Interlacing Metallic Filaments by Rotational Permanent Magnetic Field

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Abstract
In this paper the possibility of interlacing current-carrying conductive filaments in a rotational permanent magnetic field is described. The work contains two parts. Firstly, the effect of magnetic forces on current-carrying conductive filaments in a rotational permanent magnetic field is theoretically studied. Secondly, in accordance with the theoretical analysis, a prototype of the proposed system is designed and tested. The experimental results prove the capability of the method to interlace conductive filaments. The proposed method can be employed as a kernel to reach a texturing system for conductive filaments

Keywords: Conductive Filaments, Interlacing, Permanent Magnets, Rotational Magnetic Field

1. Introduction
In recent years, applications of conductive yarns in textile products are widely developed especially in electronic and smart clothing [1]. Combinations of textile structures that are lightweight, flexible, strong, and conformable with electronics have aroused keen interest from many disciplines. With technological innovations appearing in both textile and electronics, integration of these has started giving benefits. Innovations like electrical blankets and heating jackets [2], wearable electronics [2], textile based antennas [3], life shirts [4], wearable music players [5], and smart shirts [6,7], just to name a few. However, there are some general difficulties in creating conductive textiles for clothing. Textiles used for clothing should be flexible and elastic in order to achieve a high comfort of wearing. Fabrics should posses a low resistance to bending and shearing so that they can be easily deformed and draped. These demands are inconsistent with the materials and geometries that are needed for an electrical conductivity. Metal, carbon and conductive polymers are quite rigid and brittle materials. Nevertheless, textile technologies have been developed to manufacture process-able fibres and yarns out of these materials [8].

However, because of the way they are manufactured, most conductive fibres (such as synthetic polymers) have smooth surface and circular cross section, and when these continuous filament yarns are woven into a fabric ,they feel slippery to touch and clammy when worn next to the skin. To texturizing conductive filaments, an unconventional method is required for interlacing filaments. To achieve this purpose, a novel idea which is based on the conductivity feature of this kind of filament, is introduced.

2. Methodology
By considering the electrical conductivity of filaments and the effect of rotational magnetic field on a wire with electrical current, it seems that the principle of rotational magnetic force on current-carrying wires can be employed to interlace conductive filaments. As illustrated in Fig.1, a rotational magnetic field is produced by revolving two strong rectangular permanent magnets. The magnets are placed on two separate adjustable aluminum holders to be able to change the distance between them. The holders along with magnets are placed on a revolving plate to form the required rotational magnetic field.

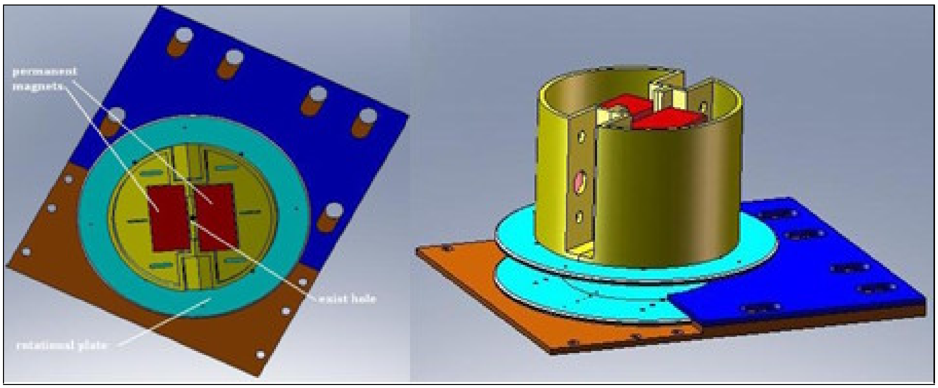

Figure 1: Unit designed for interlacing metallic filament

In Fig.2 the conductive filaments, which are carrying opposite currents, are fed between the rotational permanent magnets. The forces induced in the filaments by the rotational magnetic field, interlaces the filaments.
These induced forces are:

- magnetic force between two current-carrying conductive filaments,
- magnetic force between current-carrying conductive filaments and rotational magnetic field,
- magnetic force produced by the interaction of induced current from the back electro-motive force in a conductive filament by a rotating magnetic .

The displacement of conductive filaments is the amount of their bending when they are exposed to the mentioned forces.

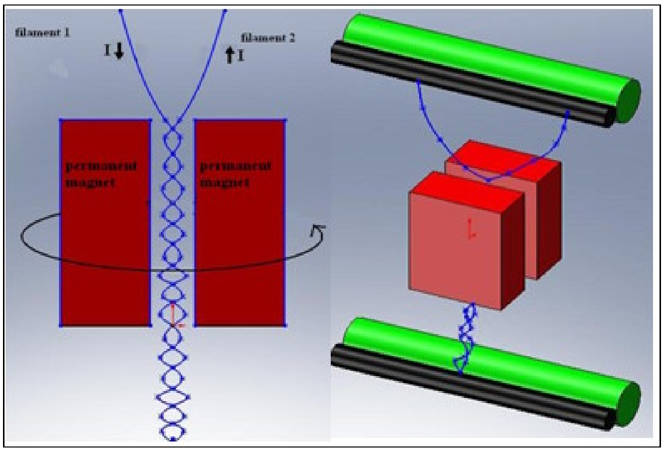

Figure 2: Schematic of interlacing zone

2.1. Magnetic force between two current-carrying conductive filaments

It is assumed that there are two parallel conductive filaments carrying opposite currents I_1 and I_2 in a magnetic field B. Every charge particle q in the filaments will experience a force. The total force on the filaments can theoretically be found. Suppose n is the charge per unit volume in a filament with a cross-sectional area A and length l as in Fig.3. Then, from (1), the Lorentz force on an element dl of current-carrying conductive filament can be found as in (2) [9].

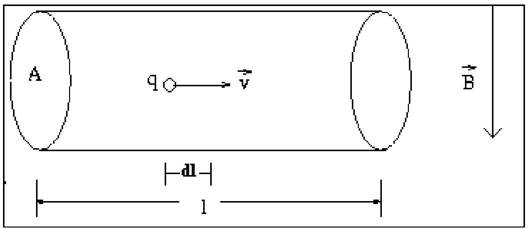

Figure 3: Current-carrying conductive filaments

$$F = q(E + V \times B) \quad (1)$$

$$dF = NA|dl|qV \times B \quad (2)$$

Where E and v are the electric field density (assumed equal to zero in our case) and the velocity of charged particles, respectively. Since v and dl are parallel, an alternative form (2) is:

$$dF = Nq|V|Adl \times B \quad (3)$$

Where $I=nqv$, therefore:

$$dF = Idl \times B \quad (4)$$

Equation 4 can be integrated to give the force on the filament:

$$F = \oint_c Idl \times B \quad (5)$$

If the distance between two filaments is d as in Fig. 4,

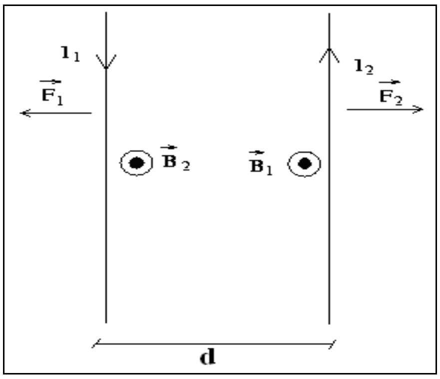

Figure 4: Force between two straight parallel conductive filaments

and:

$$B = \frac{\mu_0 I}{2\pi d} \quad (6)$$

Then, from (5) and (6) one can obtain the following:

$$\frac{F_2}{l} = \frac{\mu_0 I_1 I_2}{2\Pi d} \quad (7)$$

Filament 1 in Figure 4 experiences the force F_1 due to the magnetic field B_2 from filament 2. This force is equal to F_2 given in (7).the magnetic force between filaments according (7) is illustrated in Fig.5.as it's clear the amount of magnetic force strongly depends on filaments distance of each other.

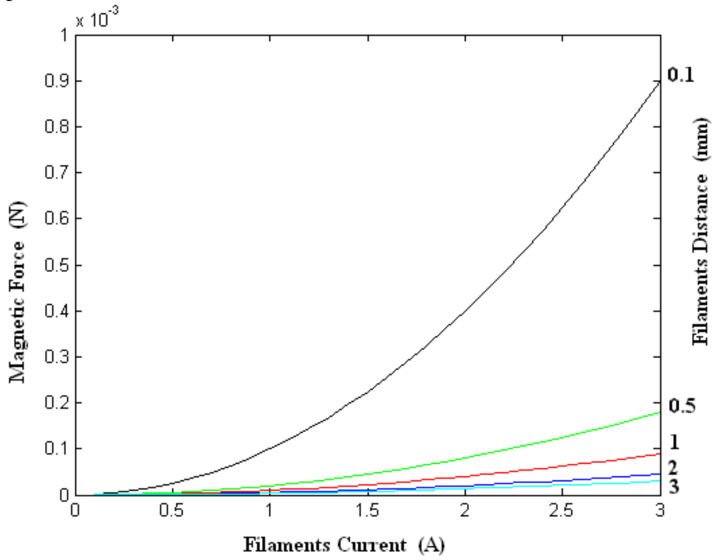

Figure 5: Magnetic force between two current-carrying conductive filaments

2.2. magnetic force between current-carrying conductive filaments and rotational magnetic field

The Ampere's circuit law [10] for the permanent magnets (PMs) and the air space in between is given by:

$$H_m l_m + H_g l_g = 0 \tag{8}$$

where (H_m), (l_m), (H_g), and (l_g) are the magnetic field intensity, and the effective length of PMs, the magnetic field intensity, and the length of the air space, respectively. Assuming no flux leakage, the continuity of magnetic flux is given by:

$$\varphi = B_m A_m = B_g A_g \tag{9}$$

where (Φ) is the magnetic flux in magnets and air space, (B_m) the flux density of magnets, A_m the magnet area, (B_g) the flux density in air space and A_g the air space area. the flux density and flux distribution between permanent magnets is simulated and illustrated in Figures 6,7.for simulating the distance between magnets assume 5mm (according to experimental set up) and the properties of magnets is shown in Table 1.

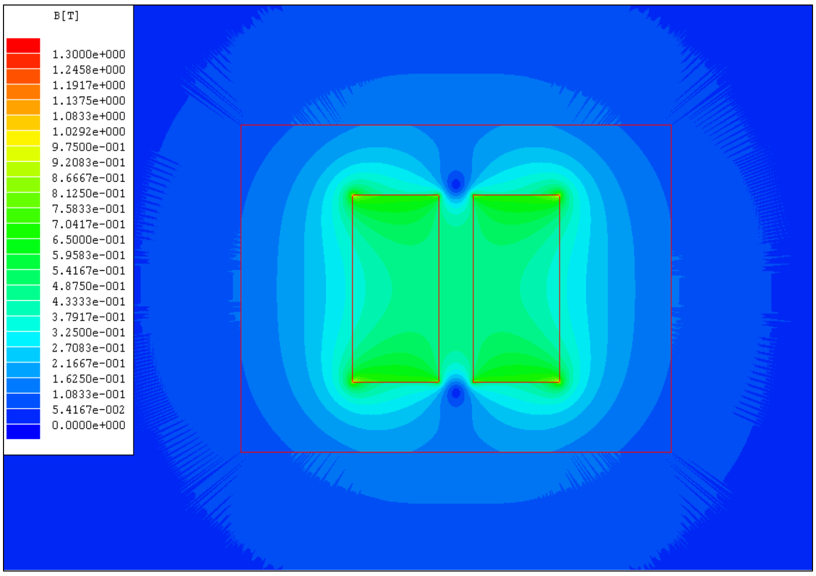

Figure 6: Flux density distribution between permanent magnets

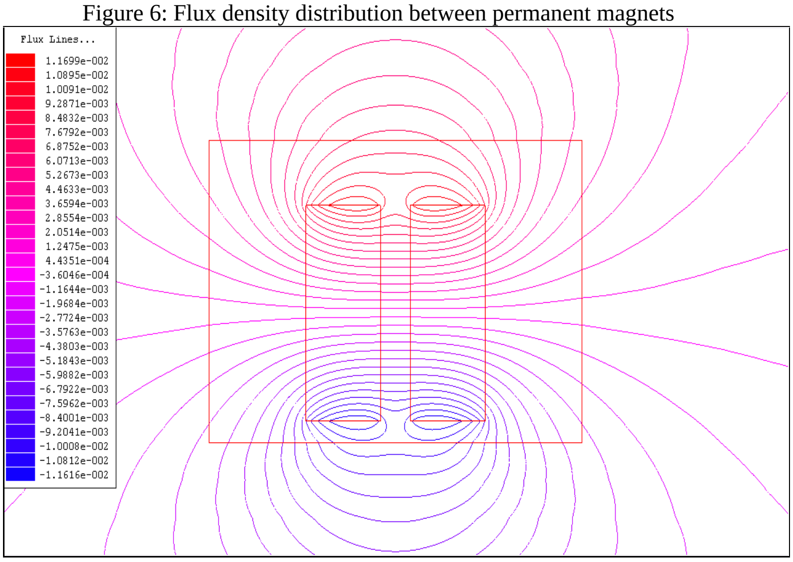

Figure 7: Flux distribution between permanent magnets

Table 1: Properties of Nd-Fe-B magnets

Code	Residual flux density	Coercive Force	Intrinsic Coercive Force	Maximum Energy Product	Curie Temperature	Maximum Operating Temperature
	B_r	H_c	iH_c	$(BH)_{max}$	T_C	T_W
	Tesla	*KA/m*	*KA/m*	KJ/m^3	°C	°C
Sintered						
N-33	>=1.14	>=840	>=960	>=248	310	80
Dimensions: 4*5*2 cm						

The magnetic force between current-carrying conductive filaments and rotational magnetic field can be calculated in any position of air space by using the flux density result of simulating and (4).

2.3. Magnetic force produced by the interaction of induced current from the back electro-motive force in a conductive filament by a rotating magnetic.

An electromotive-force (emf) *e* is induced in each filament by rotating the PMs around the conductive filaments as in below:

$$e_f = Bldv\sin(\theta) \tag{10}$$

where (B), (υ), and (θ) are the magnetic field of PMs, velocity of PMs, and the angle between directions of magnetic field velocity and the filaments, respectively. With regard to the closed loops formed in the conductive filaments between their contact points, the average emf E_a is obtained as:

$$E_a = \frac{\varphi\omega}{\pi} \tag{11}$$

where φ and ω are the flux and the rotational speed of the PMs respectively. Now, the current, I, induced by the emf is given by:

$$I = \frac{E_a}{R} \tag{12}$$

where, R is the total electric resistance of a closed loop. This current can also induce forces given by (5) ,(7).

3. Laboratory Set-Up and Experimental Results

The laboratory set-up is shown in Fig.8. Suitable DC motors are used to drive the feed- rollers, take-up rollers and to rotate the pulley of magnets. Thus, the speeds of these parts can be controlled to investigate their effects on the interlacing of filaments [10].

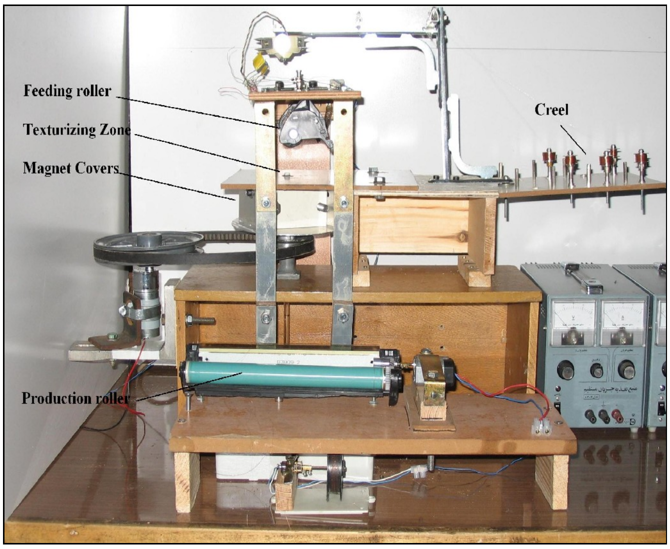

Figure 8: Schematic of interlacing zone.

The magnets are placed in two adjustable aluminum boxes to be able to vary the distance between the PMs and hence to change the flux density of the operating point. To force most of the magnetic flux to go through the air-space containing the filaments, the frame of the interlacing box and all parts which are close to the magnets are made from non- ferromagnetic materials. Two conductive filaments are fed to the interlacing box to test the operation of the designed system. The properties of conductive filaments are shown in Table 2.

Table 2: Properties of the metallic filament

Material	copper
Conductivity	56,000,000 S/m
Relative Permeability	1
Diameter	70 μm
Density	8.96 gr/cm^3
Shearing load	95 cN
Tensile strength	0.24 GP
Modules	5.32 N/tex
Cross section	circular

The air space and the speed of PMs are fixed to 5 mm and 500 rpm, respectively. The currents in the filaments are set equal to 2 Amperes. The speed of feeder and product rollers are set to 12 rpm and 10 rpm respectively to have a proper overfeed for false twisting. Fig. 9 demonstrates the two filaments interlaced by the prototype system, while the influence of rotational speed on the number of interlacing points is illustrated in Fig.10. Experiments show that for successful interlacing, at least10 % overfeeding in interlacing zone is required. The number of interlacing points depends on magnetic field rotation speed directly.

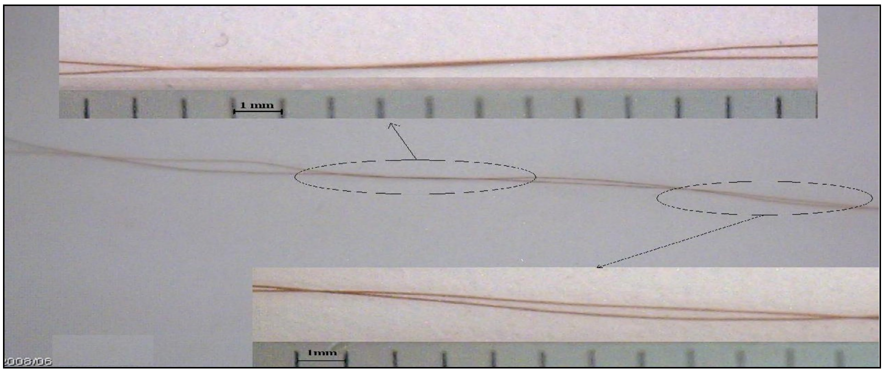

Figure 9: Two metallic filaments interlaced by the proposed method.

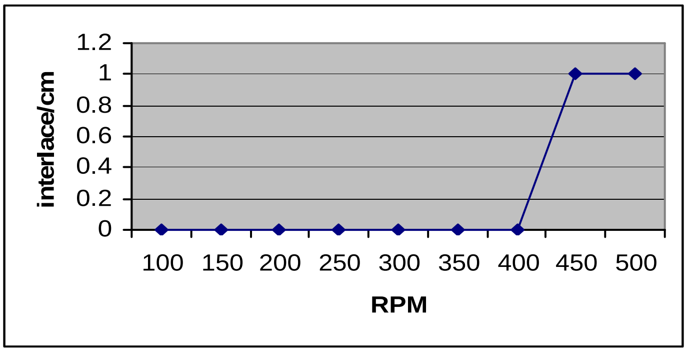

Figure 10: The effect of rotational speed of magnetic field on the number of interlaces per centimeter

Effect of filaments currents on filaments interlace is shown in Fig.11.as it’s clear by decreasing the current less than1.75A the magnetic force became so week which can’t make any interlacing point in the filaments.

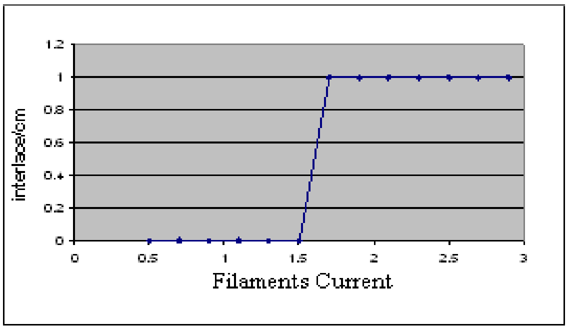

Figure 11: Effect of filaments currents on the number of interlaces per centimeter

Conclusion

The mechanical and electrical analysis of the proposed method demonstrates the feasibility of conductive filament being interlaced by rotational magnetic fields. The interlaced filaments produced by the invented interlacing box, prove the proficiency of the method. However, the proposed system still has some problems such as irregular and weak non-interlaced points. Also, the required current in the filaments is high, and that makes the filaments hot, especially at low production speeds.

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