ISSN 1392–1207. MECHANIKA. 2017 Volume 23(2): 305–309

# Friction between steel plates under the influence of magnetic field

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crossref http://dx.doi.org/10.5755/j01.mech.23.2.13839

## 1. Introduction

The frictional force is known as the opposing force when a surface slides over another surface. When frictional force is reduced the applied force required to slide a surface over another surface become trivial. But for good grip between surfaces the condition of increased friction is inevitable. There are different ways [1-3] that can be used to improve friction between two surfaces. Friction between two surfaces can be improved by creating a rougher or more adhesive point of contact, by pressing the two surfaces harder, removing lubrication between surfaces and remove wheels or bearing to create sliding friction.

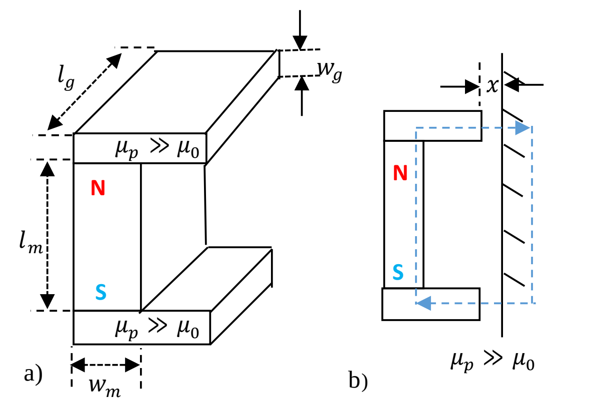
In this paper, the friction between steel plates sliding over each other under the influence of magnetic flux passing through steel is experimented and studied. The magnetic flux through steel plates is introduced by the method of magnetic latching, there coefficient of friction is considered as $\mu$ and magnetic permeability is considered as $\mu_p$.

Latching is a process to provide a force of attraction between two surfaces. The latching application can be categorized as contact and noncontact [4]. In contact latching, the magnet is attracted to another member and is placed in direct contact with the member, which can be another magnet or a soft magnetic material such as iron. In noncontact latching, the magnet and the members are separated by a gap and the magnet must project its field across the gap to exert a force of attraction (Fig. 1). The poles of the magnet must be effectively separated so that the field will span the gap. The magnetic force of attraction between magnet and plates can be explained using magnetic circuit analysis [4]. There are numerous latching circuits, and most of them can be designed and optimized using magnetic circuit theory [4].

In this paper, will be considering an arrangement as shown in Fig. 1, a [4]. The magnetic circuit of given model is as shown in Fig. 1, b [4]. Here the magnet with attached flux plates is attracted to a wall made of soft magnetic material. There exist a gap $x$ between magnetic structure and the wall, where $x > 0$. The permeability of structure and the wall are assumed as infinite permeability. Also, the magnetization of the magnet is assumed as a linear second quadrant demagnetization curve [4-6] of the form: $B_m = B_r + \mu_m H_m$ and $\mu_m = B_r / H_c$; where $B_r$ is remanence of magnet, $H_c$ coercivity and $\mu_m$ permeability of magnet. From Fig. 1, a, $l_g$ and $w_g$ are the length and width of the flux plate respectively. Whereas $l_m$ and $w_m$ are the length and width of magnet used. By using magnetic circuit theory [4] and simplifying, the force between magnetic setup and the wall, at a distance $x$ is [4]:

$$F(x) = \frac{B_r^2 A_m^2}{\mu_0 A_g \left(1 + 2(\mu_m/\mu_0)(A_m/A_g)(x/l_m)\right)^2} \hat{n}, \quad (1)$$

where $A_m = l_m w_m$ is the area of magnet and $A_g = l_g W_g$ area of the gap. Here the outward normal $\hat{n}$ of the wall points towards the magnet, and therefore the force is attractive.




a b

Fig. 1 Noncontact latching: a - magnet with two attached flux plate; b - latching circuit [4]

The force of attraction between two magnetized surfaces can also be explained using Gilbert Modeling [7]. The equation is valid only for cases in which the effect of fringing is negligible and the volume of the air gap is much smaller than that of the magnetized material [7].

$$F_{att} = \frac{\mu_0 H^2 A}{2} = \frac{B^2 A}{2\mu_0}, \quad (2)$$

where $A$ is the area of each surface in m$^2$; $H$ is their magnetizing field in A/m; the permeability of space $\mu_0 = 4\pi \times 10^{-7}$, H/m and $B$ is the flux density in Tesla, at the area of contact between two surfaces.

## 2. Experiment

During experiment certain conditions have to be considered, such as two surfaces which are highly permeable are sliding each other without any stick-slip, an ambient environment is maintained and the contact between the surfaces are dry and clean and a plane to plane contact is provided. In this paper, the internal deformation taking place and Vander Waals force is not considered. Three major laws [1-3] of friction are taken into consideration such as the frictional force is proportional to the normal load; the frictional force is independent of the apparent contact area and the frictional force is independent of sliding speed.

The steel plates were kept parallel to a steel platform, which is at an inclination $\Theta$ as shown in Fig. 2. Material of plates used for modeling is Steel C10, Its coefficient of friction with dry contact at static condition $\mu_s$ is 0.74 and at sliding condition $\mu_k$ is 0.57, density of mild steel – 7.85 g/cm$^3$ [8]. So the mass of steel plate with dimension 130 mm × 50 mm × 10 mm is 0.50986 kg, and hence weight is about 5 N.

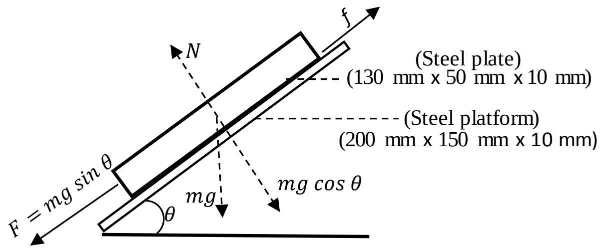



Fig. 2 Scheme of friction determination on inclined plane

When, the steel plate starts sliding over steel platform, then the force of gravitational pull is equal to the frictional force between steel plates [1-3]. That is $F = f$, where:

$$mg\ sin\Theta = \mu_s mg\ cos\Theta ; \tag{3}$$

$$\Theta = tan^{-1} \mu_s . \tag{4}$$

From Eq. (4) it was found that at an inclination 36.50° the steel plate starts sliding from the steel platform in the direction of gravitational pull. Also, for any value of the mass of steel plate, the minimum inclination required for the steel plate to slide from steel platform is 36.50°. At the point of sliding the magnitudes of frictional force and the force of gravitational pull will be equal, which is 2.97 N each.

The magnitude of frictional force can be increased by increasing the magnitude of the force of attraction between steel plates. In this paper, the magnitude of the force of attraction between steel plates is provided by magnetizing the steel plates.

The above statement is explained using a design (model 1) as shown in Fig. 3

The magnetic flux required to bring a force of attraction between two steel plates is provided by the neodymium magnet. Neodymium magnet of grade 35 (dimensions 50 mm × 50 mm × 10 mm and magnetization direction along 10 mm) is used for designing model 1. The magnetization of the magnet is assumed as a linear second quadrant demagnetization curve of the form: $B_m = B_r + \mu_m H_m$, where $\mu_m = B_r / H_c$ and $B_r$ = 1.17 T and $H_c$ = 859000 A/m.

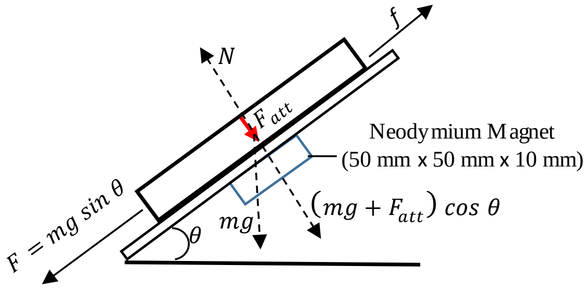



Fig. 3 Schematic presentation of model 1

Using FEMM 4.2 software, the model 1 (Fig. 3) is designed and simulated (Fig. 4) in order to study the magnitude of flux density passing through steel plates. Fig. 5 shows the flux density through steel platform. Fig. 6 shows flux density at the area of contact between the steel plate and steel platform. The average of the magnitude of flux density at the area of contacts is found to be 0.01 T.

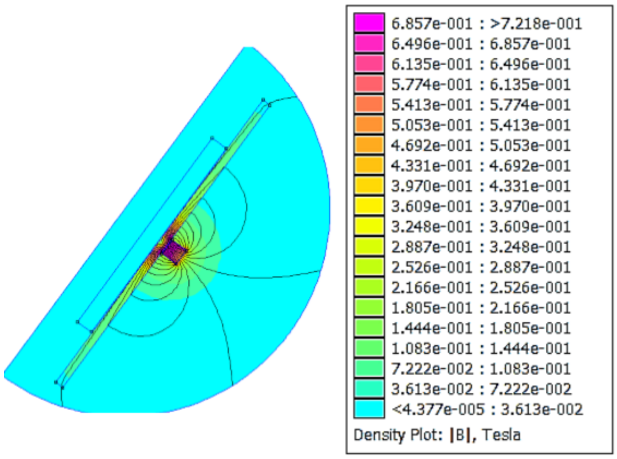



Fig. 4 Simulation results of model 1

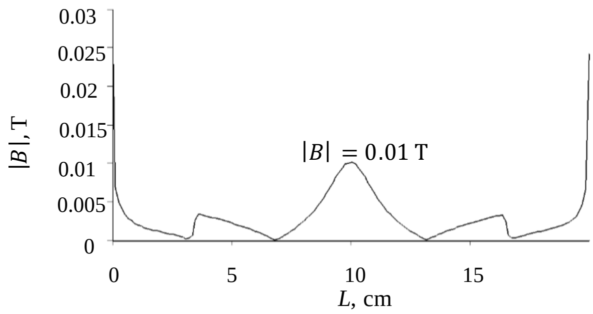



Fig. 5 Flux density through Steel platform

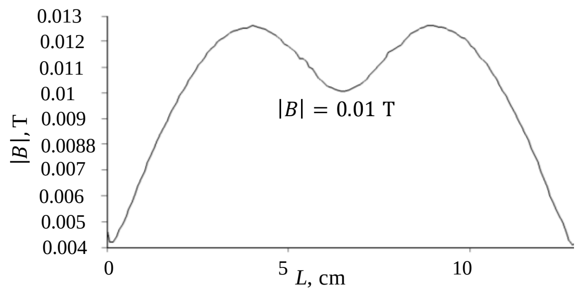



Fig. 6 Flux density through plate, at area of contact with platform

From Eq. (1) and (2) the force of attraction between plates can be obtained as, $F_{att}$ = 0.26 N.

The static friction with presence of magnetic latching can be modified as:

$$|f| = \mu\left(\left(W + F_{att}\right)cos\Theta\right). \quad (5)$$

When there is magnetic flux passing through steel plates, the magnitude of frictional force acting between steel plates, is given by the Eq. (5) and $|f|$ = 3.128 N.

Magnetizing the surfaces, will not affect the mass of the steel plate. Therefore, the magnitude of gravitational pull acting on steel plate remains the same, 2.97 N. Now the magnitude of the frictional force is greater than the force due to gravitational pull, so the steel plate remains static with respect to steel platform at an inclination 36.50°.

It was observed that in model 1 the magnetic flux through the steel platform to the steel plate is a small value, 0.01 T. This result in a small value of attractive force between steel plates. Improved field through plates can be achieved by completing a magnetic circuit in the design. This can be achieved by directing the magnetic field from the North to the South Pole of the magnet. Here the poles of the magnet must be effectively separated so that the field will span the gap [4]. Such a design is shown in Fig. 8 (model -2).

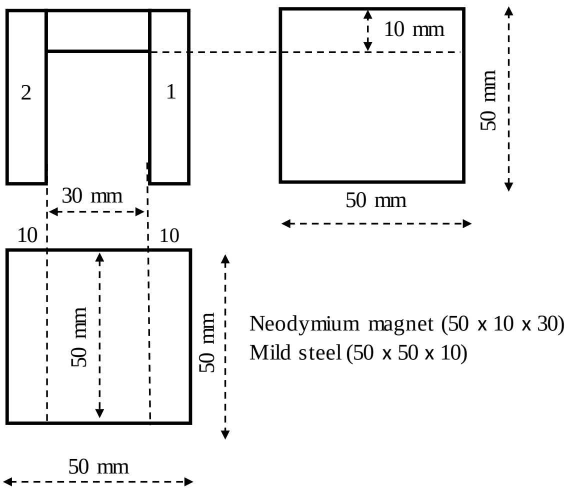



Fig. 7 Geometric characteristics of stand for model 2

In this research, a stand with two legs (Fig. 7) for designing model 2 is considered. The stand consists of two steel plate (section 1 and 2) as the legs of the stand. The steel plates are connected to each other by neodymium magnet. Neodymium magnet of grade 35 (dimensions 50 mm × 10 mm × 30 mm, and magnetization direction along 30 mm) is used for designing model 2.

The schematic presentation of model 2 is shown in Fig. 8, where the weight $W_1$ is acting on section 1 is and weight $W_{total}$ (total weight of the stand) is acting on section 2. In practical environment [9-11] the weight distributing among the legs depends on the change in inclination of the platform. So the weight on section 1 has to be the sum of the weight of section 1 and a part of other section's weight, which consist of section 2 and magnet attached to section 1.

For model 2, weight's distributions for the stand are: weight $W_1$ of section 1 and weight $W_2$ of section 2 is 1.923 N each and weight of magnet – 1.0731 N. Total weight of stand is $W_{total}$ = 4.9191 N.

It was found that minimum inclination $\Theta$ of platform required, for the stand to start sliding from steel platform is 45.83°.

The magnitude of frictional force $f_1$ at area of contact between section 1 and steel platform at an inclination 45.83°, without considering the flow of magnetic field through plates: $\mu_s W_1 \, cos\Theta = 0.992$ N.

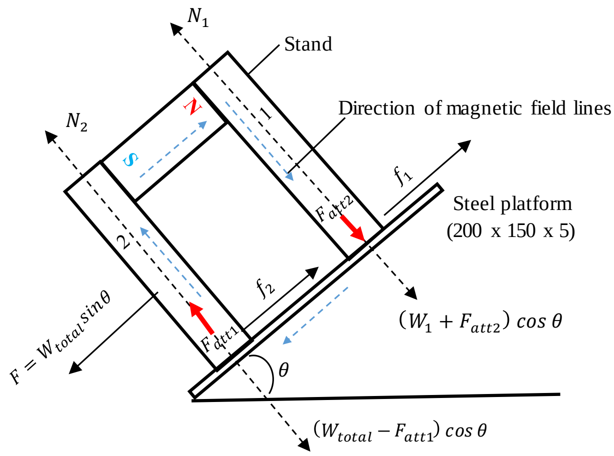



Fig. 8 Schematic representation of model 2

The magnitude of frictional force $f_2$ at area of contact between section 2 and steel platform at an inclination 45.83°, without considering the flow of magnetic field through plates: $\mu_s W_{total} \, cos\Theta = 2.536$ N. Therefore magnitude of frictional force: $f_1 + f_2 = 3.528$ N.

Force $F$ due to gravitational pull on stand, at an inclination 45.83°: $F = W_{total} \, cos\Theta = 3.528$ N, where the value of gravitational pull is equal to net frictional force. Hence the condition for sliding is satisfied and minimum inclination required is 45.83°.

Using FEMM 4.2 software model 2 is designed and simulated (Fig. 9) in order to study the magnitude of flux density passing through steel plates. Fig. 10 shows the flux density through section 2 and section 1, at the area of contact with the platform. Fig. 11 shows flux density through platform plate, at the area of contact with section 2 and section 1.

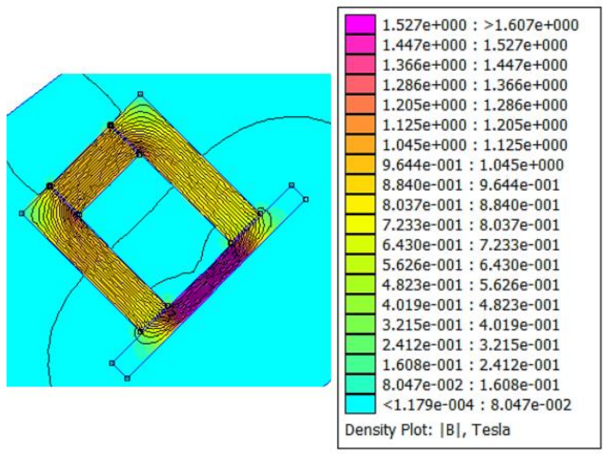



Fig. 9 Simulation results of model 2

The results obtained from graphs in Fig. 10 and Fig. 11 show that the magnetic flux density at the place where section 1 makes a contact with the platform is 0.66 T and the magnetic flux density at the place where section 2 makes a contact with platform is 0.72 T. From Eq. (1) and (2) the force of attraction between section 1 and platform is $F_{att1}$ = 86.7 N and the force of attraction between section 2 and platform is $F_{att2}$ = –103.13 N, here negative sign shows the direction of force is upward and opposite to the direction of $F_{att1}$.

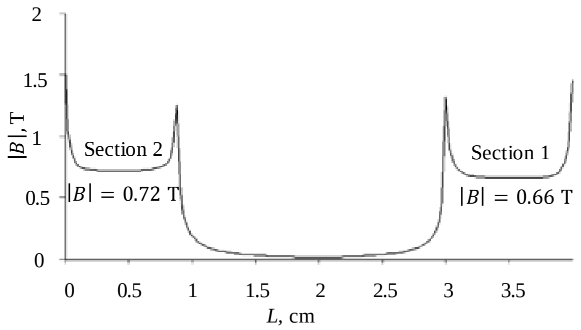



Fig. 10 Flux density through section 2 and section 1, at area of contact with platform

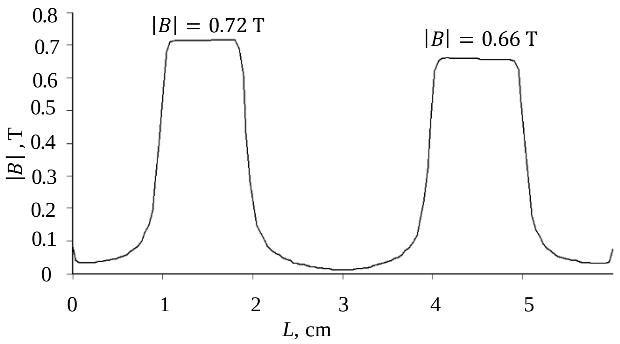



Fig. 11 Flux density through platform plate, at area of contact with Section 2 and Section 1

After solving for forces from Fig. 8, the net static friction with the presence of magnetic flux passing through steel plate and platform is given by:

$$\left.\begin{aligned} f_s &= f_1 + f_2 = \mu\left(W + F_{aat1}\right)cos\,\Theta - \mu\left(W - F_{aat2}\right)cos\,\Theta; \\ f_s &= \mu\,cos\,\Theta\left[\left(W + F_{aat1}\right) - \left(W - F_{aat2}\right)\right]. \end{aligned}\right\} \quad (6)$$

From Eq. (6) the net frictional force obtained as $f_s$ = –4.9 N. The negative sign shows that the net frictional force is acting upward and opposite to the direction of gravitational pull on stand is $F$ = 3.528 N. Now the magnitude of frictional force is greater than force due to gravitational pull, therefor the stand remains static with respect to steel platform at an inclination 45.83°.

## 3. Proposed method for interlocking of surface

Based on above experimental observations and from model 2 (Fig. 8) the frictional force between two highly permeable surfaces under the influence of magnetic field can be written as in Eq. (6).

A model for interlocking of the surface using magnetic latching is developed by using the result from the experiment. This is shown in the form of the block diagram in Fig. 12. Initially, static friction $f_s$ is greater than applied force $F$, and it results the steel plates to stay static or interlocked. When the applied force is greater than static friction, then the surface starts to move with respect to each other. The steel plates attracts each other with a force $F_{att}$ by the method of magnetic latching. This increases the magnitude of normal force $N = mg$ (where $m$ the mass of sliding object and $g$ acceleration due to gravity) acting between steel plates. Accordingly law of friction, the normal force is proportional to frictional force, so the magnitude of frictional force also increases with increase in the magnitude of the normal force, thereby the steel plates will be kept interlocked.

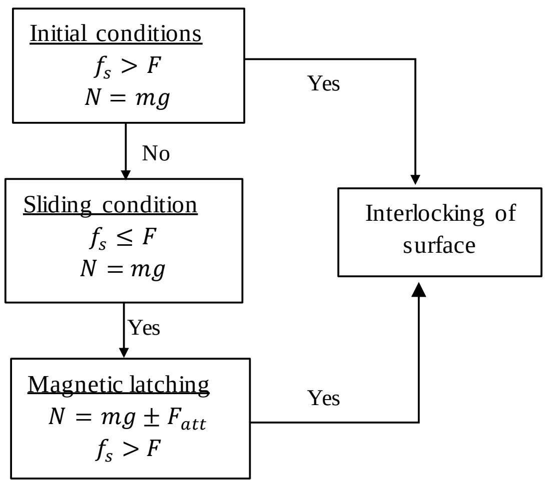



Fig. 12 Model for interlocking of the steel plates using magnetic latching.

The possible application of proposed idea can be implemented in Coulomb Damping. Where the magnitude of frictional force can be varied by varying the magnitude of magnetic field.

## 4. Conclusions

In this paper the friction between steel plates sliding over each other under the influence of magnetic flux passing through steel was experimented and results shows; that:

1. The magnitude of frictional force $f$ between steel plates can be improved by increasing the magnitude of normal force $N$. Where the magnitude of the normal force is improved by introducing force of attraction $F_{att}$ between steel plates by using the method of magnetic latching.

2. The force of attraction between two magnetized surfaces can be analyzed using magnetic circuit theory and Gilbert model.

3. The minimum inclination required for any value of the mass of steel plates to slide from each other under the effect of gravitational pull is $\theta$ = 36.50°. At the point of sliding the magnitudes of gravitational pull and frictional force are equal: $F = f$ = 2.97 N. When the steel plates are magnetized the magnitude of frictional force was analyzed as 3.128 N, which is greater than the magnitude of gravitational pull $F$ = 2.97 N. Since the magnitude of frictional force is slightly greater than magnitude of gravitational pull, this results that the steel plates can be in static with

respect to each other at an inclination $\Theta = 36.50°$ as was explained in model 1.

4. When the steel plates are magnetized using a permeant magnet, then the intensity of magnetic flux passing through steel plates can be increased by completing a magnetic circuit. That means the magnetic flux from magnet's North Pole is directed to magnet's South Pole by using steel plates. This is shown in the design of model 2. From model 1 and model 2 obtained simulation results can be stated that the magnitude of flux density between steel plates for model 1 is $|B| = 0.01$ T and for a completed magnetic circuit theory model 2 is $|B| = 0.69$ T (average value).

5. The minimum inclination required for the stand to slide from steel platform in the case of model 2 is $\Theta = 45.83°$. At the time of sliding it was observed that the magnitudes of gravitational pull and frictional force are equal: $F = f = 3.528$ N. The magnitude of frictional force, when magnetic flux is passing through steel plates, is calculated as 4.9 N, which is greater than the magnitude of gravitational pull $F = 3.528$ N. This results in keeping the stand static with respect to steel platform at an inclination $\Theta = 45.83°$.

Based on the above observations, a model for interlocking of steel plates was proposed and designed in the form of a block diagram.

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FRICTION BETWEEN STEEL PLATES UNDER THE INFLUENCE OF MAGNETIC FIELD

S u m m a r y

An idea to improve friction between two steel plates by directing the magnetic flux through steel plates are presented in this paper. For research, minimum inclination required for steel surfaces to start sliding and the magnitude of frictional force at the point of sliding was observed and compared with the nature of sliding while there is a flow of magnetic flux through the steel plates.

From the research observation, an idea to increase friction using varying magnetic field and thereby providing interlocking of the steel plates was proposed and designed in the form of block diagram.

**Keywords**: static friction, magnetic latching, magnetic circuit, the magnetic force of attraction, steel plates.

Received December 18, 2015
Accepted April 14, 2017