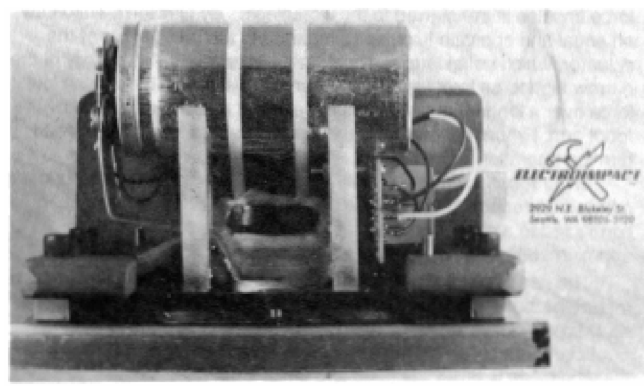

Plate 3: Prototype LVEIDI Module