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**Giovanardi**

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(54) **DETENT FORCE CORRECTING**

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(52) **U.S. Cl.** ..... **310/12.22; 310/12.24; 310/12.25; 310/12.26**

(58) **Field of Classification Search** ..... **310/12, 310/12.22, 12.24, 12.25, 12.26**  
See application file for complete search history.

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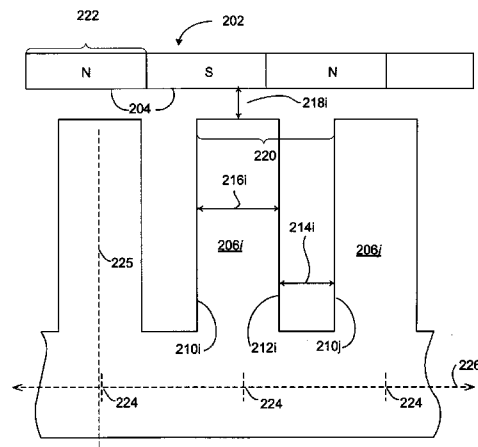
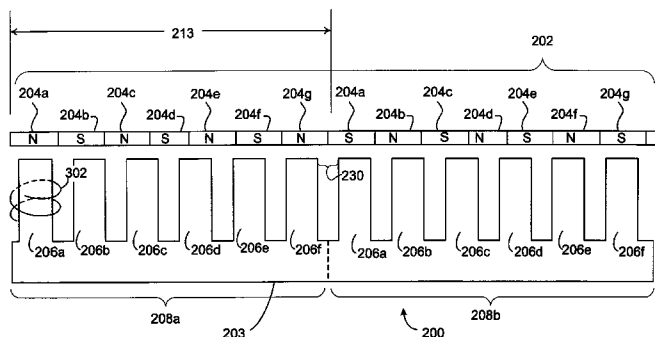
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(57) **ABSTRACT**

An apparatus comprises a linear electromagnetic actuator which has a series of ferromagnetic poles, coils, and a series of permanent magnets to interact with the poles to induce movement of the actuator along a path. The poles have non-uniform configurations.

**4 Claims, 7 Drawing Sheets**



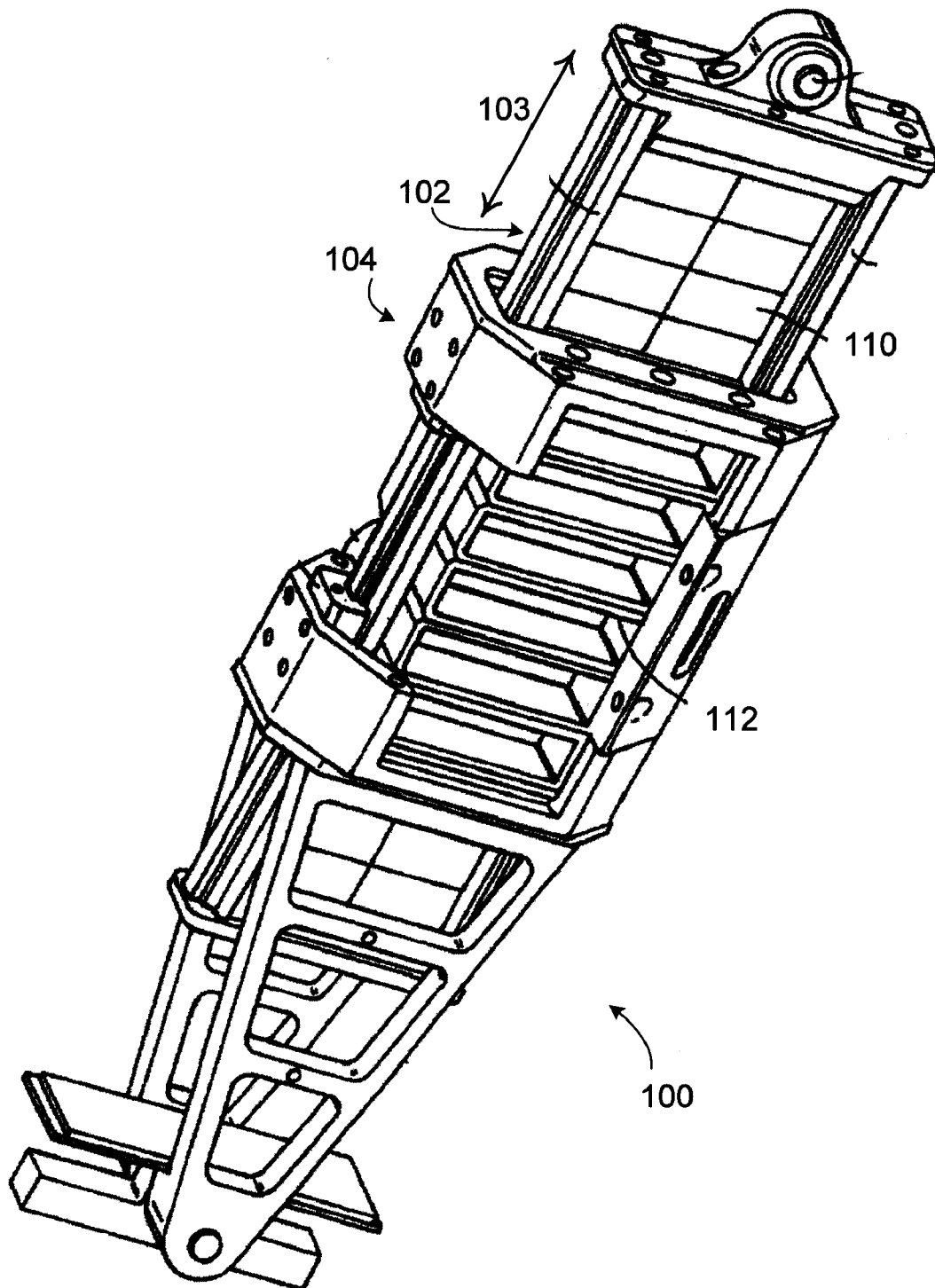


Fig. 1

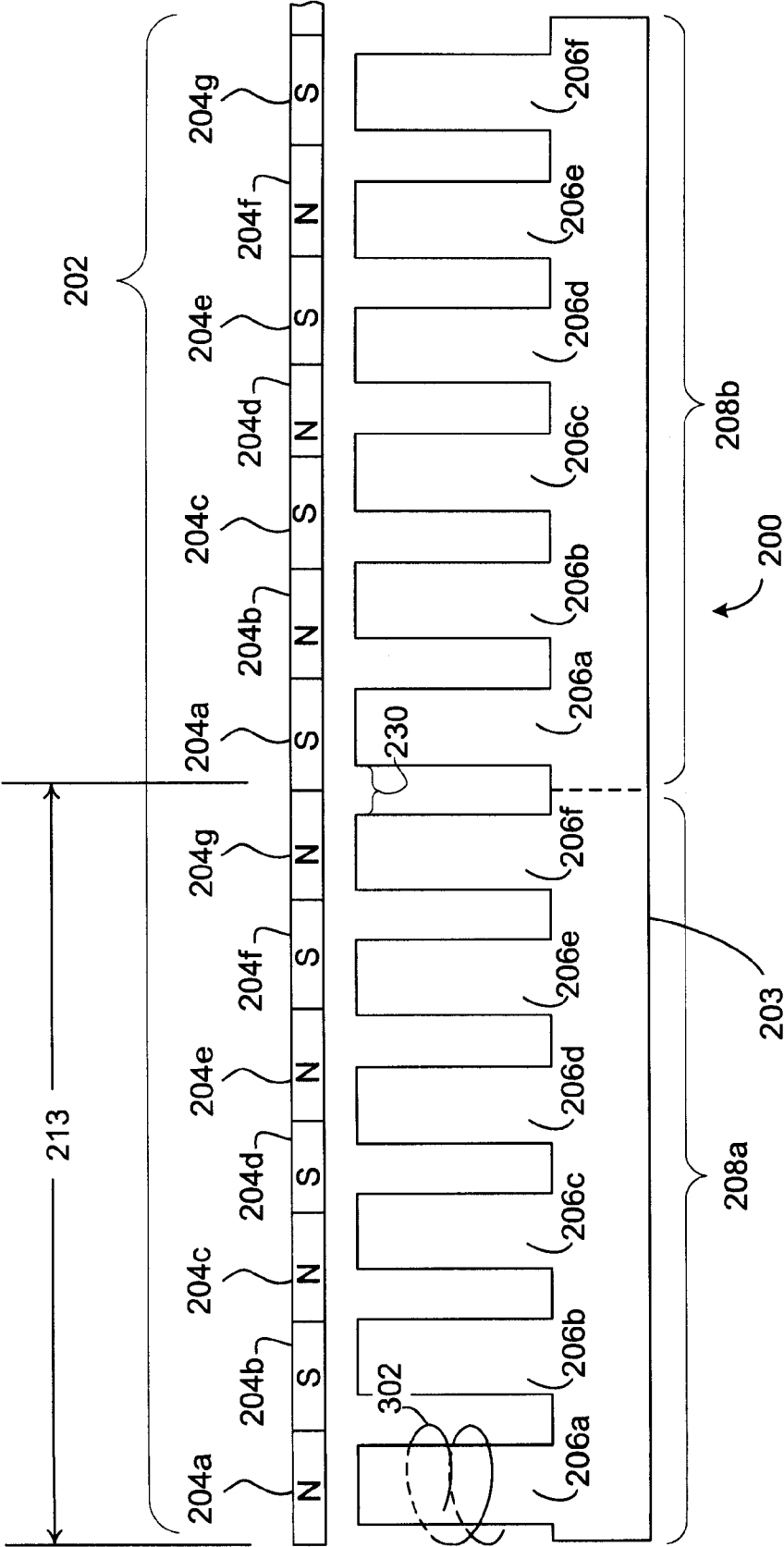
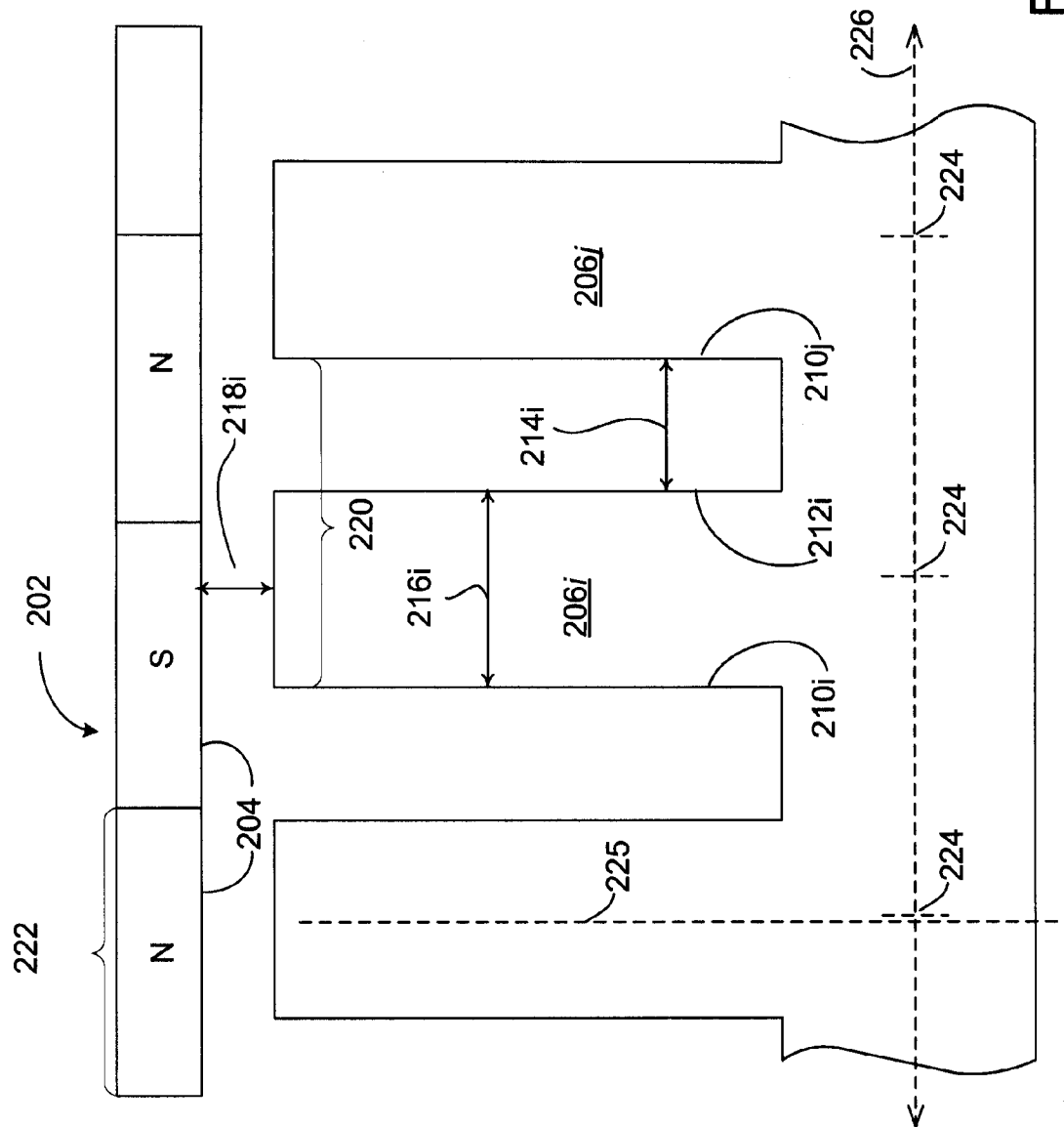


Fig. 2A



**Fig. 2B**

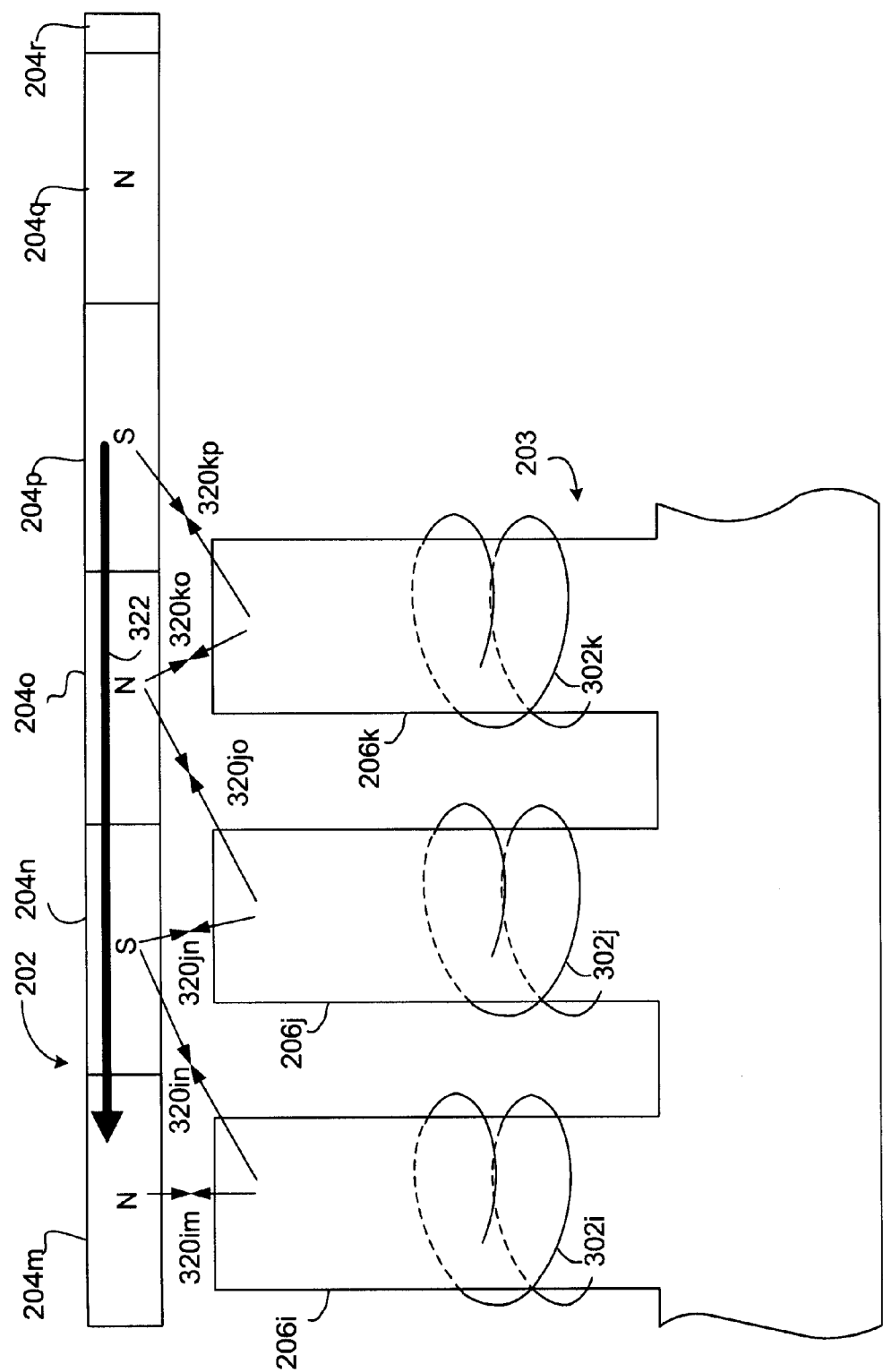


Fig. 3

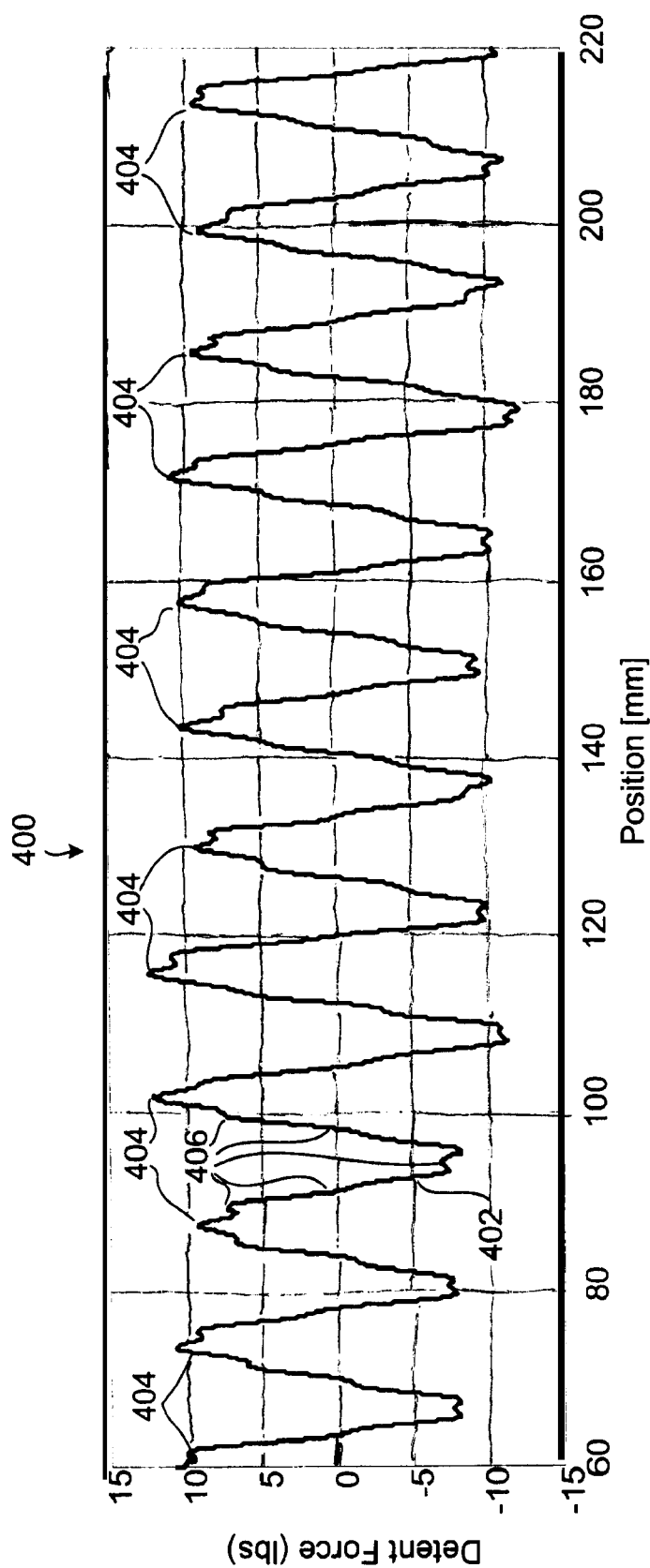


Fig. 4

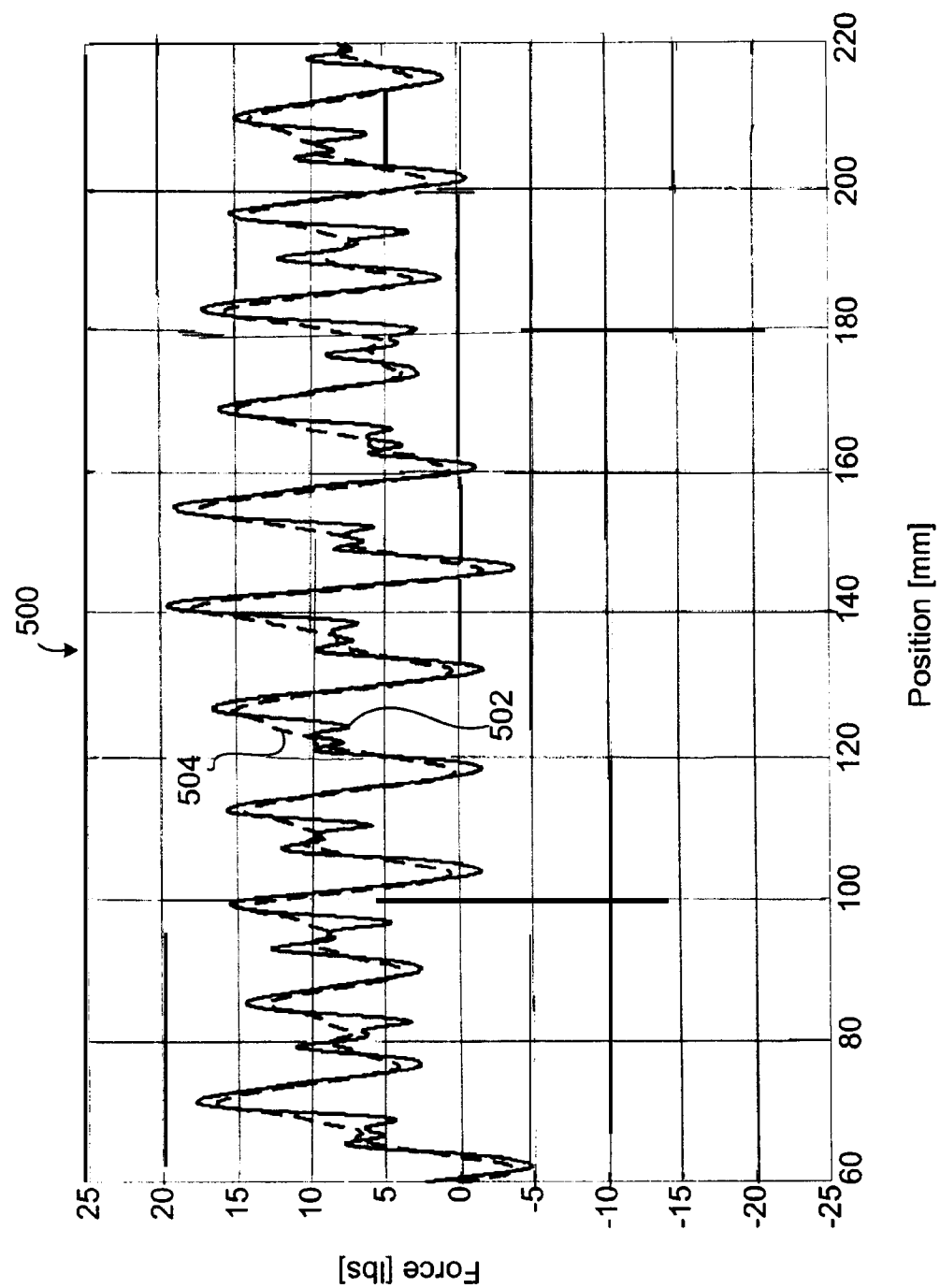


Fig. 5

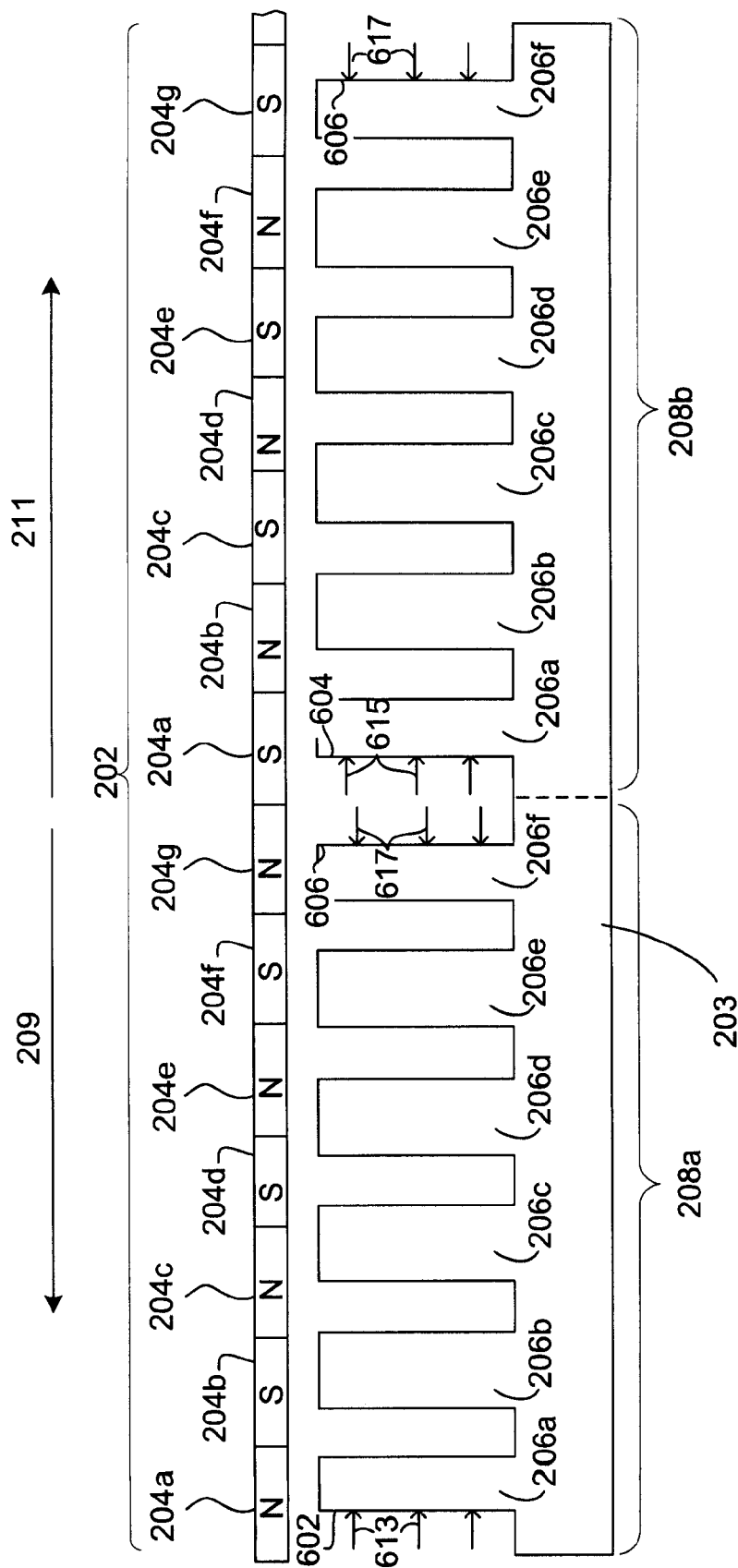


Fig. 6



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## DETENT FORCE CORRECTING

## BACKGROUND

This disclosure relates to detent force correcting.

In typical linear electromagnetic actuators, for example, the detent force tends to oppose motion of the moving element of the actuator relative to the stationary element of the actuator and is sometimes overcome using energy to apply an opposing force.

One proposed way to compensate for detent force in linear electromagnetic actuators was to add additional, smaller, poles before the first and after the last poles in a series of poles. Another approach included skewing the shapes of the poles to distribute magnetic forces more evenly, as shown in U.S. Pat. No. 5,701,039, which is incorporated here by reference.

## SUMMARY

In general, in one aspect, a linear electromagnetic actuator has a series of permeable poles and a series of electromagnets to interact with the permanent magnets to induce movement of the permanent magnets along a path, and the poles have non-uniform configurations.

Implementations may include one or more of the following features. The non-uniform configurations reduce a detent force that occurs along the path. The non-uniform configurations do not substantially affect a force output of the actuator over a range of motion of the actuator. The non-uniform configurations of the poles include different widths of the poles. The widths of the poles vary such that detent forces between the poles and the permanent magnets are of lesser variation than those which would result from uniform widths. Each pole is associated with one of a set of commonly-spaced points along the path, and the non-uniform configurations of the poles include an offset of one of the poles' centers from the commonly-spaced point by an amount that differs from the amount that another pole's center is offset from the commonly-spaced point associated with that pole. The series of poles includes repeating sets of poles, and each pole of each set has the same configuration as a corresponding pole of each other set. Each set of poles includes two symmetric subsets of poles. Each pole is associated with one of a set of commonly-spaced points, the poles each have a first edge and a second edge, and poles in a set of at least some of the poles are positioned such that the first edge of each pole in the set is a different distance from the commonly-spaced point associated with that pole than the first edge of another pole is from the commonly-spaced point associated with that other pole. The second edge of each pole in the set is the same distance as the first edge of that pole from the commonly-spaced point associated with that pole. The second edge of each pole in the set is also a different distance from the commonly-spaced point associated with that pole than the second edge of another pole is from the commonly-spaced point associated with that other pole.

In general, in one aspect, a linear electromagnetic actuator including poles having non-uniform configurations is driven, and a detent force between an armature and a stator of the actuator is reduced so that a force output of the actuator is substantially constant over a range of motion of the actuator.

In general, in one aspect at least some of poles of a linear electromagnetic actuator are configured differently from other poles to reduce a detent force that occurs when an armature of the actuator is moved along a path.

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Implementations may include one or more of the following features. The poles are configured to reduce differences in the detent force that occur between different positions of the armature. Configuring the poles differently includes configuring the poles to have different widths.

In general, in one aspect, an active suspension system for a vehicle includes a linear electromagnetic actuator having a series of poles and a series of electromagnets to interact with a series of permanent magnets to induce movement of the permanent magnets along a path, while the poles have non-uniform configurations. A mounting assembly couples the actuator between the body of the vehicle and a wheel assembly.

Advantages include reducing the energy required to overcome passive detent forces in a linear motor and improving the smoothness of the operation of a linear motor.

Other features and advantages will be apparent from the description and from the claims.

## DETAILED DESCRIPTION

FIG. 1 is a perspective cut-away view of an actuator.

FIGS. 2A and 6 are schematic views of actuators.

FIGS. 2B and 3 are schematic views of sections of actuators.

FIGS. 4 and 5 are graphs.

A linear electromagnetic actuator **100**, as shown in FIG. 1, can be used in a suspension of a vehicle, for example, between the body of the vehicle and a wheel assembly in place of a shock absorber. The actuator **100** includes an armature **102** that moves back and forth (as indicated by arrows **103**) and outer housing **104** (shown with its outer cover removed). In general, linear actuators can be used in any applications where a linear force is useful.

The armature comprises a set of permanent magnets **110**. The housing supports a corresponding set of electromagnets including coils **112** which produce magnetic fields when current is passed through them. The magnetic fields produced by the coils **112** interact with the magnetic fields of the permanent magnets **110** to produce a force which moves the armature **102** relative to the housing **104**. The electromagnets composed of coils **112** and other electromagnetic components such as poles the coils are wound around (not shown) within the housing **104** make up the stator of the actuator **100**.

As shown schematically in FIG. 2A, in some examples, a linear electromagnetic actuator **200** has an armature **202** including permanent magnets **204** and a stator **203** including ferromagnetic teeth or poles **206**. Coils **302i**, **302j**, and **302k** as shown FIG. 3, are wrapped around individual poles to form electromagnets. (In some examples, the permanent magnets are part of the stator and the poles and coils are part of the armature.) It should be noted that what is shown in FIG. 2A is half of a symmetric actuator structure, another mirrored half along a first horizontal symmetric axis of the permanent magnets is not shown (two-sided armature). It also should be noted that although what is shown and described is in light of a symmetric two-sided actuator, the description is also applicable to one-sided actuator structures.

In some examples, the poles are arranged in repeating sets **208a**, **b** of poles **206a-f**—symmetric along a second vertical axis. The poles **206** and the permanent magnets **204** are sized and arranged such that different numbers of poles and magnets fit within a given length of the actuator. In the example of FIG. 2A, one set of six poles **206a-f** align with seven permanent magnets **204a-g** within a length **213** of the actuator. The same ratio of poles to permanent magnets exists for each of the repeating sets **208a** and **208b**.

In operation, currents are applied to the coils **302** to form electromagnets generating magnetic fields which interact with magnetic fields of the permanent magnets **204**. As shown in FIG. 2B, each pole **206i** has a first edge **210i** and a second edge **212i**. Each pole **206i**, has a width **216i**, is separated from the next pole by a distance **214i**, and is a distance **218i** from the armature **202**. The distance **220** from the first edge **210i** of one pole **206i** to the first edge **210j** of the next pole **206j** is referred to as pole pitch. The distance **222** from one end of one permanent magnet **204** to the same end on the next permanent magnet **204** is the magnet pitch. The poles **206** are associated with respective evenly-spaced center points **224** along an axis **226** that runs along the length of the actuator in the direction of motion. As explained below, the poles **206** are not necessarily centered over the center points **224**, that is, the midline **225** of a pole does not necessarily contain one of the center points **224**.

The total force exerted on the armature can be divided into two components: one component is the energized force created by electrical currents flowing through the coils; the other component is the passive force created by the interaction of the permanent magnets with the ferromagnetic stator materials. The passive horizontal force, also known as detent force, varies in magnitude and direction. At any given position of the armature with respect to the stator, the armature may thus be pushed or pulled in a certain direction. In a typical configuration, there will be equilibrium points, that is, locations with no detent force present, and the armature will be biased towards those locations.

During operation, as the armature is moved along the stator, certain components of the detent force will variably aid or oppose the desired motion, thus tending to make it less smooth. This is sometimes referred to as cogging, and the detent force as the cogging force.

In the example of FIG. 3, pole **206i** is near permanent magnet **204m**, so a strong force **320im** exists between them. The force **320in** between pole **206i** and permanent magnet **204n**, on the other hand, is much weaker. The forces **320jn**, **jo**, **ko**, and **kp** between the other poles **206j**, **206k** and permanent magnets **204n**, **204o**, **204p** are similarly varied, with current flowing in opposite directions in alternating poles for alternating magnetic polarities, resulting in net detent force **322**. If the armature **202** is pushed by some external force toward a position other than an equilibrium point, the detent force will oppose that movement and tend to push or pull the armature back to an equilibrium point. When the actuator is in operation, the detent force is still present, and will interfere with the goal of smooth linear movement of the armature.

What is described herein is a way of reducing the detent force by changing the design of the actuator. In some examples, changes are made to the poles, for example, to their configurations, to decrease and smooth the detent force. By changing the configurations, we mean that the dimensions, spacing, or shape of one or more of the poles can be modified from the nominal, within the normal manufacturing tolerances of the uniformly-sized, evenly-spaced, rectangular configuration shown in FIG. 2B. Different modifications are made to different poles resulting in the poles having non-uniform configurations.

In some examples, the changes are made so that collectively, they reduce the detent force, but they do not change the force output of the actuator. This can be done by assuring that individual changes are small—small changes in each of the poles can result in significant changes to the detent force without significantly increasing or decreasing the force output during active operation.

In a linear electromagnetic actuator, the detent force is essentially periodic with the position of the armature, as the arrangement of poles and permanent magnets that results in an equilibrium position tends to repeat. For example, in FIG. 3, if the armature moves the length **222** (FIG. 2B) of one magnet, then the same detent forces will exist between the poles **206i-k** and the permanent magnets **204n, o, p**, and **q** that existed in the original position. This periodic force has a fundamental spatial frequency reciprocal to the length **222** of each of the individual permanent magnets. Because the stator is not infinite in length (as is effectively the case in a rotary motor), the forces acting on the last pole at each end are not the same as those in the middle, and the magnitude of the net detent force **322** is not uniform in strength as the armature moves with respect to the actuator, as shown in FIG. 4.

In the example above, where there are six poles for seven permanent magnets, the detent force exhibits a significant sixth harmonic component, at six times the fundamental spatial frequency. A graph **400** shows the measured detent force in one actuator, with a curve **402** showing the detent force as a function of the position of the armature along its potential range of movement along the length of the actuator. In this example, each set of the repeating sets of seven permanent magnets or six poles is 98 mm long (14 mm magnet pitch, 16.3 mm pole pitch). The peaks **404** are spaced apart by the width of the permanent magnets, indicating that they correspond to the fundamental spatial frequency (first harmonic), the reciprocal of magnet pitch **222**. Minor peaks **406** occur five times between the major peaks **404**, indicating the presence of a strong sixth harmonic component in curve **402** (either of the adjacent peaks **404** comprising the sixth minor peak). In graph **400**, non-periodic forces that might affect measurement of the detent force, such as those resulting from eddy currents and friction, have been removed.

In some examples, increasing the spacing **230** between the two repeating sets **208** (FIG. 2A) of poles produces a reduction in the sixth harmonic component of the detent force. An increased spacing **230** that corresponds to  $\frac{1}{12}$  th of the magnet pitch puts the 6th harmonic components of the detent forces resulting from the two sets **208** of poles out of phase, thus canceling that component. As shown in FIG. 5, a graph **500** shows the detent force as a function of the position of the armature for actuators with and without a gap between the two sets of poles. Curve **502** (solid line) is the detent force in the actuator without the gap, and curve **504** (dashed line) is the detent force in the actuator with the gap.

In some examples, in addition to or instead of adding a gap between the sets of poles, individual poles can be modified. For example, referring back to FIG. 2B, the width **216** of a pole can be changed, and the center **225** of the pole can be shifted from its nominal center point **224**. In some examples, these changes are described in terms of moving individual edges **210, 212** of the poles rather than in terms of their widths **216** and centers **225**. Non-uniform configurations of poles include examples in which at least two poles (and possibly more than two or even all of the poles) intentionally have different configurations that are chosen to produce particular effects on the detent force. In some examples, adjacent poles have different (that is, non-uniform) configurations, and there may be patterns of non-uniform configurations among the different poles of the actuator.

In some examples, the symmetry and periodicity of the sets of poles is used to determine changes to their configurations. For example, the changes that are made to the poles of one set can also be made to corresponding poles in the other set, as shown in FIG. 6. In the example of FIG. 6, the left edge **602** of the first pole **206a** of the first set **208a** is shifted by a certain

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amount (arrows **613**), and the left edge **604** of the first pole **206a** of the second set **208b** is shifted by the same amount and in the same direction (arrows **615**).

Each set **208** experiences symmetrical behavior for motions of the actuator **202** in each of the two opposite directions **209**, **211** (shown by arrows), because as the permanent magnets **204** approach the first pole **206a** from the left (when moving right in FIG. 6), they experience the same magnetic effects as permanent magnets **204** approaching the last pole **206f** from the right (when moving left in FIG. 6). For this reason, to reduce the detent force, opposite changes are made to the poles in the second half of each set to the changes made in the first half. For example, if pole **206a** in each set **208** has its left edge **602** repositioned towards the center of the pole (arrows **613**, **615**) by some amount, then pole **206f** in each set **208** has its right edge **606** repositioned towards its center (arrows **617**) by the same amount.

The result of the periodic and symmetric constraints on changes to the poles is shown in table 1 for a three-phase actuator with six poles in each of two sets. The description is applicable to any number of phase actuators. In table 1, each column represents one potential change, and the rows for that column indicate which poles are changed together, and which edge of each is changed. All the edges indicated in one column are moved the same amount, either toward or away from the center of the pole. For example, column 3 indicates that if the left edge of pole **2** is moved, then the left edge of pole **8** and the right edges of poles **5** and **11** are moved by the same amount. The changes indicated in different columns can be combined to determine changes to all the poles.

TABLE 1

Pole	Edge to change					
	1	2	3	4	5	6
Pole 1	Left	Right				
Pole 2			Left	Right		
Pole 3					Left	Right
Pole 4					Right	Left
Pole 5			Right	Left		
Pole 6	Right	Left				
Pole 7	Left	Right				
Pole 8			Left	Right		
Pole 9					Left	Right
Pole 10					Right	Left
Pole 11			Right	Left		
Pole 12	Right	Left				

In some examples, the end poles **206a** and **206f** are modified the most, and the center poles **206c** and **206d** are modified the least, with the intermediate poles **206b** and **206e** modified an intermediate amount. In some examples, the inner and outer poles are adjusted similarly, and the intermediate poles are adjusted differently. In some examples, the changes

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exhibit a pattern based on the fundamental frequency of the actuator so that changes to the detent force resulting from the changes to the configuration will have components with the same harmonic frequencies as the original detent force, and be able to cancel them out. If the changes in detent force were at a different frequency than the harmonic components of the detent force, they might decrease it in some locations but increase it in others.

Although the configuration of the poles has been described in terms of “moving” edges or otherwise changing their geometry, in practice these changes may be made as part of the design process, and a set of poles may be manufactured as a single piece with the poles shaped and positioned in the manner described from the outset. This has the advantage of avoiding manufacturing variations that might arise if the poles were modified from a standard shape during production. Because the changes to any single pole are small, manufacturing variations could offset any intended change from the nominal dimensions.

Other embodiments are within the scope of the following claims.

What is claimed is:

1. An apparatus comprising:

a multiple phase linear electromagnetic actuator with a stator having repeating sets of ferromagnetic poles and corresponding sets of coils, for interacting with an armature having corresponding sets of permanent magnets to induce movement of the armature along a path, wherein; each pole is associated with one of a set of evenly spaced center points along an axis that runs along the length of the actuator in the direction of motion, and;

a plurality of poles of a first set of poles are modified by either one or both of non-uniformly varying the displacement of the centers of the poles with respect to each associated center point and non-uniformly changing the width of the poles, wherein the modifications to the plurality of poles within the first set of poles are made symmetrically with respect to a nominal center of the first set of poles, and wherein:

the modifications to the poles are small such that they do not substantially change the force output of the actuator.

2. The apparatus of claim 1 wherein:

changes to a second set of poles are made symmetrically with respect to changes made to the first set of poles with respect to the nominal center of the stator.

3. The apparatus of claim 1 wherein:

the spacing between the first set of poles and the second set of poles is increased by a small amount.

4. The apparatus of claim 3 wherein:

the spacing between the first set of poles and the second set of poles is about  $\frac{1}{12}$  of the magnet pitch of the armature.

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