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Development of a Linear Induction Motor Based Artificial Muscle System

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Abstract— **We present the design of a linear induction motor based on electromagnetic interactions. The engine is capable of producing a linear movement from electricity. The design consists of stators arranged in parallel, which produce a magnetic field sufficient to displace a plunger along its axial axis. Furthermore, the winding has a shell and cap of ferromagnetic material that amplifies the magnetic field. This produces a force along the length of the motor that is similar to that of skeletal muscle. In principle, the objective is to use the engine in the development of an artificial muscle system for prosthetic applications, but it could have multiple applications, not only in the medical field, but in other industries.**

Keywords: Linear induction motor, artificial muscle, prosthetics,

I. INTRODUCTION

The basic function of an electric motor is to convert electrical energy into mechanical energy through electromagnetic interactions. Most designs proposed hitherto use electrical energy to produce a circular motion. There are many applications which require a linear motion. To this end, an electric motor which generates circular motion can be coupled to a gear system, to produce linear movement. This has certain advantages such as power leverage of conventional engines, but also disadvantages such as its increased size. Linear induction motors (LIMs) were conceptualized many years ago [1],[2],[3], however, the practical applications of these were overshadowed by rotational motors. LIMs have been used to move rail trains, reaching high speeds due to reduced friction [4],[5]. In these linear motors, the rotor or moving part moves along the stator (rail), ie, the stator is elongated or stretched and the rotor moves along the former. These engines have high power consumption so their applications are based on large-scale devices [6].

Regarding the development of artificial muscles, there have been several attempts for the utilization of various types of linear actuators. The oldest types being pneumatic actuators [7], while the newest are based on various electroactive polymers [8],[9]. The movement is based on the volume change of the actuator which is coupled to the joint displacement mechanism.

The main objective of this paper is to propose a linear motor design, which through electromagnetic interactions, transforms electrical energy into mechanical linear motion. The most similar example to our design is that of the flexible linear actuator [10], where a permanent magnet is coupled to an elastomer, allowing for tensile strenght.

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II. ENGINE DESIGN

The Biot-Savart law can be applied to any driver by which an electric current flows. To determine the magnetic field within a coil, we first need to describe magnetic field within a loop as shown in fig. 1.

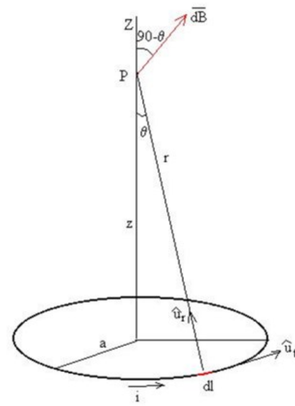

Figure 1. Magnetic field produced by a coil at a point on its axis.

Analyzing fig. 1, we can see that each differential dl whereby a current I produces a differential magnetic field $\overrightarrow{dB}$, which has two components, one on the axis and another perpendicular to the axis. The sum of the differential magnetic field produced by each dl along the loop, can be seen as the magnetic field component perpendicular to the axis of the coil cancel each other, and that the components on the shaft add together. Therefore, after some mathematical operations, the resulting magnetic field on a point on the axis of the loop is as follows:

$$\vec{B} = \frac{\mu_0 i a^2}{2(\sqrt{z^2 + a^2})^3} \quad (1)$$

Where i is the current in the loop, a, is the radius thereof, z is the distance from coil center to the point P.

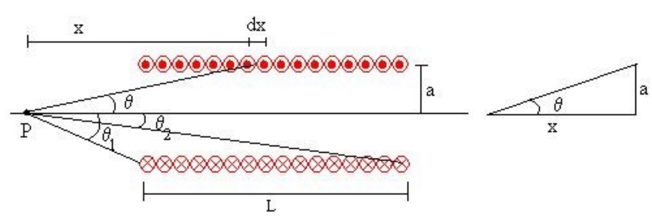

Figure 2. Geometry for calculating the magnetic field inside the coil. [11].

After calculating the magnetic field produced by a loop, one can proceed to calculate the magnetic field inside the coil. A coil of length L, number of turns N, and radius a. From Fig. 2 dx is the differential of L along the coil, x is the distance along the axis to point P, a is the radius of the coil, ɵ is the angle between the axis and the line connecting the point with the loop. We analyze the magnetic field produced by a coil segment dn, which is the number of turns between x dx. The magnetic field produced at a point P is equal to the field produced by a coil multiplied by the number of turns in dn.

$$\overrightarrow{dB} = \frac{\mu_0 i a^2}{2(\sqrt{z^2 + a^2})^3} \frac{N}{L} dx \quad (2)$$

By doing some mathematical operations we can obtain the mathematical expression which defines the magnetic field inside the coil.

$$\vec{B} = \frac{\mu_0 i N}{2L} \left(\frac{L/_2 - x}{\sqrt{\left(-L/_2 - x\right)^2 + a^2}} - \frac{-L/_2 - x}{\sqrt{\left(-L/_2 - x\right)^2 + a^2}} \right) \quad (3)$$

It can be stablished that the magnetic field in the center of the coil is maximum, if the length L is at least 4 times greater than the radius. When approaching the ends of the coil, the magnetic field starts to decrease, until the ends just falls to half. Outside the coil, the magnetic field decreases until it becomes zero abruptly.

III. METHODOLOGY

A. Motor coupled joint design

The joint consists of two articulated arms which depend on the movement of the linear motor and a spring. The design is divided into two parts, the first is the specification of the dimensions of the arms and position of the pulleys, and the specification of the points of application of force on the movable arm.

Two arms, one fixed where the engine will be mounted and a mobile where forces are applied. The latter is connected via a pulley to the movable core of the linear motor and the spring that acts as an antagonist. Fig. 3 shows the overall design of the joint.

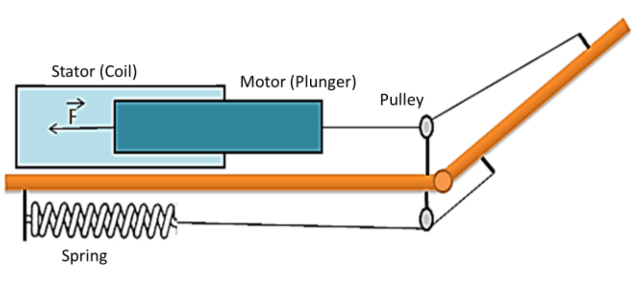

Figure 3. Overall design of the linear motor and articulation.

The dimensions of the fixed arm will depend on the maximum elongation position of the motor and the pulley. The length of the coil is 80mm. It is estimated that the minimum plunger insertion is 25mm. The maximum insertion is 65mm. Fig. 4 illustrates the maximum and minimum motor elongation.

As can be seen, the maximum elongation of the engine is 135 mm, and the minimum is 95 mm. Therefore, the maximum displacement of the movable core is 40 mm. The distance from the plunger end to the pulley, and the distance from the pulley to the point of articulation are calculated. It must ensure that at maximum elongation the arm is extended, and that for minimum elongation the arm is fully flexed.

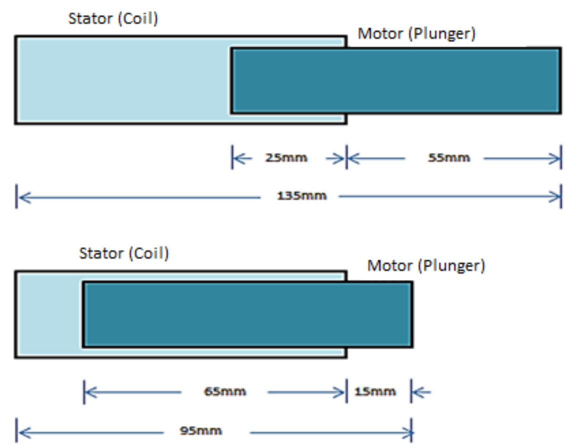

Figure 4. Maximum and minimum elongation of the linear motor..

B. Design of the stator (coil)

The first step is to address the design of the stator, which is the fundamental piece in the operation of the motor. Here you must specify the dimensions of the coil (width, length), number of turns, power supply and from there determine the magnitude of the magnetic field and its behavior over the coil, and the mechanical force that is capable to generate.

Design of the coil: i = 0.5A is chosen because it is an average magnitude which does not require sophisticated equipment to achieve. The length of the coil is L = 70 mm, with equal sized plunger, which allows extension and contraction in proportion equal to a skeletal muscle (biceps brachii), since it can shrink up to 30% of its length in rest [29]. The radius is R = 15 mm, which meets the condition that the length of the coil is at least four times greater than the radius in order to fulfill the equation 3 which determines the magnetic field within the coil. The number of turns is N = 4400.

C. Design of the Housing

Using equation (3) and MATLAB (R2009b) the magnitude and behavior of the magnetic field inside and outside of the coil along its axis can be determined. To amplify the magnetic field within the winding, keeping constant the number of turns (N) and the electric current (I), it is necessary to add a ferromagnetic material housing on the outside, because it requires the inside open to allow movement of the plunger. A stop is placed at one end, which amplifies the field in the area close to it. Fig. 5 shows the dimensions of the ferromagnetic housing, which was built in the Laboratory D (Metallurgical Laboratory) at Simon Bolivar University.

The whole piece is made of iron, because it has high magnetic permeability, which will amplify the magnetic field considerably. The weight of the motor assembly is around 2 Kg. The magnetic permeability of materials varies with the magnetic field increases as the magnetic field to which it is subjected, its magnetic permeability decreases.

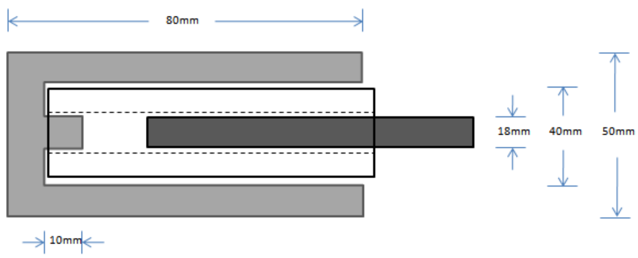

Figure 5. Dimensions of the ferromagnetic housing to amplify the magnetic field.

Relative magnetic permeability of soft iron is 200 with a magnetic field 20 Gauss, and saturated with 21000 Gauss. The materials have a saturation point where even when the field strength increases, the magnetic field remains constant. In the case of soft iron, the saturation occurs with a field of 21000 Gauss, i.e., 2.1 Tesla.

As seen in Fig. 6, the magnetic field inside the coil behaves differently when it has a casing and a cap. The calculations were made using the Matlab (R2009b) making approximations of the soft iron magnetic permeability in the presence of different magnetic fields. It is observed that the largest increase was in the area near the center reaching maximum 1.537Tesla. The the magnetic field shown in Fig.6 is not symmetry to zero position, since the cap limits displacement to the left side.

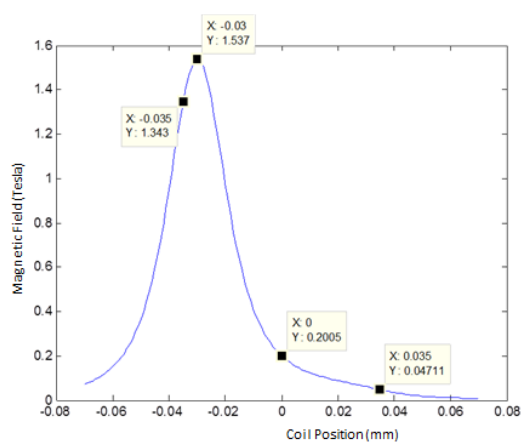

Figure 6. Behavior of the magnetic field in the coil casing and cap.

IV. RESULTS

It should be emphasized that the motor produced in the laboratory corresponds to a proof of concept which aims to corroborate the results obtained by theoretically design. Below are the results of tests made to the linear motor mounted in the laboratory:

A. Motor mechanical strength

Using a dynamometer, engine power was measured as a function of percentage of plunger insertion and as a function of voltage for the two cases: without casing and with casing and stopper. Fig. 7 shows a comparison of the strength of the motor without casing and cap, with that of the motor plus casing and cap. The curve was normalized with the maximum recorded force, which was of 2.5N with the coil casing and cap. The force measurements were made in N. The precision is of 0.05N. The maximum voltage was applied, i.e. 40V.

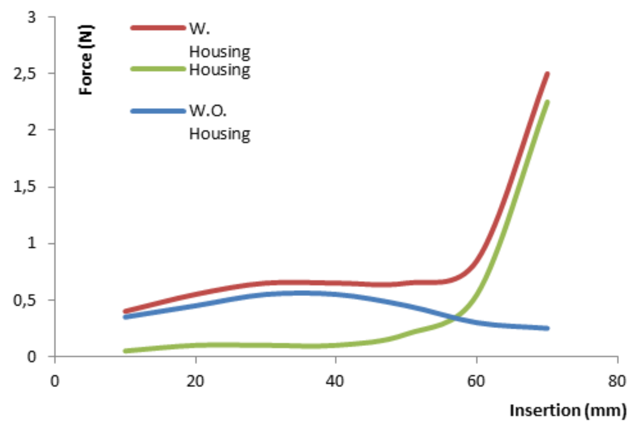

Figure 7. Measured force as a function of plunger insertion with and without casing and cap for maximum voltage (40 V).

As shown in Fig. 7, the blue line represents the strength of the coil without casing and cap. The green line represents the contribution to the force by the casing and cap. The red line represents the total force, that is, the sum of the input coil without a casing and cap, plus the contribution The higher value of force occurs with the presence of the envelope and the cap of ferromagnetic material, is approximately 2.5N, while in the case of the single coil, the maximum value amounted to just 0.5N. This translates to an increase of more than twice the force. The force behavior is similar to that obtained theoretically. It is noted that the greatest increase in strength occurred in the area near the top, i.e. when the gap is smaller. At the height of insertion (70mm), when the gap is virtually zero, the engine power is maximum. This means that the force is maximum when the engine is retracted to the maximum.

As noted, the strength with casing and cap, follows a quadratic relationship with the voltage. This force has two components, one contributed by the coil, and other contributed by the casing and cap. The first has a linear relationship with the voltage, and the second has a quadratic relationship.

One can observe also a similarity between the performance of the motor force and the forces in the skeletal muscle. In muscle, the total force is given by the sum of the active and passive force. The first is when the muscle exceeds its resting length and stretches parts of non-contracting muscle. This behavior is similar to the force provided by the casing and stop. The active component in muscle force is produced by the contractile parts. This has similar behavior to that of the force produced by the coil alone.

The sum total of the forces in the muscle has a similar behavior, to the sum total of forces on the engine. This allows in any way, that the force development in the motor can have a behavior similar to the muscle.

V. Discussion

The electrical resistance of the motor is 37.5Ω when offline. This increased by 30.67% due to the temperature increase. This represents an increase of 30% in power consumption.

The rate of increase in engine temperature is greater the higher the power consumption. Maximum power consumption, increased to its maximum in approximately 16 minutes. That is, for an average current consumption less than the maximum current, motor resistance reaches its maximum value in a longer time. The maximum power output is within a range: $37.5W \leq P_{max} \leq 49W$

The power consumption is relatively high if the engine runs at maximum current. For the engine to generate the movement of the joint, the range of total current is $0.3A \leq I \leq 0.7A$. Therefore the average power consumption is lower.

The peak force generated by the motor is 2.5N. This corresponds to the maximum current consumption when the plunger is inserted to the fullest. The average range of force that permits movement of the mechanical arm is $0.4N \leq F \leq 0.9N$.

The strength behavior of the engine along its length is similar to the behavior of muscle strength along its length. The difference is that the maximum engine power is produced when fully contracted. Instead the maximum muscle force occurs when fully stretched. This is highly interesting since this nonlinear behavior is desirable for a biomimetic joint [12]

To maintain similarity with skeletal muscle, it is necessary for the engine to maintain a voltage equivalent to the average tension of the muscle relaxation. This is necessary to maintain a constant engine power, equal to 20V, with a total current of 0.5A.

The behavior of the total engine power as a function of applied voltage is quadratic. That is, the relationship between the force and the applied voltage is quadratic and follows equation Ft = 0.0001 + 0.0142 V2 V.

The relationship between the strength and the percentage of insertion of the plunger is polynomial of order 6. From Fig. 5 shows the equation that relates the Total engine force with the insertion of the plunger in millimeters is: Ft = 2E-09x6 - 4E-07x5 + 3E-05x4 - x3 + 0.0279 0.0013 x2 - 0.2787 x + 1.4147.

VI. Conclusion

The linear motor has a behavior similar to a skeletal muscle and is able to exert force as a function of its length. In the case of linear motor, the force is maximum when the elongation is minimum, and vice versa.

It is possible to generate a linear movement from electromagnetic interactions, and without any rotary motion. Therefore, it is possible to use a linear motor as an actuator for the movement of an artificial joint. To produce linear displacement a simple PID current controller is sufficient.

The motor power consumption, which enables the movement of the joint, is relatively low. That is, with low power consumption, it is possible to generate the force necessary for the movement of a single joint.

With the use of electrical voltage signals, it is possible to control the process of contraction and relaxation of a linear motor and therefore the movement of an artificial joint that can simulate any of the extremities of the human body.

The input voltage of the linear motor can be controlled by an electronic microprocessor, which opens the possibility that the motor movement could be controlled by the body's electromyographic signals.

The spring can be replaced by a second actuator such that an antagonistically driven joint can be manufactured. This system could have potential applications not only in prosthetics but in other industries. The concept needs further optimization for practical use.

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