

## **Dual Coil Linear Motor with Compensated Cogging and Attraction Force**

### **Field of Invention**

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The present invention relates to a permanent magnet synchronous linear motor with compensated cogging force and attraction force, thereby giving superior performance and efficiency.

### **10 Prior Art**

Generally, there are 2 types of permanent magnet synchronous linear motors which are commonly used in the industry. These are the ironless linear motor (also called coreless linear motor) and the iron core linear motor. Ironless  
15 linear motor derives its name from the fact that it does not contain iron core or iron laminations in the coil. The coil comprises only copper wire formed or molded into a desired shape. Iron core motors on the other hand uses iron laminations to form a core where the copper wires are wound. The iron core helps to focus the magnetic flux onto the copper wire. Iron core linear motor  
20 provides much higher force than an ironless linear motor. It also uses less magnet material in the design compared to ironless motors, thereby making it more cost effective. However, there are 2 disadvantages of the iron core motor compared to the ironless linear motors. Firstly, a cogging force is present in iron core linear motors. This force is formed by the magnetic  
25 interaction of the magnets and the teeth of the iron core. It is a well known phenomenon in permanent magnet iron core motors. This cogging force is sometimes called parasitic force or reluctant force. This force is directed along the axis of motion of the linear motor and is present even when no electric current is passed through the motor coils. It disturbs the proper  
30 operation of the linear motor by interfering with the desired force from the motor, thereby also disturbing the required motion. Fig 1 illustrates the cogging force,  $F_c$  acting on an iron core linear motor. The direction of the force can be positive or negative, depending on the relative position of the coil and the magnet track. In other words, it adds to or reduces the desired  
35 force during motion or when the motor is stationary. While this interference can be counteracted by giving more current to the motor from the servo amplifier and controller, it reduces the performance of the linear motor, especially in increasing the settling time, which is the time it takes for the motor to come to rest within a desired position tolerance. In applications

which require high precision, where the position tolerance has to be within microns from the desired target position within a short time, this effect becomes very undesirable. Moreover, in applications where smooth velocity is required and critical, cogging force will have negative effects, causing the motor to have velocity ripple or uneven travel speed. Another disadvantage of the iron core linear motor is the presence of a very strong magnetic attraction force between the teeth of the iron core and the magnets. This is apparent since the gap between the teeth and the magnets is typically between 0.8 to 1.0 mm. This force and its direction are illustrated by  $F_a$ , as shown in Fig 1. In a typical iron core linear motor with a coil length of 200 mm and coil width of about 75 mm, the attraction force is about 1,450 N, or equivalent to 145 Kg of force. In a large iron core linear motor with a coil length of 700 mm and coil width of 220 mm, the attraction force is 23,000 N, or equivalent to 2,300 Kg of force. This attraction force is highly undesirable because very large bearing guide rails and runner blocks need to be installed to hold the coil against the magnet track. In large machines such as PCB drilling machines, multiple guide rails have to be used to mount the linear motor coil, to prevent the collapse or joining of the coil and magnet track and to maintain the air gap between the two parts. This also means that the mechanical parts that are used to hold the motor coil must also be very stiff and strong, resulting in bulky designs and reduced dynamic performance due to increase in mass. This attraction force also results in inefficiency of the linear motor as it increases friction during motion.

Various methods have been employed to reduce cogging force in iron core linear motors. One method is to skew the magnets on the magnet track. By slanting the magnets at an angle, this cogging force will be reduced, although the reduction is not very significant. Another commonly used method is to skew the iron laminations on the coil portion, which gives the same effect as skewing the magnets. While this method of skewing the magnets or the laminations can reduce cogging force to a certain extent, it does not address the problem caused by the attraction force. It also reduces the efficiency of the motor, since the magnetic flux is not fully optimized through the skewing of the magnets.

Another commonly used method is the addition of 2 auxiliary teeth at the ends of the iron core linear motor. This is illustrated in Fig 2, where 5a and 5b are the auxiliary teeth. U.S. Patent No. 5,910,691 describes such a design where two auxiliary teeth (5a,5b) are added to an iron core linear motor. The

auxiliary teeth (5a,5b) are designed with a slanted angle. With a certain optimized angle, the cogging force can be reduced to a minimum, even though it cannot be eliminated completely. U.S. Patent No. 4,912,746 uses auxiliary teeth (5a,5b) in the shape of a triangular wedge to reduce cogging  
5 force. U.S. Patent No. 6,831,379 B2 also describes a linear motor with a 8 pole and 9 slot design, and 2 auxiliary teeth (5a,5b) are also added to the ends of the linear motor coil. By optimizing the length of the auxiliary teeth (5a,5b) with respect to the main teeth and the distance between these 2 auxiliary teeth (5a,5b), it has been shown that the cogging force can be  
10 minimized as well. With this method of adding auxiliary teeth (5a,5b), while the cogging force can be reduced, the attraction force between the coil and the magnet track is still not reduced or eliminated. In fact, the auxiliary teeth (5a,5b) only increase the attraction force.

15 U.S. Patent No. 6,476,524 B1 describes another method whereby at least 2 or 3 linear motor coils are arranged in series. Each individual motor coil is made up of 8 poles and 9 slots. By varying the gap or space between the individual coils to a fraction of the magnetic pitch, it has been shown that the net cogging force can be completely eliminated by superimposing the cogging  
20 force caused by the individual coils. However, with this design, the minimum coil length of the linear motor is the length of at least 2 linear motor coils, or the equivalent of 16 poles. This makes the linear motor coil very long and not suitable for applications where the moving carriage has space or length limitation. Moreover, this method does not solve the problem caused by the  
25 attraction force between the linear motor coil and the magnet track.

PCT/NL2005/000029 describes a modular linear motor comprising a number of magnets of alternating polarity placed successively in a plane; at least two successively placed coil modules which modules comprise a stack of  
30 parallel plates form, each provided with at least three parallel fingers, and electric coils arranged around the fingers, where the at least two modules are arranged at a distance from each other. This prior art document describes the "cogging effect" of linear motors is hereby reduced when the lamination stacks of the different coil modules are thus not in contact but  
35 have a certain distance between them. However, this prior art document failed to describe the "certain distance" nor suggest neutralizing the "cogging effect".

**Problem to be solved by the invention**

The inventors had observed that the cogging force produced by the linear motor as it moves through one cycle has a period of 60 electrical degrees or an equivalent of the distance of  $1/3$  of the magnetic pitch. By building  
5 2 opposing track assemblies which are intentionally offset from each other with a distance of  $1/3$  magnetic pitch, the cogging force  $F_{c1}$  produced by the top linear motor coil is counterbalanced or compensated by the cogging force  $F_{c2}$  produced by the bottom linear motor coil. The net attraction force as  
10 seen by the load on which the two linear motors are thus arranged, is effectively zero. In other words, the opposing cogging forces are mutually cancelled

These and still other objects, which are made apparent in the following  
15 disclosure and description of the invention, are attained in the present invention.

**Summary Of The Invention**

20 A first object of the invention is a dual coil linear motor having

a first set of one or more linear motor coils assembled from the same reference position, to form a first magnet track assembly,

25 a second set of one or more linear motor coils assembled from the same reference position, to form a second magnet track assembly,

wherein each one or more linear motor coils in the first set is diametrically opposed and corresponds to each one or more linear motor coils of the  
30 second set, and each linear motor coil in the first set and each corresponding linear motor coil in the second set are offset by a distance of  $1/3$  the magnetic pitch,  $P_m$  such that the dual coil linear motor produces net zero cogging force and attraction force.

35 A second object of the invention is a dual coil linear motor having

a first linear motor coil assembled from the same reference position, to form a first magnet track assembly,

a second linear motor coil assembled from the same reference position, to form a second magnet track assembly,

5 wherein the first magnet track assembly and the second magnet track assembly are diametrically opposite each other and are offset from each other by the distance of  $1/3$  the magnetic pitch,  $P_m$  such that the dual coil linear motor produces net zero cogging force and attraction force.

10 Preferably the dual core linear motor having a first magnet track assembly, and a second magnet track assembly are mounted on a mounting plate.

Preferably the mounting plate is an aluminum plate.

15 Preferably the dual coil linear motor has a plurality of ducts in the mounting plate for water to pass through to cool the dual coil linear motor.

#### **Brief description of Drawings**

20 For a better understanding of the invention, its advantages, and the objects attained by its use, reference should now be made to the accompanying drawings. The accompanying drawings illustrate one or more embodiments of the invention and together with the description herein, serve to explain the workings and principles of the invention.

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Fig 1 shows a conventional linear motor.

Fig 2 shows another type conventional linear motor.

30 Fig 3 shows the cogging force produced by the linear motor when it moves through one electrical cycle.

Fig 4 shows a configuration where 2 linear motor coils are assembled opposite and facing each other.

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Fig 5 shows the cogging force for a configuration of Fig. 4

Fig 6 is a cross section of the preferred embodiment.

Fig 7 shows the magnetic circuits of the linear motors.

Fig 8 shows another embodiment of this invention.

- 5 Fig 9 shows the use of mounting plates to join the 2 linear motors and to strengthen the mounting of the 2 linear motor coils

Fig 10 shows a complete module using this configuration proposed in Fig. 9

- 10 Fig 11 shows another embodiment where the linear motor coil mounting plate is designed with water channels to allow water cooling of the linear motor.

#### Description of Preferred Embodiment of Invention

- 15 Referring back to Fig 1, a conventional dual coil linear motor using a 8 pole, 6 slot design is shown. The linear motor coil (1a,1b) is formed by stacks of iron laminations and the copper coil (2) are formed around the slots of the linear motor coil (1a,1b). Permanent magnets (3) are assembled on a back iron (4). The magnetic pitch,  $P_m$  is the distance between one magnet (3) and another. 2 magnets (3) will form one complete electrical cycle, or 360 electrical degrees. The cogging force produced by the dual coil linear motor when it moves through one electrical cycle is shown in Fig 3, where 6 repetitive cycles are observed over one complete electrical cycle of 360 electrical degrees. This means that each of those repetitive cycles has a period of 60 electrical degrees, or an equivalent of the distance of 1/3 of the magnetic pitch.
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- Fig 4 shows a configuration where 2 linear motor coils (1a,1b) are assembled opposite, facing each other. There are 2 magnet track assembly (6a,6b), one for each linear motor coil (1a,1b), separated by an aluminum track mounting piece (7). It should be noted that the 2 magnet track assemblies (6a,6b) are intentionally offset from each other with a distance of 1/3 magnetic pitch.
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- Referring to Fig 5, with such an arrangement, the cogging force  $F_{c1}$  produced by the top linear motor coil (1a) is counterbalanced or compensated by the cogging force  $F_{c2}$  produced by the bottom linear motor coil (1b).
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As shown in Fig 6, which is a cross section view of the embodiment, the 2 linear motor coils (1a,1b) can be mechanically connected by a mounting plate

(8) where the load is to be mounted. The linear motor coil (1a,1b) can also be electrically connected together, either in parallel or in series. This means that the 2 linear motor coils (1a,1b) can be seen effectively as a single linear motor coil and be driven by one single servo amplifier, with the same current  
5 passing to or through the linear motor coil (1a,1b), depending on whether a series or parallel connection is used.

Other than compensating the cogging forces, it can be seen from Fig 4 that the attraction forces Fa1 and Fa2 acts in opposing direction. By mounting the  
10 2 linear motor coils (1a,1b) in this configuration, the net attraction force as seen by the load on the mounting plate (8) which joins the 2 linear motors (11a,11b) is effectively zero. In other words, the 2 attraction forces are also mutually cancelled.

15 Fig 7 shows the magnetic circuits of the linear motors (11a,11b). Since the aluminum track mounting plate (7) is non magnetic, and both linear motors (11a,11b) are separated by this piece, the magnetic circuit of the top motor (9a) and the magnetic circuit of the bottom motor (9b) are separate. There is no interference between the 2 magnetic circuits.

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Fig 8 shows another embodiment of this invention whereby instead of offsetting the magnetic track assemblies (6a,6b), the linear motor coil assemblies (10) are offset by the same distance, which is 1/3 of the magnetic pitch or 60 electrical degrees. The effect of this configuration is the same as  
25 that described in Fig 4.

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To strengthen the mounting of the 2 linear motor coils (1a,1b), end plates (15) are used to join the 2 linear motor coils (1a,1b), as shown in Fig 9. These end plates (15) also made of aluminum are very stiff in the lateral  
30 direction and helps to maintain the air gap between the linear motor coil (1a,1b) and the magnet track assembly (6a,6b).

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A complete module using this configuration is shown in Fig 10, where the linear motor coil assembly (10) is mounted in the center of the module on  
35 carriage plate (12), with 2 guide rails (13) on each side on the linear motor assembly (10). The carriage plate (12) is actually joined to the top of the mounting plate (8). With this design, the size of the guide rails (13) can be significantly reduced compared to the conventional dual coil linear motors, due to the net zero attraction force acting on the guide rails (13). The guide

rails (13) are just used to support the load and guide the linear motors (11a,11b) in the direction of motion. Such a design can be used in applications such as PCB drilling machines and machine tools.

- 5 Fig 11 shows another embodiment where the linear motor coil mounting plate (8) is designed with water channels to allow water cooling of the linear motors (11a,11b). Although copper coils (2) can typically operate up to 130 degrees, cooling is necessary for applications where it is not desirable to have heat being transferred to the load. In conventional designs, water
- 10 cooling tubes (14) are typically installed within the linear motor coils (1a,1b) to provide cooling. This method makes the manufacturing process very expensive and tedious, as care needs to be taken to properly isolate the cooling fluid from the copper coil (2) where electric currents are passed. Any
- 15 leakage will cause shorting and failure of the linear motor coil (1a,1b). This method also takes up useful space on the linear motor coil (1a,1b), replacing some of the copper coils (2) in the limited space available between the slots of the linear motor coil (1,1b). In our design, by machining the mounting plate (8) to incorporate cooling channels, manufacturing costs is significantly reduced, and more space is available for the windings of the copper coil (2),
- 20 thereby making the dual coil linear motor more efficient. Any replacement of linear motor coil (1a,1b) or worn out parts is also possible with this modular design.

- Having described preferred embodiments of the invention with reference to
- 25 the accompanying drawings, it is to be understood that the invention is not limited to those precise embodiments, and that various changes and modifications may be effected therein by one skilled in the art without departing from the scope or spirit of the invention as defined in the claims.

### 30 Advantageous Effects of the Invention

- The cogging forces interferes with the proper operation of the linear motor (11a,11b) by reducing the desired force output from the motor. In so doing, the cogging forces reduces the efficiency of the linear motors
- 35 (11a,11b). By effectively cancelling the cogging forces, the linear motor (11a,11b) becomes more efficient and uses less energy in the process. Savings in energy costs as well as higher productivity will accrue to this invention.

Claims:

1. A dual coil linear motor having

5           a first set of one or more linear motor coils (1a) assembled from the same reference position, to form a first magnet track assembly (6a),

          a second set of one or more linear motor coils (1b) assembled from the same reference position, to form a second magnet track assembly (6b),

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wherein each one or more linear motor coils (1a) in the first set is diametrically opposed and corresponds to each one or more linear motor coils of the second set (1b), and each linear motor coil in the first set (1a) and each corresponding linear motor coil in the second set (1b) are  
15       offset by a distance of  $1/3$  the magnetic pitch,  $P_m$  such that the dual coil linear motor produces net zero cogging force and attraction force.

2. A dual coil linear motor having

20           a first linear motor coil (1a) assembled from the same reference position, to form a first magnet track assembly (6a),

          a second linear motor coil (1b) assembled from the same reference position, to form a second magnet track assembly (6b),

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wherein the first magnet track assembly (6a) and the second magnet track assembly (6b) are diametrically opposite each other and are offset from each other by the distance of  $1/3$  the magnetic pitch,  $P_m$  such that the dual  
coil linear motor produces net zero cogging force and attraction force.

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3. A dual core linear motor having a first magnet track assembly (6a), and a second magnet track assembly (6b) as claimed in Claim 1 or 2, wherein the first magnet track assembly (6a) and second magnet track assembly (6b) are mounted on a mounting plate (8).

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4. A mounting plate (8) as claimed in Claim 3 wherein the mounting plate (8) is an aluminum plate.

5. A dual coil linear motor having a plurality of ducts in the mounting plate (8) for water to pass through to cool the dual coil linear motor.

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