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(54) **DESIGN METHOD AND APPARATUS FOR NONLINEAR TERM-CANCELLED MOVING MAGNET VIBRATOR, AND USE**

(57) Provided is a moving-magnet vibrator with nonlinear term cancellation. The moving-magnet vibrator with nonlinear term cancellation includes a moving-magnet vibrator body, which includes an outer cylinder, a vibration transmission plate, a stator assembly and a movable assembly. The movable assembly is configured to be simultaneously subjected to paired electromagnetic forces of push and pull, thereby presenting push-pull structural characteristics.

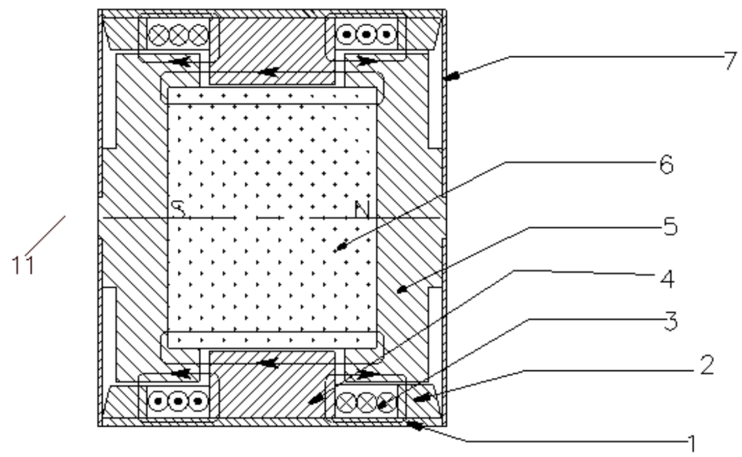

FIG. 1

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Description

CROSS-REFERENCE OF RELATED APPLICATIONS

[0001] This application is a continuation of international application no. PCT/CN2024/082548 filed March 20, 2024, which claims priority to Chinese patent application NO. 202310832430.9, filed July 07, 2023, and the entire disclosures of the above-identified applications is incorporated herein by reference.

TECHNICAL FIELD

[0002] This application relates to the technical field of vibrators, specifically to a moving-magnet vibrator with nonlinear term cancellation.

BACKGROUND

[0003] For the designed vibrators in bone conduction headphones and/or haptic feedback actuators, the moving-magnet design has many advantages. For example, the coil has good heat dissipation, and the movable assembly acting as a load is not heated; the coil adopts a hollow shaft with the magnet provided inside, enabling a compact overall structure. In addition, since the coil is stationary, it avoids the vulnerability of coil connection wires to damage. Moreover, the moving-magnet design enables a high peak force and a high ratio of peak force to moving mass, thereby achieving a high acceleration G-value.

[0004] The existing designed moving-magnet vibrator often suffer from relatively high nonlinear terms, due to certain deficiencies in the combination of magnets and coils. That is, the force or acceleration value of the movable assembly have relatively high distortion in a low-frequency band or a high-frequency band, which is also referred to as the total harmonic distortion (THD). FIG. 22 is a THD test chart of the existing moving-magnet vibrator. It can be seen that the distortion reaches 99% around 25 Hz, and the distortion reaches 46% around 100 Hz. Such a large distortion indicates that, near low frequencies, the distortion of the audio signal or haptic feedback signal causes the perceived sound quality or haptic feedback to deviate significantly from the actual case. Generally, when the distortion is greater than 10%, it is unacceptable according to audio standards.

SUMMARY

[0005] One objective of the disclosure is to provide a moving-magnet vibrator with nonlinear term cancellation.

[0006] The moving-magnet vibrator with nonlinear term cancellation includes moving-magnet vibrator body. The moving-magnet vibrator body includes an outer cylinder, a vibration transmission plate, a stator assembly and a movable assembly. The stator assembly includes a coil combination structure, and the movable assembly includes a magnet combination structure. The stator assembly is fixed inside the outer cylinder, the vibration transmission plate is fixed on the outer cylinder, and the movable assembly is fixedly connected to the vibration transmission plate through at least one contact point. The movable assembly moves while the stator assembly remains stationary, and the movable assembly is referred to as a moving component.

[0007] The movable assembly is configured to be simultaneously subjected to paired electromagnetic forces of push and pull, thereby presenting push-pull structural characterizes.

BRIEF DESCRIPTION OF THE DRAWINGS

[0008] The disclosure is further explained with reference to the accompanying drawings and embodiments.

FIG. 1 is a diagram illustrating a cross-sectional view of Embodiments 1 and 2 of the disclosure.
FIG. 2 is a diagram illustrating closed magnetic flux curves of a coil and a permanent magnet in Embodiments 1 and 2 of the disclosure.
FIG. 3 is a magnetic domain analysis diagram of Embodiments 1 and 2 of the disclosure.
FIG. 4 is a diagram illustrating a relationship between magnetic domains and a stator assembly in Embodiments 1 and 2 of the disclosure.
FIG. 5 is a force analysis diagram of magnetic domains and a movable assembly in Embodiments 1 and 2 of the disclosure.
FIG. 6 is a force analysis diagram of the movable assembly in Embodiments 1 and 2 of the disclosure.
FIG. 7 is a diagram illustrating a cross-sectional view of Embodiments 3 and 4 of the disclosure.
FIG. 8 is a diagram illustrating closed magnetic flux curves of a coil and a permanent magnet in Embodiments 3 and 4

of the disclosure.

FIG. 9 is a magnetic domain analysis diagram of Embodiments 3 and 4 of the disclosure.

FIG. 10 is a force analysis diagram of magnetic domains, a movable assembly, and a stator assembly in Embodiments 3 and 4 of the disclosure.

FIG. 11 is a force analysis diagram of the magnetic domains and the movable assembly in Embodiments 3 and 4 of the disclosure.

FIG. 12 is a diagram illustrating a cross-sectional view of Embodiments 5 and 6 of the disclosure.

FIG. 13 is a diagram illustrating closed magnetic flux curves of a coil and a permanent magnet in Embodiments 5 and 6 of the disclosure.

FIG. 14 is a magnetic domain analysis diagram of Embodiments 5 and 6 of the disclosure.

FIG. 15 is a force analysis diagram of magnetic domains, a stator assembly, and a movable assembly in Embodiments 5 and 6 of the disclosure.

FIG. 16 is a force analysis diagram of the magnetic domains and the movable assembly in Embodiments 5 and 6 of the disclosure.

FIG. 17 is a diagram illustrating a cross-sectional view of Embodiments 7 and 8 of the disclosure.

FIG. 18 is a diagram illustrating closed magnetic flux curves of a coil and a permanent magnet in Embodiments 7 and 8 of the disclosure.

FIG. 19 is a magnetic domain analysis diagram of Embodiments 7 and 8 of the disclosure.

FIG. 20 is a force analysis diagram of magnetic domains, a stator assembly, and a movable assembly in Embodiments 7 and 8 of the disclosure.

FIG. 21 is a force analysis diagram of the movable assembly in Embodiments 7 and 8 of the disclosure.

FIG. 22 is a diagram illustrating THD test of a moving-magnet vibrator in the related art.

FIG. 23 is a diagram illustrating THD test of the moving-magnet vibrator in Embodiments 1 and 2 of the disclosure.

FIGS. 24 to 40a are schematic diagrams of the magnet component in the disclosure.

FIGS. 41 to 53 are schematic diagrams of the coil component in the disclosure.

FIGS. 54 to 59 are schematic diagrams of the magnetic domains in the disclosure.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

[0009] The disclosure will be described in detail below, and the technical solutions in the embodiments of the disclosure will be clearly and completely described. Apparently, the described embodiments are only a part of the embodiments of the disclosure, not all of them. Based on the embodiments of the disclosure, all other embodiments obtained by those of ordinary skill in the art without creative efforts shall fall within the protection scope of the disclosure.

[0010] For the design of nonlinear term cancellation, there are 2N magnetic domains within a vibrator, in which the magnetic domains are in pairs, defined as magnetic domains $D_{1,i}$ and $D_{2,i}$, where i=1, 2, 3, ..., N. Closed main magnetic flux lines of a coil and closed main magnetic flux lines of a permanent magnet each pass through the magnetic action domains $D_{1,i}$ and $D_{2,i}$. In the magnetic domain $D_{1,i}$, a direction of the magnetic flux lines of the coil is the same as a direction of the magnetic flux lines of the permanent magnet, and in the magnetic domain $D_{2,i}$, a direction of the magnetic flux lines of the coil is opposite to a direction of the magnetic flux lines of the permanent magnet. Alternatively, in the magnetic domain $D_{1,i}$, the direction of the magnetic flux lines of the coil is opposite to the direction of the magnetic flux lines of the permanent magnet; and in the magnetic domain $D_{2,i}$, the direction of the magnetic flux line of the coil is the same as the direction of the magnetic flux lines of the permanent magnet.

[0011] When the direction of the magnetic flux lines of the coil passing through a certain magnetic domain is the same as the direction of the magnetic flux lines of the permanent magnet passing through the magnetic domain, a total magnetic flux is equal to a sum of a magnetic flux generated by the coil and a magnetic flux generated by the permanent magnet. When the direction of the magnetic flux lines of the coil passing through a certain magnetic domain is opposite to the direction of the magnetic flux lines of the permanent magnet passing through the magnetic domain, the total magnetic flux is equal to a difference between the magnetic flux generated by the coil and the magnetic flux generated by the permanent magnet.

[0012] There is at least one magnetic action domain in the vibrator. The magnetic action domain refers to a spatial region where there is a certain electromagnetic field or multiple electromagnetic fields, which causes mutual forces between various components surrounding the magnetic action domain. Such region is defined as the magnetic action domain, or the magnetic field for short.

[0013] The magnetic domain is a spatial region filled with electromagnetic energy, is generally composed of air or a medium with a low magnetic permeability (e.g., a relative magnetic permeability < 1000), and includes a region where a magnet material is located. The moving-coil vibrator with nonlinear term cancellation of the disclosure includes at least one magnetic action domain. The magnetic action domain refers to a spatial region where a certain electromagnetic field or multiple electromagnetic fields exist, which causes mutual forces between various components surrounding the magnetic action domain. Such region is defined as the magnetic action domain, referred to as the magnetic domain for short. The magnetic domain is a spatial region where magnetic forces interact with each other, such as a spatial region between permanent magnets (generating attractive or repulsive interactions), or a spatial region enclosed by a permanent magnet and a magnetic conductor (generating attractive interactions), or a spatial region enclosed by magnetic conductors (yoke iron) magnetized by a permanent magnet, or a spatial region where magnetic force interactions occurs in a permanent magnet (a magnetic permeability of a hard magnetic material forming the permanent magnet is close to the magnetic permeability of air).

[0014] The magnetic domains have various types as follows.

1) A space between permanent magnets is filled with medium (air, with a relative magnetic permeability slightly greater than 1).

[0015] The above medium may be replaced with paramagnetic materials (paramagnetic substances), diamagnetic materials (diamagnetic substances), or ferromagnetic materials (ferromagnetic substances) with the relative magnetic permeability less than 1000. Examples are given as follows.

a. Paramagnetic substances: The relative magnetic permeability of the paramagnetic substances is slightly greater than 1. Examples include air, oxygen, tin, aluminum, and lead. When the paramagnetic substances are placed in a magnetic field, the magnetic flux density B increases slightly.

b. Diamagnetic substances: The relative magnetic permeability of the diamagnetic substances is slightly less than 1. Examples include hydrogen, copper, graphite, silver, and zinc. Diamagnetic substances are also known as anti-magnetic substances. When the diamagnetic substances are placed in a magnetic field, the magnetic induction intensity B decreases slightly.

c. Ferromagnetic substances: The relative magnetic permeability of the ferromagnetic substances is much greater than 1 but less than 1000. Examples include iron, steel, cast iron, nickel, cobalt and other substances are ferromagnetic substances. The ferromagnetic substances with the relative magnetic permeability less than 1000 include, for example, cobalt, unannealed cast iron, annealed cast iron, etc. For example, magnetorheological fluid has a relative magnetic permeability below 10.

[0016] As illustrated in FIG. 54, there are permanent magnet 1 and permanent magnet 2 surrounded by air. The permanent magnets attract each other.

[0017] Magnetic domain D1: The spatial region enclosed by the air medium between permanent magnet 1 and permanent magnet 2.

[0018] Magnetic domain D2: The spatial region enclosed by part of permanent magnet 2 and the air medium around part of permanent magnet 2.

[0019] Magnetic domain D3: The spatial region enclosed by the entire permanent magnet 1 and the air medium near permanent magnet 1.

[0020] Magnetic domain D4: The spatial region enclosed by the entire permanent magnet 1, the entire permanent magnet 2, and the air medium near permanent magnet 1 and permanent magnet 2.

[0021] Magnetic domain D5: The spatial region enclosed by the air medium on the side of permanent magnet 2 away from permanent magnet 1.

[0022] Magnetic domain D6: The spatial region enclosed by the permanent magnet material medium surrounding part of permanent magnet 1.

[0023] As illustrated in FIG. 55, there are permanent magnet 1 and permanent magnet 2 surrounded by air. The permanent magnets attract each other. D1-D6 may be defined in a similar way.

[0024] 2) A space between a permanent magnet and a magnetic conductor is filled with a medium (air, with a relative magnetic permeability close to 1).

[0025] 3) A space between magnetic conductors is filled with a medium (air, with a relative magnetic permeability close to 1), as illustrated in FIGS. 56-57.

[0026] Magnetic domain D1: The spatial region enclosed by the air medium between magnetic conductor 1 and magnetic conductor 2.

[0027] Magnetic domain D2: The spatial region enclosed by part of the permanent magnet, part of magnetic conductor 2, and the surrounding air medium.

[0028] Magnetic domain D3: The spatial region enclosed by the entire magnetic conductor 1, part of the permanent magnet, and the air medium near magnetic conductor 1.

[0029] Magnetic domain D4: The spatial region enclosed by the entire magnetic conductor 1, the entire magnetic conductor 2, the entire permanent magnet, and the air medium near them.

[0030] Magnetic domain D5: The spatial region enclosed by the air medium on the side of magnetic conductor 2 away from magnetic conductor 1.

[0031] Magnetic domain D6: The spatial region enclosed by the permanent magnet material medium surrounding part of the permanent magnet.

[0032] 4) A space between magnetic conductors is filled with a medium (magnetorheological fluid, with a relative magnetic permeability between 5 and 9), as illustrated in FIG. 58.

[0033] 5) The spatial region inside a permanent magnet is filled with a medium (permanent magnet material, with a relative magnetic permeability<1000).

[0034] As illustrated in FIG. 59, magnetic domain D6 in the previous examples contains a permanent magnet material as the medium. For example, the magnetic permeability of sintered ferrite, samarium-cobalt and neodymium-iron-boron is approximately 1.05, the magnetic permeability of bonded ferrite is approximately 1.05, and the magnetic permeability of bonded neodymium magnets approximately ranges from 1.1 to 1.7.

[0035] There are two types of magnetic action domains: the first type is the magnetic action domain enclosed inside the movable assembly or the stator assembly, and the second type is the magnetic action domain enclosed between the movable assembly and the stator assembly. We are more interested in the second type of magnetic action domain. Therefore, through the analysis of the second type of magnetic action domain, a force analysis of the movable assembly may be obtained, thereby obtaining a resultant force of the movable assembly of the vibrator system, and further obtaining the vibration equation.

Embodiment 1

[0036] Referring to FIGS. 1 to 5, a design method of a moving-magnet vibrator with nonlinear term cancellation includes conditions as follows.

(1) A moving-magnet vibrator body 11 is provided. The moving-magnet vibrator body 11 includes an outer cylinder 1, a vibration transmission plate 7, a stator assembly and a movable assembly. The stator assembly includes a coil combination structure, the movable assembly includes a magnet combination structure, the coil combination structure includes a coil 3 and a first magnetic conductor 4, and the magnet combination structure includes a permanent magnet 6 and a second magnetic conductor 5. The stator assembly is fixed inside the outer cylinder 1, the vibration transmission plate 7 is fixed on the outer cylinder 1, and the movable assembly is fixedly connected to the vibration transmission plate 7 through at least one contact point. The movable assembly moves while the stator assembly remains stationary, and the movable assembly is referred to as a moving component.

(2) The movable assembly is simultaneously subjected to paired electromagnetic forces of push and pull, presenting push-pull structural characteristics.

[0037] 2N magnetic domains $D_{1,i}$ and $D_{2,i}$ which are designed as N symmetrical pairs, are provided in the moving-magnet vibrator body 11, where N is 1, 2, 3, ..., 100, and i=1, 2, 3, ...

[0038] The number of a permanent magnet in the magnet combination structure and the number of a coil in the coil combination structure are limited, in such a manner that $N_{magnet}>N_{coil}$ or $N_{magnet} < N_{coil}$, where N_{magnet} represents the number of the permanent magnet, and N_{coil} represents the number of the coil, N_{magnet}=1, 2, 3, ..., 100, and N_{coil}=1, 2, 3, ..., 100.

[0039] In the push-pull structural characteristics, linear terms of the electromagnetic force acting on the movable assembly are superimposed so as to be increased, and nonlinear terms of the electromagnetic force acting on the movable assembly are partially or completely canceled so as to be decreased.

[0040] The closed main magnetic flux lines of the coil in the coil combination structure and the closed main magnetic flux lines of the permanent magnet in the magnet combination structure each pass through the magnetic domains $D_{1,i}$ and $D_{2,i}$. The magnetic domain is a spatial region filled with electromagnetic energy, is generally composed of air or a medium with low magnetic permeability (e.g., a relative magnetic permeability<1000), and includes a region where the magnet material is located. In the magnetic domain $D_{1,i}$, a direction of magnetic flux lines of the coil is the same as a direction of magnetic flux lines of the permanent magnet, while in the magnetic domain $D_{2,i}$, the direction of the magnetic flux lines of the coil is opposite to the direction of the magnetic flux lines of the permanent magnet. Alternatively, in the magnetic domain $D_{1,i}$, the direction of the magnetic flux lines of the coil is opposite to the direction of the magnetic flux lines of the permanent magnet, while in the magnetic domain $D_{2,i}$ the direction of the magnetic flux lines of the coil is the same as the direction of the magnetic flux lines of the permanent magnet.

[0041] Specifically, the vibration transmission plate 7 may be a rectangular, circular, racetrack-shaped or three-dimensional structures according to different application scenarios, and may be used in various combinations according to different application scenarios. The vibration transmission plate 7 is usually fixed on a top surface, bottom surface or middle of the outer cylinder 1.

[0042] The stator assembly is fixed inside the outer cylinder 1, and may be arranged on an inner side wall, top surface or bottom surface of the outer cylinder 1.

[0043] The movable assembly is fixedly connected to the vibration transmission plate 7 through at least one contact point, in which the contact point includes point contact and surface contact. There may be one contact point, two contact points or multiple contact points.

[0044] The number of the permanent magnet 6 and the number of the coil 3 are limited, in which there are one permanent magnet, and two coils.

[0045] Two symmetrically paired magnetic domains $D_{1,1}$ and $D_{2,1}$ are provided in the moving-magnet vibrator body 11. The closed main magnetic flux lines of the coil 3 and the closed main magnetic flux lines of the permanent magnet 6 each pass through the magnetic domains $D_{1,1}$ and $D_{2,1}$. In the magnetic domain $D_{1,1}$, the direction of the magnetic flux lines of the coil 3 is the same as the direction of the magnetic flux lines of the permanent magnet 6, while in the magnetic domain $D_{2,1}$, the direction of the magnetic flux lines of the coil 3 is opposite to the direction of the magnetic flux lines of the permanent magnet 6.

[0046] The moving component is subjected to 2 forces. Each component force includes two parts: one part is a linear term of an excitation current i, and the other part is a nonlinear term of the excitation current i:

$$F_{\text{moving-magnet,n}}(i) = F_{\text{moving-magnet,n,linear}}(i) + F_{\text{moving-magnet,n,nonlinear}}(i),$$

where n = 1, 2, 3, ..., 2N - 1, 2N.

[0047] Accordingly, a resultant force on the moving component also includes two parts: one part is a linear term of the current i, and the other part is a nonlinear term of the current i, which is expressed as:

$$F_{\text{moving-magnet,resultant force}}(i) = F_{\text{moving-magnet,resultant force,linear}}(i) + F_{\text{moving-magnet,resultant force,nonlinear}}(i)$$

where:

$$F_{\text{moving-magnet,resultant force}}(i) = \sum_{n=1}^{2N} F_{\text{moving-magnet,n}}(i) = \sum_{n=1}^{N} \left(F_{\text{moving-magnet,n,1}}(i) + F_{\text{moving-magnet,n,2}}(i)\right)$$

$$F_{\text{moving-magnet,resultant force,linear}}(i) = \sum_{n=1}^{2N} F_{\text{moving-magnet,n,linear}}(i) = \sum_{n=1}^{N} \left(F_{\text{moving-magnet,linear,1}}(i) + F_{\text{moving-magnet,linear,2}}(i)\right)$$

$$F_{\text{moving-magnet,resultant force,nonlinear}}(i) = \sum_{n=1}^{2N} F_{\text{moving-magnet,n,nonlinear}}(i) = \sum_{n=1}^{N} \left(F_{\text{moving-magnet,nonlinear,1}}(i) + F_{\text{moving-magnet,nonlinear,2}}(i)\right)$$

[0048] That is, the nonlinear terms in each component force are partially or completely canceled. In the final total resultant force $\sum_i (F_{1,i} + F_{2,i})$, the nonlinear terms of the total resultant force relative to the current are partially or completely canceled, and the linear terms are superimposed so as to be increased, thereby obtaining the moving-magnet vibrator with nonlinear term cancellation.

[0049] The movable assembly and the stator assembly are in concave-convex shapes and arranged in an interleaved engagement manner, and the closed main magnetic flux lines of the coil 3 and the closed main magnetic flux lines of the permanent magnet 6 alternately pass through the movable assembly and the stator assembly.

[0050] The design method further includes conditions as follows.

[0051] (3.1) Looking outward from a center, the permanent magnet 6 is located inside and the coil 3 is located outside.

[0052] (3.2) N_{coil}=2, n=1.

[0053] (3.3) When N_{coil}>1, the directions of the currents in the adjacent coils 3 are opposite; and for two adjacent coils 3, the polarities of the electromagnetic fields at the adjacent end faces are the same.

[0054] The magnetic conductor is arranged at a position of the outer cylinder 1 close to the coil 3, so as to minimize the magnetic resistance of the magnetic circuit of an electromagnet generated by the coil 3. The permanent magnet 6 in the magnet assembly is isolated by the magnetic conductor. A yoke iron is arranged around the coils 3 and the permanent magnet 6, or alternatively, for the coil combination structure, a part of the outer cylinder 1 close to the coil 3 is magnetically conductive.

Embodiment 2

[0055] Referring to FIGS. 1 to 5, a moving-magnet vibrator device with nonlinear term cancellation designed by the method of Embodiment 1 includes a moving-magnet vibrator body 11. The moving-magnet vibrator body 11 includes an outer cylinder 1, a vibration transmission plate 7, a stator assembly and a movable assembly. The stator assembly includes a coil combination structure. The movable assembly includes a magnet combination structure. The coil combination structure includes a coil 3 and a first magnetic conductor 4. The magnet combination structure includes a permanent magnet 6 and a second magnetic conductor 5. The outer cylinder 1 may be magnetic or non-magnetic. Preferably, the outer cylinder is a magnetic conductive to reduce magnetic resistance. A cross-section of the outer cylinder may be circular, square, special-shaped, etc., and may be continuous or discontinuous, such as columnar connection or grid-like discontinuity.

[0056] The coil combination structure further includes a first magnetic conductive ring 2. Viewed from a center outward, the coil 3 is located outside and the permanent magnet 6 is located inside. There is one permanent magnet 6, and two coils 3. Directions of the currents in the adjacent coils 3 are opposite, and polarities of electromagnetic fields at adjacent end faces of the two adjacent coils 3 are the same. Two vibration transmission plates 7 are provided, and the two vibration transmission plates 7 are respectively fixed on a top surface and a bottom surface of the outer cylinder 1. The permanent magnet 6 is fixed in the second magnetic conductor 5. Two ends of the second magnetic conductor 5 are respectively fixed on the vibration transmission plates 7. The first magnetic conductor 4 is fixed in the middle of an inner side wall of the outer cylinder 1. The two coils 3 are respectively fixed on two sides of the first magnetic conductor 4. A first magnetic conductive ring 2 is fixedly arranged on an outer side of the coils 3. The coils 3 and the first magnetic conductive ring 2 are fixed on the inner side wall of the outer cylinder 1. The movable assembly and the stator assembly are in concave-convex shapes and arranged in an interleaved engagement manner (i.e., in a concave-convex interleaved engagement shape). Closed main magnetic flux lines of the coil 3 and closed main magnetic flux lines of the permanent magnet 6 alternately pass through the movable assembly and the stator assembly. Two magnetic domains $D_{1,1}$ and $D_{2,1}$ designed as a symmetrical pair are provided in the moving-magnet vibrator body. The closed main magnetic flux lines of the coil 3 and the closed main magnetic flux lines of the permanent magnet 6 each pass through the magnetic domains $D_{1,1}$ and $D_{2,1}$. In the magnetic domain $D_{1,1}$, the direction of the magnetic flux lines of the coil 3 is the same as the direction of the magnetic flux lines of the permanent magnet 6, and in the magnetic domain $D_{2,1}$, the direction of the magnetic flux lines of the coil 3 is opposite to the direction of the magnetic flux lines of the permanent magnet 6.

[0057] To further describe the design method of the moving-magnet vibrator with nonlinear term cancellation, referring to FIGS. 2 and 3, an air gap 1 constitutes a magnetic action domain $D_{1,1}$, and an air gap 2 constitutes a magnetic action domain $D_{2,1}$. In the magnetic action domain, a total magnetic flux/magnetic induction intensity generated by the superposition of the magnetic field generated by the permanent magnet 6 and the magnetic field generated by the electromagnet of the coil 3 causes mutual forces between the components around the magnetic domain.

[0058] The current passing through the coil C_1 and the current passing through the coil C_2 are represented as i, but the direction of the current in the coil C_1 is opposite to the direction of the current in the coil C_2. Assuming that the magnetic flux corresponding to the coil C_1 is Φ_{i1}, the magnetic flux corresponding to the coil C_2 is Φ_{i2}, and the magnetic flux corresponding to the permanent magnet is Φ_m. In the magnetic domain D_1 (magnetic action domain D_1), the direction of the magnetic flux lines corresponding to the coil C_1 is the same as the direction of the magnetic flux lines corresponding to the permanent magnet, so the total magnetic flux in the magnetic domain D_1 is a sum of Φ_{i1} and Φ_m. In the magnetic domain D_2 (magnetic action domain D_2), the direction of the magnetic flux lines corresponding to the coil C_2 is opposite to the direction of the magnetic flux lines corresponding to the permanent magnet, so the total magnetic flux in the magnetic domain D_2 is a difference between Φ_{i2} and Φ_m. Assuming that the direction of the magnetic flux lines of the permanent magnet 6 is a positive direction in each magnetic domain, we have:

$$\Phi_{D1} = \Phi_m + \Phi_{i1};$$

and

$$\Phi_{D2} = \Phi_m - \Phi_{i2}.$$

[0059] Assuming that the magnetic resistances of the magnetic circuits formed by the electromagnetic fields generated by the currents in the coil 1 and the coil 2 are Z_{i1} and Z_{i2} respectively, where N is the number of turns of the coil, and i is the current intensity, we have:

$$\emptyset_{i1} * Z_{i1} = N * i;$$

and

$$\emptyset_{i2} * Z_{i2} = N * i.$$

[0060] Since the magnetic circuit structures of the coils C_1 and C_2 are symmetrically designed, $Z_{i1} = Z_{i2} = Z_i$, so $\emptyset_{i1} = \emptyset_{i2} = \emptyset_i$; in addition, assuming that the magnetic conductance of the magnetic circuit formed by the electromagnetic field generated by the current is G_1, we have:

$$\emptyset_i = G_i * N * i.$$

[0061] The magnetic flux corresponding to the permanent magnet 6 may also be represented by the equation of magnetic induction intensity. Assuming that the magnetic induction intensity at the magnetic pole end face of the permanent magnet is B_m and the area of the magnetic pole end is S_m, we may obtain $\emptyset_m = B_m * S_m$.

[0062] Thus, we have:

$$\begin{cases} \emptyset_{D1} = \emptyset_m + \emptyset_i = \emptyset_m + \emptyset_i = B_m\, S_m + G_i * N * i \\ \emptyset_{D2} = \emptyset_m - \emptyset_i = \emptyset_m - \emptyset_i = B_m\, S_m - G_i * N * i \end{cases}.$$

[0063] Referring to FIG. 2, FIG. 2 illustrates the closed magnetic flux lines of the coil C1, the coil C2 and the permanent magnet. In FIG. 2, the closed magnetic flux lines generated by the coil C1 passes through the magnetic gap D1, the closed magnetic flux lines generated by the coil C2 passes through the magnetic gap D2, and the closed magnetic flux generated by the permanent magnet sequentially passes through the magnetic gap D1 and the magnetic gap D2.

[0064] Referring to FIG. 3, FIG. 3 is a diagram illustrating the relationship between the movable assembly, the magnetic domains $D_{1,1}$, $D_{2,2}$ and the stator assembly. In the magnetic domain $D_{1,1}$, the movable assembly is subjected to a rightward attractive force F_1 from the stator assembly, and in the magnetic domain $D_{2,1}$, the movable assembly is subjected to a leftward attractive force F_2 from the stator assembly. Taking the rightward direction as the positive direction, the resultant force of the stator assembly on the movable assembly is $F_1 - F_2$.

[0065] Referring to FIG. 5, FIG. 5 is a force analysis diagram of the isolated movable assembly. The movable assembly is subjected to forces from the stator assembly, that is, a rightward attractive force F_1 and a leftward attractive force F_2, and the resultant force is $F_1 - F_2$, expressed as:

$$F_{moving-magnet} = F_1 - F_2.$$

[0066] Further derive the equation for the electromagnetic force generated by each magnetic domain. The magnitude of the electromagnetic attractive force acting on a magnetized ferromagnetic object is proportional to the total area of the magnetic poles through which the magnetic flux lines passes and the square of the magnetic induction intensity. If the magnetic induction intensity B is uniformly distributed along the surface of the magnetic pole and the calculated air gap length is small, the equation for calculating the electromagnetic attractive force is calculated by the Maxwell formula, expressed as:

$$F = C\,\frac{B^2 \cdot S}{2\mu_0} = C\,\frac{\emptyset^2}{2\mu_0 \cdot S}$$

where:

F: Electromagnetic attractive force
B: Magnetic flux density or magnetic induction intensity
Ø: Magnetic flux passing through the medium
S: Area of the magnetic pole through which the magnetic flux passes
μ_0: Air permeability
C: Coefficient related to the combination type and shape of the magnetic pole end face, with different values for different scenarios. When the force is generated between permanent magnets, it is denoted as C_{m2m}, usually taking a value of 1, and the accurate value is obtained through actual measurement in the actual design process. When the force is generated between a permanent magnet and a magnetic conductor (yoke iron), it is denoted as C_{m2y}, usually taking a value of 1/2, and the accurate value is obtained through actual measurement in the actual design process. When the force is generated between magnetic conductors (yoke iron), it is denoted as C_{y2y}, usually taking a value of 1/4, and the accurate value is obtained through actual measurement in the actual design process.

[0067] Applying the above equation to calculate the electromagnetic attractive forces in the above magnetic domain 1 and magnetic domain 2:

$$\begin{cases} F_1 = C_{y2y} \dfrac{(\emptyset_m + \emptyset_i)^2}{2\mu_0 \cdot S_{D1}} \\ F_2 = C_{y2y} \dfrac{(\emptyset_m - \emptyset_i)^2}{2\mu_0 \cdot S_{D2}} \end{cases}$$

where S_{D1} and S_{D2} represent the areas of the annular end faces corresponding to magnetic domain 1 and magnetic domain 2 respectively, and $S_{D1} = S_{D2} = S_D$, thus:

$$\begin{cases} F_1 = C_{y2y} \dfrac{(\emptyset_m + \emptyset_i)^2}{2\mu_0 \cdot S_{D1}} = \dfrac{C_{y2y}}{2\mu_0 \cdot S_D} (\emptyset_m + \emptyset_i)^2 \\ F_2 = C_{y2y} \dfrac{(\emptyset_m - \emptyset_i)^2}{2\mu_0 \cdot S_{D2}} = \dfrac{C_{y2y}}{2\mu_0 \cdot S_D} (\emptyset_m - \emptyset_i)^2 \end{cases}$$

$$\begin{cases} F_1 = F_{1,linear} + F_{1,nonlinear} \\ F_2 = F_{2,linear} + F_{2,nonlinear} \end{cases}$$

where:

$$\begin{cases} F_{1,linear} = \dfrac{C_{y2y}}{2\mu_0 \cdot S_D} (\emptyset_m^2 + 2\emptyset_m \emptyset_i) \\ F_{1,nonlinear} = \dfrac{C_{y2y}}{2\mu_0 \cdot S_D} {\emptyset_i}^2 \end{cases}$$

$$\begin{cases} F_{2,linear} = \dfrac{C_{y2y}}{2\mu_0 \cdot S_D} (\emptyset_m^2 - 2\emptyset_m \emptyset_i) \\ F_{2,nonlinear} = \dfrac{C_{y2y}}{2\mu_0 \cdot S_D} {\emptyset_i}^2 \end{cases}$$

Since:

$$F_{moving-magnet} = F_1 - F_2$$

We obtain

$$F_{moving-magnet,linear} = F_{moving-magnet,linear} + F_{moving-magnet,nonlinear}$$

$$\begin{cases} F_{moving-magnet,linear} = F_{1,linear} - F_{2,linear} \\ F_{moving-magnet,nonlinear} = F_{1,nonlinear} - F_{2,nonlinear} \end{cases}$$

Substitute $F_{1,linear}$, $F_{2,linear}$, $F_{1,nonlinear}$, $F_{1,nonlinear}$ into $F_{moving\text{-}magnet,linear}$ and $F_{moving\text{-}magnet,nonlinear}$ respectively, we obtain:

$$F_{moving-magnet,linear} = F_{1,linear} - F_{2,linear}$$

$$= \frac{C_{y2y}}{2\mu_0 \cdot S_D}(\emptyset_m^2 + 2\emptyset_m\emptyset_i) - \frac{C_{y2y}}{2\mu_0 \cdot S_D}(\emptyset_m^2 - 2\emptyset_m\emptyset_i)$$

$$= \frac{C_{y2y}}{2\mu_0 \cdot S_D}\ (\emptyset_m^2 + 2\emptyset_m\emptyset_i - (\emptyset_m^2 - 2\emptyset_m\emptyset_i)$$

$$= \frac{C_{y2y}}{2\mu_0 \cdot S_D}\ (4\emptyset_m\emptyset_i)$$

$$= \frac{2C_{y2y}\emptyset_m}{\mu_0 \cdot S_D}\ \emptyset_i$$

Since:

$$\emptyset_{\mathrm{m}} = \mathrm{B_m S_m}$$

$$\emptyset_i = G_i N i$$

It follows that:

$$F_{moving-magnet,linear} = \frac{2C_{y2y}\emptyset_m}{\mu_0 \cdot S_D}\ \emptyset_i = \frac{2C_{y2y}B_m S_m}{\mu_0 \cdot S_D}\ G_i N i = \frac{2C_{y2y}B_m S_m G_i N}{\mu_0 \cdot S_D} *\ i$$

Calculate $F_{moving\text{-}magnet,nonlinear}$ in a similar way as follows:

$$F_{moving-magnet,nonlinear} = F_{1,nonlinear} - F_{2,nonlinear}$$

$$= \frac{C_{y2y}}{2\mu_0 \cdot S_D}\ {\emptyset_i}^2 - \frac{C_{y2y}}{2\mu_0 \cdot S_D}\ {\emptyset_i}^2 = 0$$

Thus, the resultant force acting on the moving magnet, which serves as the moving member, is:

$$F_{moving-magnet} = F_{moving-magnet,linear} + F_{moving-magnet,nonlinear}$$

$$= \frac{2C_{y2y}B_m S_m G_i N}{\mu_0 \cdot S_D} *\ i + 0$$

$$= \frac{2C_{y2y}B_m S_m G_i N}{\mu_0 \cdot S_D} *\ i$$

[0068] From the above derivation process, the following characteristics may be seen:

1) In the linear term of the resultant force $F_{moving\text{-}magnet,linear}$, the linear terms of the component forces $F_{1,linear}$ and $F_{2,linear}$ are superimposed, so that the linear term of the resultant force $F_{moving\text{-}magnet,linear}$ and the coil current is larger.
2) In the nonlinear term of the resultant force $F_{moving\text{-}magnet,nonlinear}$, the nonlinear terms of the component forces $F_{1,nonlinear}$ and $F_{2,nonlinear}$ cancel each other out, so that the nonlinear term of the resultant force $F_{moving\text{-}magnet,nonlinear}$ is zero.

[0069] The above design method is called the design method of the moving-magnet vibrator with nonlinear term cancellation. This method can not only be used to design vibrators, but also be applied to design actuators. The moving-magnet vibrators or actuators obtained by the above method are called moving-magnet vibrator devices or actuators with nonlinear term cancellation.
[0070] Referring to FIG. 22, it can be seen from the FIG. 22 that the total harmonic distortion in the low-frequency band is greatly reduced, decreasing from the original peak value of 99% to below 15%, realizing a significant improvement.
[0071] The reduction of the distortion curve is equivalently interpreted as the reduction of the resonant frequency of the vibrator system, thereby achieving better sound quality. In addition, the reduction of the distortion curve may be further equivalently interpreted as the improvement of the sensitivity of the vibrator system and the reduction of power consumption.

Embodiment 3

[0072] Referring to FIGS. 7-11, a design method of a moving-magnet vibrator with nonlinear term cancellation includes conditions as follows.

(1) A moving-magnet vibrator body 11 is provided. The moving-magnet vibrator body 11 includes an outer cylinder 1, a vibration transmission plate 8, a stator assembly and a movable assembly. The stator assembly includes a coil combination structure, the movable assembly includes a magnet combination structure. The coil combination structure includes a coil 3 and a first magnetic conductor 7, and the magnet combination structure includes a permanent magnet 6 and a second magnetic conductor 4. The stator assembly is fixed inside the outer cylinder 1, the vibration transmission plate 8 is fixed on the outer cylinder 1, and the movable assembly is fixedly connected to the vibration transmission plate 8 through at least one contact point. The movable assembly moves while the stator assembly remains stationary, and the movable assembly is referred to as a moving component.
(2) The movable assembly is simultaneously subjected to paired electromagnetic forces of push and pull, presenting push-pull structural characteristics.

[0073] 2N magnetic domains $D_{1,i}$ and $D_{2,i}$ which are designed as N symmetrical pairs are provided in the moving-magnet vibrator body 11, where N is 1, 2, 3, ..., 100, and i=1, 2, 3, ...
[0074] The number of a permanent magnet in the magnet combination structure and the number of a coil in the coil combination structure are limited, in such a manner that $N_{magnet}>N_{coil}$ or $N_{magnet} < N_{coil}$, where N_{magnet} represents the number of the permanent magnet, and N_{coil} represents the number of the coil, N_{magnet}=1, 2, 3, ..., 100, and N_{coil}=1, 2, 3, ..., 100.
[0075] In the push-pull structural characteristics, linear terms of an electromagnetic force acting on the movable assembly are superimposed so as to be increased, while nonlinear terms of the electromagnetic force acting on the movable assembly are partially or completely canceled so as to be decreased.
[0076] The closed main magnetic flux lines of the coil in the coil combination structure and the closed main magnetic flux lines of the permanent magnet in the magnet combination structure each pass through the magnetic domains $D_{1,i}$ and $D_{2,i}$. The magnetic domain is a spatial region filled with electromagnetic energy, is generally composed of air or a medium with low magnetic permeability (e.g., a relative magnetic permeability<1000), and includes a region where the magnet material is located. In the magnetic domain $D_{1,i}$, a direction of magnetic flux lines of the coil is the same as a direction of magnetic flux lines of the permanent magnet, while in the magnetic domain $D_{2,i}$, the direction of the magnetic flux lines of the coil is opposite to the direction of the magnetic flux lines of the permanent magnet. Alternatively, in the magnetic domain $D_{1,i}$, the direction of the magnetic flux lines of the coil is opposite to the direction of the magnetic flux lines of the permanent magnet, while in the magnetic domain $D_{2,i}$ the direction of the magnetic flux lines of the coil is the same as the direction of the magnetic flux lines of the permanent magnet.
[0077] The number of the permanent magnet 6 and the number of the coil 3 are limited, in which there are two permanent magnets, and one coil.
[0078] Two symmetrically paired magnetic domains $D_{1,1}$ and $D_{2,1}$ are provided in the moving-magnet vibrator body 11. The closed main magnetic flux lines of the coil 3 and the closed main magnetic flux lines of the permanent magnet 6 each

pass through the magnetic domains $D_{1,1}$ and $D_{2,1}$. In the magnetic domain $D_{1,1}$, the direction of the magnetic flux lines of the coil 3 is opposite to the direction of the magnetic flux lines of the permanent magnet 6, while in the magnetic domain $D_{2,1}$, the direction of the magnetic flux lines of the coil 3 is the same as the direction of the magnetic flux lines of the permanent magnet 6.

[0079] The moving component is subjected to 2 forces. Each component force includes two parts: one part is a linear term of an excitation current i, and the other part is a nonlinear term of the excitation current i:

$$F_{moving-magnet,n}(i) = F_{moving-magnet,n,linear}(i) + F_{moving-magnet,n,nonlinear}(i),$$

where n = 1,2 3, ..., 2N - 1,2N.

[0080] Accordingly, a resultant force on the moving component also includes two parts: one part is a linear term of the current i, and the other part is a nonlinear term of the current i, which is expressed as:

$$F_{moving-magnet,resultant\ force}(i) = F_{moving-magnet,resultant\ force,linear}(i) + F_{moving-magnet,resultant\ force,nonlinear}(i)$$

where:

$$\mathrm{F}_{\mathrm{moving-magnet,resultant\ force}}(\mathrm{i}) = \sum_{n=1}^{2N} \mathrm{F}_{\mathrm{moving-magnet,n}}(\mathrm{i}) = \sum_{n=1}^{N} (\mathrm{F}_{\mathrm{moving-magnet,n,1}}(\mathrm{i}) + \mathrm{F}_{\mathrm{moving-magnet,n,2}}(\mathrm{i}))$$

$$\mathrm{F}_{\mathrm{moving\text{-}magnet,\ resultant\ force,\ linear}}(\mathrm{i}) = \sum_{n=1}^{2N} \mathrm{F}_{\mathrm{moving\text{-}magnet,\ n,\ linear}}(\mathrm{i}) = \sum_{n=1}^{N} (\mathrm{F}_{\mathrm{moving\text{-}magnet,\ linear,\ 1}}(\mathrm{i}) + \mathrm{F}_{\mathrm{moving\text{-}magnet,\ linear,\ 2}}(\mathrm{i}))$$

$$\mathrm{F}_{\mathrm{moving\text{-}magnet,\ resultant\ force,\ nonlinear}}(\mathrm{i}) = \sum_{n=1}^{2N} \mathrm{F}_{\mathrm{moving\text{-}magnet,\ n,\ nonlinear}}(\mathrm{i}) = \sum_{n=1}^{N} (\mathrm{F}_{\mathrm{moving\text{-}magnet,\ nonlinear,\ 1}}(\mathrm{i}) + \mathrm{F}_{\mathrm{moving\text{-}magnet,\ nonlinear,\ 2}}(\mathrm{i}))$$

[0081] That is, the nonlinear terms in each component force are partially or completely canceled. In the final total resultant force $\sum_i(F_{1,i} + F_{2,i})$, the nonlinear terms of the total resultant force relative to the current are partially or completely canceled, and the linear terms are superimposed to be increased, thereby obtaining the moving-magnet vibrator with nonlinear term cancellation.

[0082] Furthermore, the movable assembly and the stator assembly are in concave-convex shapes and arranged in an interleaved engagement manner, and the closed main magnetic flux lines of the coil 3 and the closed main magnetic flux lines of the permanent magnet 6 alternately pass through the movable assembly and the stator assembly.

[0083] The design method further includes conditions as follows.

[0084] (3.1) Looking outward from a center, the coil 3 is located inside and the permanent magnet 6 is located outside.

[0085] (3.2) N_{magnet}=2, where n is a natural number, and n=1.

[0086] (3.3) When N_{magnet}>1, the polarities of the two opposite end faces of the adjacent permanent magnets are the same.

[0087] The magnetic conductor is arranged at a position of the outer cylinder 1 close to the coil 3, so as to minimize the magnetic resistance of the magnetic circuit of an electromagnet 6 generated by the coil 3. The permanent magnet 6 in the magnet assembly is isolated by the magnetic conductor. A yoke iron is arranged around the coil 3 and the permanent magnet 6, or alternatively, for the coil combination structure, a part of the outer cylinder 1 close to the coil is magnetically conductive.

Embodiment 4

[0088] Referring to FIGS. 7 to 11, a moving-magnet vibrator device with nonlinear term cancellation designed by the method of Embodiment 3 includes a moving-magnet vibrator body 11. The moving-magnet vibrator body includes an outer cylinder 1, a vibration transmission plate 8, a stator assembly and a movable assembly. The stator assembly includes a coil combination structure. The movable assembly includes a magnet combination structure. The coil combination structure includes a coil 3 and a first magnetic conductor 7. The magnet combination structure includes a permanent magnet 6 and a second magnetic conductor 4. The coil combination structure further includes a first magnetic conductive ring 5, and the magnet combination structure further includes a second magnetic conductive ring 2. Viewed from a center outward, the coil 3 is inside and the permanent magnet 6 is outside. There are two permanent magnets 6, and one coil. The two opposite end faces of adjacent permanent magnet 6 have the same polarity. There is one vibration transmission plate 8 which is fixed on a top surface of the outer cylinder 1. Preferably, the outer cylinder is a magnetic conductive to reduce magnetic resistance.

[0089] An end of the first magnetic conductor 7 is fixed on a bottom surface of the outer cylinder 1. The coil 3 is wound around and fixed on the first magnetic conductor 7, and the first magnetic conductive ring 5 is fixed at an end of the first magnetic conductor 7. An L-shaped vibration transmission bracket 9 is provided. A horizontal part of the vibration transmission bracket 9 is parallel to a vibration direction. The second magnetic conductor 4 is fixed on the horizontal part of the vibration transmission bracket 9. The two permanent magnets 6 are fixedly arranged on two sides of the second magnetic conductor 4, and the two permanent magnets 6 are fixed on the horizontal part of the vibration transmission bracket 9. The movable assembly and the stator assembly are in concave-convex shapes and arranged in an interleaved engagement manner. Closed magnetic flux lines of the coil 3 and closed magnetic flux lines of the permanent magnet 6 alternately pass through the movable assembly and the stator assembly. Two magnetic domains $D_{1,1}$ and $D_{2,1}$ which are designed as a symmetrical pair are provided in the moving-magnet vibrator body, the closed magnetic flux lines of the coil and the closed magnetic flux lines of the permanent magnets each pass through the magnetic domains $D_{1,1}$ and $D_{2,1}$. In the magnetic domain $D_{1,1}$, a direction of magnetic flux lines of the coil is opposite to a direction of magnetic flux lines of the permanent magnet. In the magnetic domain $D_{2,1}$, the direction of the magnetic flux lines of the coil is the same as the direction of the magnetic flux lines of the permanent magnet.

[0090] To further describe the design method of the moving-magnet vibrator with nonlinear term cancellation, referring to FIG 8, an air gap 1 constitutes a magnetic action domain $D_{1,1}$, and an air gap 2 constitutes a magnetic action domain $D_{2,1}$, thereby forming a magnetic domain pair D = ($D_{1,1}$, $D_{2,1}$). In the magnetic action domain, a total magnetic flux/magnetic induction intensity generated by the superposition of the magnetic field generated by the permanent magnet 6 and the magnetic field generated by the electromagnet of the coil 3 causes mutual forces between the components around the magnetic domain.

[0091] With regard to the magnetic domain pair D = ($D_{1,1}$, $D_{2,1}$), assuming that the current passing through the coil is i, the magnetic flux corresponding to the coil is Φ_i. The magnetic flux corresponding to the permanent magnet M_1 is Φ_{m1}, and the magnetic flux corresponding to the permanent magnet M_2 is Φ_{m2}. In the magnetic domain $D_{1,1}$ (magnetic action domain $D_{1,1}$), the direction of the magnetic flux lines corresponding to the coil C is opposite to that corresponding to the permanent magnet M_1, so the total magnetic flux in the magnetic domain $D_{1,1}$ is the difference between Φ_i and Φ_{m1}. In the magnetic domain $D_{2,1}$ (magnetic action domain $D_{2,1}$), the direction of the magnetic flux lines corresponding to the coil is to the same as that corresponding to the permanent magnet M_2, so the total magnetic flux in the magnetic domain $D_{2,1}$ is the sum of Φ_i and Φ_{m2}. Since the magnetic field formed by the permanent magnet is static, assuming that the direction of the magnetic flux lines of the permanent magnet is positive, the magnetic flux is also positive, then:

$$\Phi_{D1,1} = \Phi_{m1} - \Phi_{i1};$$

and

$$\Phi_{D2,1} = \Phi_{m2} + \Phi_{i2}.$$

[0092] Assuming that the magnetic resistance of the magnetic circuit formed by the electromagnetic field generated by the coil current i is Z_i, N is the number of turns of the coil, and i is the current intensity, we have:

$$\emptyset_i * Z_i = N * i.$$

[0093] Assuming that the magnetic conductance of the magnetic circuit formed by the electromagnetic field generated by the current is G_i, we have:

$$\emptyset_i = G_i * N * i.$$

[0094] The magnetic flux corresponding to the permanent magnet may also be expressed by the equation of magnetic induction intensity. Assuming that the magnetic induction intensities at the magnetic pole end faces of the permanent magnet M_1 and the permanent magnet M_2 are B_{m1} and B_{m2} respectively, and $B_{m1} = B_{m2} = B_m$. In addition, assuming that the areas of the magnetic pole end faces of the permanent magnet 1 and the permanent magnet 2 are S_{m1} and S_{m2} respectively, and $S_{m1} = S_{m2} = S_m$, it follows that $Ø_{m1} = Ø_{m2} = Ø_m = B_m S_m$.

[0095] Thus, we have:

$$\emptyset_{D1} = -\emptyset_i + \emptyset_m = -G_i * N * i + B_m S_m$$

$$\emptyset_{D2} = \emptyset_i + \emptyset_m = G_i * N * i + B_m S_m \; .$$

[0096] Referring to FIG. 8, FIG. 8 illustrates only the closed magnetic flux lines of the coil, the permanent magnet M_1 and the permanent magnet M_2. In FIG. 8, the closed magnetic flux lines generated by the permanent magnet M_1 passes through the magnetic gap $D_{1,1}$, the closed magnetic flux lines generated by the permanent magnet M_2 passes through the magnetic gap $D_{2,1}$, and the closed magnetic flux generated by the coil sequentially passes through the magnetic gap D_1 and the magnetic gap D_2.

[0097] Referring to FIG. 9, FIG. 9 is a diagram illustrating the relationship between the movable assembly, the magnetic domains $D_{1,1}$, $D_{2,2}$ and the stator assembly. In the magnetic domain $D_{1,1}$, the movable assembly is subjected to a leftward attractive force F_1 from the stator assembly, and in the magnetic domain $D_{2,1}$, the movable assembly is subjected to a rightward attractive force F_2 from the stator assembly. Taking the rightward direction as the positive direction, the resultant force of the stator assembly on the movable assembly is $-F_1 + F_2$.

[0098] Referring to FIG. 10, FIG. 10 is a force analysis diagram of the isolated movable assembly. The movable assembly is subjected to forces from the stator assembly, that is, a leftward attractive force F_1 and a rightward attractive force F_2, and the resultant force is $-F_1 + F_2$, expressed as:

$$F_{moving-magnet} = -F_1 + F_2.$$

[0099] Further derive the equation for the electromagnetic force generated by each magnetic domain. The magnitude of the electromagnetic attractive force acting on a magnetized ferromagnetic object is proportional to the total area of the magnetic poles through which the magnetic flux lines passes and the square of the magnetic induction intensity. If the magnetic induction intensity B is uniformly distributed along the surface of the magnetic pole and the calculated air gap length is small, the equation for calculating the electromagnetic attractive force is calculated by the Maxwell formula, expressed as:

$$F = C\,\frac{B^2 \cdot S}{2\mu_0} = C\,\frac{\emptyset^2}{2\mu_0 \cdot S}$$

where:

F: Electromagnetic attractive force
B: Magnetic flux density or magnetic induction intensity
Ø: Magnetic flux passing through the medium
S: Area of the magnetic pole through which the magnetic flux passes
μ_0: Air permeability
C: Coefficient related to the combination type and shape of the magnetic pole end faces, with different values for different scenarios. When the force is generated between permanent magnets, it is denoted as C_{m2m}, usually taking a value of 1, and the accurate value is obtained through actual measurement in the actual design process. When the

force is generated between a permanent magnet and a magnetic conductor (yoke iron), it is denoted as C_{m2y}, usually taking a value of 1/2, and the accurate value is obtained through actual measurement in the actual design process. When the force is generated between magnetic conductors (yoke iron), it is denoted as C_{y2y}, usually taking a value of 1/4, and the accurate value is obtained through actual measurement in the actual design process.

[0100] Applying the above equation to calculate the electromagnetic attractive forces in the above magnetic domain D_1 and magnetic domain D_2:

$$\begin{cases} F_1 = C_{y2y}\dfrac{(-\emptyset_i + \emptyset_m)^2}{2\mu_0 \cdot S_{D1}} \\ F_2 = C_{y2y}\dfrac{(\emptyset_i + \emptyset_m)^2}{2\mu_0 \cdot S_{D2}} \end{cases}$$

where S_{D1} and S_{D2} represent the areas of the annular end faces corresponding to magnetic domain $D_{1,1}$ and magnetic domain $D_{2,1}$ respectively, and $S_{D1} = S_{D2} = S_D$, thus:

$$\begin{cases} F_1 = C_{y2y}\dfrac{(\emptyset_m - \emptyset_i)^2}{2\mu_0 \cdot S_{D1}} = \dfrac{C_{y2y}}{2\mu_0 \cdot S_D}(\emptyset_i - \emptyset_m)^2 \\ F_2 = C_{y2y}\dfrac{(\emptyset_m + \emptyset_i)^2}{2\mu_0 \cdot S_{D2}} = \dfrac{C_{y2y}}{2\mu_0 \cdot S_D}(\emptyset_i + \emptyset_m)^2 \end{cases}$$

$$\begin{cases} F_1 = F_{1,linear} + F_{1,nonlinear} \\ F_2 = F_{2,linear} + F_{2,nonlinear} \end{cases}$$

where:

$$\begin{cases} F_{1,linear} = \dfrac{C_{y2y}}{2\mu_0 \cdot S_D}(\emptyset_m^2 - 2\emptyset_m\emptyset_i) \\ F_{1,nonlinear} = \dfrac{C_{y2y}}{2\mu_0 \cdot S_D}{\emptyset_i}^2 \end{cases}$$

$$\begin{cases} F_{2,linear} = \dfrac{C_{y2y}}{2\mu_0 \cdot S_D}(\emptyset_m^2 + 2\emptyset_m\emptyset_i) \\ F_{2,nonlinear} = \dfrac{C_{y2y}}{2\mu_0 \cdot S_D}{\emptyset_i}^2 \end{cases}$$

Since:

$$F_{moving-magnet} = -F_1 + F_2$$

We obtain:

$$F_{moving-magnet,linear} = F_{moving-magnet,linear} + F_{moving-magnet,nonlinear}$$

$$\begin{cases} F_{moving-magnet,linear} = F_{1,linear} - F_{2,linear} \\ F_{moving-magnet,nonlinear} = F_{1,nonlinear} - F_{2,nonlinear} \end{cases}$$

Substitute $F_{1,linear}$, $F_{2,linear}$, $F_{1,nonlinear}$, $F_{2,nonlinear}$ into $F_{moving-magnet,linear}$ and $F_{moving-magnet,nonlinear}$ respectively, we obtain:

$$F_{moving-magnet,linear} = -F_{1,linear} + F_{2,linear}$$
$$= -\frac{C_{y2y}}{2\mu_0 \cdot S_D}(\emptyset_m^2 - 2\emptyset_m\emptyset_i) + \frac{C_{y2y}}{2\mu_0 \cdot S_D}(\emptyset_m^2 + 2\emptyset_m\emptyset_i)$$
$$= -\frac{C_{y2y}}{2\mu_0 \cdot S_D}(\emptyset_m^2 - 2\emptyset_m\emptyset_i - (\emptyset_m^2 + 2\emptyset_m\emptyset_i)$$
$$= \frac{C_{y2y}}{2\mu_0 \cdot S_D}(4\emptyset_m\emptyset_i)$$
$$= \frac{2C_{y2y}\emptyset_m}{\mu_0 \cdot S_D}\emptyset_i$$

Since:

$$\emptyset_m = B_m S_m$$

$$\emptyset_i = G_i N i$$

It follows that:

$$F_{moving-magnet,linear} = \frac{2C_{y2y}\emptyset_m}{\mu_0 \cdot S_D}\emptyset_i = \frac{2C_{y2y}B_m S_m}{\mu_0 \cdot S_D}G_i N i = \frac{2C_{y2y}B_m S_m G_i N}{\mu_0 \cdot S_D} * i$$

Calculate $F_{moving\text{-}magnet,nonlinear}$ in a similar way as follows:

$$F_{moving-magnet,nonlinear} = -F_{1,nonlinear} + F_{2,nonlinear}$$
$$= -\frac{C_{y2y}}{2\mu_0 \cdot S_D}{\emptyset_i}^2 - \frac{C_{y2y}}{2\mu_0 \cdot S_D}{\emptyset_i}^2 = 0$$

Thus, the resultant force acting on the moving magnet, which serves as the moving component, is:

$$F_{moving-magnet} = F_{\text{moving-magnet},linear} + F_{\text{moving-magnet},nonlinear}$$
$$= \frac{2C_{y2y}B_m S_m G_i N}{\mu_0 \cdot S_D} * i + 0$$
$$= \frac{2C_{y2y}B_m S_m G_i N}{\mu_0 \cdot S_D} * i$$

[0101] From the above derivation process, the following characteristics may be seen:

1) In the linear term of the resultant force $F_{moving\text{-}magnet,linear}$, the linear terms of the component forces $F_{1,linear}$ and $F_{2,linear}$ are superimposed, so that the linear term of the resultant force $F_{moving\text{-}magnet,linear}$ and the coil current is larger.
2) In the nonlinear term of the resultant force $F_{moving\text{-}magnet,nonlinear}$, the nonlinear terms of the component forces $F_{1,nonlinear}$ and $F_{2,nonlinear}$ cancel each other out, so that the nonlinear term of the resultant force $F_{moving\text{-}magnet,nonlinear}$ is zero.

[0102] The above design method is called the design method of the moving-magnet vibrator with nonlinear term cancellation. This method can not only be used to design vibrators, but also be applied to design actuators. The moving-magnet vibrators or actuators obtained by the above method are called moving-magnet vibrator devices or actuators with nonlinear term cancellation.

Embodiment 5

[0103] Referring to FIGS. 12 to 16, a design method of a moving-magnet vibrator with nonlinear term cancellation includes conditions as follows.

(1) A moving-magnet vibrator body 11 is provided. The moving-magnet vibrator body 11 includes an outer cylinder 1, a vibration transmission plate 10, a stator assembly and a movable assembly. The stator assembly includes a coil combination structure, the movable assembly includes a magnet combination structure. The coil combination structure includes a coil 7 and a first magnetic conductor 5, and the magnet combination structure includes a permanent magnet 3 and a second magnetic conductor 2. The coil combination structure is fixed inside the outer cylinder 1, the vibration transmission plate 10 is fixed on the outer cylinder 1, and the movable assembly is fixedly connected to the vibration transmission plate 10 through at least one contact point. The movable assembly moves while the stator assembly remains stationary, and the movable assembly is referred to as a moving component.
(2) The movable assembly is simultaneously subjected to paired electromagnetic forces of push and pull, presenting push-pull structural characteristics.

[0104] 2N magnetic domains $D_{1,i}$ and $D_{2,i}$ which are designed as N symmetrical pairs are provided in the moving-magnet vibrator body 11, where N is 1, 2, 3, ..., 100, and i=1, 2, 3, ...
[0105] The number of a permanent magnet in the magnet combination structure and the number of a coil in the coil combination structure are limited, in such a manner that $N_{magnet}>N_{coil}$ or $N_{magnet} < N_{coil}$, where N_{magnet} represents the number of the permanent magnet, and N_{coil} represents the number of the coil, N_{magnet}=1, 2, 3, ..., 100, and N_{coil}=1, 2, 3, ..., 100.
[0106] In the push-pull structural characteristics, linear terms of an electromagnetic force acting on the movable assembly are superimposed so as to be increased, while nonlinear terms of the electromagnetic force acting on the movable assembly are partially or completely canceled so as to be decreased.
[0107] The closed main magnetic flux lines of the coil in the coil combination structure and the closed main magnetic flux lines of the permanent magnet in the magnet combination structure each pass through the magnetic domains $D_{1,i}$ and $D_{2,i}$. The magnetic domain is a spatial region filled with electromagnetic energy, is generally composed of air or a medium with low magnetic permeability (e.g., a relative magnetic permeability<1000), and includes a region where the magnet material is located. In the magnetic domain $D_{1,i}$, a direction of magnetic flux lines of the coil is the same as a direction of magnetic flux lines of the permanent magnet, while in the magnetic domain $D_{2,i}$, the direction of the magnetic flux lines of the coil is opposite to the direction of the magnetic flux lines of the permanent magnet. Alternatively, in the magnetic domain $D_{1,i}$, the direction of the magnetic flux lines of the coil is opposite to the direction of the magnetic flux lines of the permanent magnet, while in the magnetic domain $D_{2,i}$, the direction of the magnetic flux lines of the coil is the same as the direction of the magnetic flux lines of the permanent magnet.
[0108] The number of the permanent magnet 3 and the number of the coil 7 are limited, in which there are one permanent magnet 3, and two coils.
[0109] Four symmetrically paired magnetic domains $D_{1,1}$, $D_{2,1}$, $D_{1,2}$ and $D_{2,2}$ are provided in the moving-magnet vibrator body 11. The closed main magnetic flux lines of the coil 7 and the closed main magnetic flux lines of the permanent magnet 3 each pass through the magnetic domains $D_{1,1}$, $D_{2,1}$, $D_{1,2}$and $D_{2,2}$. In the magnetic domain $D_{1,1}$, the direction of the magnetic flux lines of the coil 7 is the opposite to the direction of the magnetic flux lines of the permanent magnet 3, while in the magnetic domain $D_{2,1}$, the direction of the magnetic flux lines of the coil 7 is the same as the direction of the magnetic flux lines of the permanent magnet 3.
[0110] The moving component is subjected to four forces. Each component force includes two parts: one part is a linear term of an excitation current i, and the other part is a nonlinear term of the excitation current i:

$$F_{moving-magnet,n}(i) = F_{moving-magnet,n,linear}(i) + F_{moving-magnet,n,nonlinear}(i),$$

where n = 1, 2, 3, ..., 2N - 1, 2N.
[0111] Accordingly, a resultant force on the moving component also includes two parts: one part is a linear term of the current i, and the other part is a nonlinear term of the current i, which is expressed as:

$$F_{moving-magnet,resultant\ force}(i) = F_{moving-magnet,resultant\ force,linear}(i) + F_{moving-magnet,resultant\ force,nonlinear}(i)$$

where:

$$F_{moving-magnet,resultant\ force}(i) = \sum_{n=1}^{2N} F_{moving-magnet,n}(i) = \sum_{n=1}^{N}(F_{moving-magnet,n,1}(i) + F_{moving-magnet,n,2}(i))$$

$$F_{moving-magnet,resultant\ force,linear}(i) = \sum_{n=1}^{2N} F_{moving-magnet,n,linear}(i) = \sum_{n=1}^{N}(F_{moving-magnet,linear,1}(i) + F_{moving-magnet,linear,2}(i))$$

$$F_{moving-magnet,resultant\ force,nonlinear}(i) = \sum_{n=1}^{2N} F_{moving-magnet,n,nonlinear}(i) = \sum_{n=1}^{N}(F_{moving-magnet,nonlinear,1}(i) + F_{moving-magnet,nonlinear,2}(i))$$

[0112] That is, the nonlinear terms in each component force are partially or completely canceled. In the final total resultant force $\sum_i(F_{1,i} + F_{2,i})$, the nonlinear terms of the total resultant force relative to the current are partially or completely canceled, and the linear terms are superimposed to be increased, thereby obtaining the moving-magnet vibrator with nonlinear term cancellation.

[0113] The movable assembly and the stator assembly are in concave-convex shapes and arranged in an interleaved engagement manner, and the closed main magnetic flux lines of the coil 7 and the closed main magnetic flux lines of the permanent magnet 3 alternately pass through the movable assembly and the stator assembly.

[0114] The design method further includes conditions as follows.

[0115] (3.1) Looking outward from a center, the coil 7 is located inside and the permanent magnet 3 is located outside.

[0116] (3.2) N_{coil}=2, where n is a natural number, and n=1.

[0117] (3.3) When N_{coil}>1, the currents in adjacent coils have opposite directions, and the polarities of the electromagnetic fields on the two end faces of two adjacent coils are the same.

[0118] The magnetic conductor is arranged at a position of the outer cylinder 1 close to the coil 7, so as to minimize the magnetic resistance of the magnetic circuit of an electromagnet 3 generated by the coil 7. The permanent magnet 3 in the magnet assembly is isolated by the magnetic conductor. A yoke iron is arranged around the coil 7 and the permanent magnet 3, or alternatively, for the coil combination structure, a part of the outer cylinder 1 close to the coil is magnetically conductive.

Embodiment 6

[0119] Referring to FIGS. 12 to 16, a moving-magnet vibrator device with nonlinear term cancellation designed by the method of Embodiment 5 includes a moving-magnet vibrator body 11. The moving-magnet vibrator body 11 includes an outer cylinder 1, a vibration transmission plate 10, a stator assembly and a movable assembly. The stator assembly includes a coil combination structure. The movable assembly includes a magnet combination structure. The coil combination structure includes a coil 7 and a first magnetic conductor 9. The magnet combination structure includes a permanent magnet 3 and a second magnetic conductor 2. The coil combination structure further includes a first magnetic conductive ring 4 and a second magnetic conductive ring 5. Viewed from a center outward, the coil 7 is inside and the permanent magnet 3 is outside. There are one permanent magnet 3, and two coils 7. The currents in adjacent coils have opposite directions. For two adjacent coils, the polarities of the electromagnetic fields on the adjacent faces are the same. There is one vibration transmission plate 10 fixed on a top surface of the outer cylinder 1. An end of the first magnetic conductor 9 is fixed on a bottom surface of the outer cylinder 1, and the two coils 7 are wound around and fixed on the first magnetic conductor 9. The second magnetic conductive ring 5 is fixed at an end of the first magnetic conductor 9, and the first magnetic conductive ring 4 is wound around and fixed on a middle part of the first magnetic conductor 9 and located between the two coils 7. An L-shaped vibration transmission bracket 8 is provided, a horizontal part of the vibration transmission bracket 8 is parallel to a vibration direction. The permanent magnet 3 is fixed in middle of the horizontal part of the vibration transmission bracket 8, and two second magnetic conductors 2 are located on two sides of the permanent magnet 3 and fixed on the horizontal part of the vibration transmission bracket 8. The movable assembly and the stator assembly are in concave-convex shapes and arranged in an interleaved engagement manner. Closed magnetic flux lines of the coils 7 and closed magnetic flux lines of the permanent magnet 3 alternately pass through the movable assembly and the stator assembly. Four magnetic domains $D_{1,1}$, $D_{2,1}$, $D_{1,2}$and $D_{2,2}$ which are designed as two symmetrical pairs are provided in the moving-magnet vibrator body, where $D_{1,1}$ is symmetric to $D_{2,1}$, and $D_{1,2}$ is symmetric to $D_{2,2}$. The closed magnetic flux lines of the coils 7 and the closed magnetic flux lines of the permanent magnet 3 each pass through the magnetic domains $D_{1,1}$, $D_{2,1}$, $D_{1,2}$ and $D_{2,2}$ respectively. In the magnetic domain $D_{1,1}$, a direction of magnetic flux lines of the coil 7 is opposite to a direction of magnetic flux lines of the permanent magnet 3. In the magnetic domain $D_{2,1}$, the direction of the magnetic flux lines of the coil 7 is the same as the direction of the magnetic flux lines of the permanent magnet 3.

[0120] To further illustrate the design method of the moving-magnet vibrator with nonlinear term cancellation, referring to FIGS. 12 to 14, there are 4 air gaps forming magnetic action domains $D_{1,1}$, $D_{2,1}$, $D_{1,2}$ and $D_{2,2}$ respectively. In the magnetic action domain, the total magnetic flux/magnetic induction intensity generated by the superposition of the magnetic field generated by the permanent magnet 3 and the magnetic field generated by the electromagnet of the coils 7 causes mutual forces between the components around the magnetic domain. The above magnetic domains $D_{1,1}$, $D_{2,1}$, $D_{1,2}$ and $D_{2,2}$ are enclosed by the stator assembly and the movable assembly. Therefore, in these magnetic domains, mutual component forces are generated between the stator assembly and the movable assembly.

[0121] The current passing through the coil C_1 is i_1, the current passing through the coil C_2 is i_2 , and the corresponding magnetic fluxes of the coils are Φ_{i1} and Φ_{i2} respectively. The magnetic flux corresponding to the permanent magnet M_1 is Φ_{M1}.

[0122] The magnetic domains $D_{1,1}$, $D_{2,1}$, $D_{1,2}$ and $D_{2,2}$ may be paired into magnetic domain pairs $D_j = (D_{1,j}, D_{2,j})$ according to symmetry, where j=1, 2. The domain pairs include $D_1 = (D_{1,1}, D_{2,1})$ and $D_2 = (D_{1,2}, D_{2,2})$.

1) For the magnetic flux of the magnetic domain pair $D_j = (D_{1,j}, D_{2,j})$ when j = 1, that is, the magnetic flux of the magnetic domain pair $D_1 = (D_{1,1}, D_{2,1})$.

In the magnetic domain $D_{1,1}$, the direction of the magnetic flux lines corresponding to the coil C_1 is opposite to that corresponding to the permanent magnet M_1. Therefore, the total magnetic flux in the magnetic domain $D_{1,1}$ is the difference between Φ_{i1} and $\Phi_{M1} = \Phi_m$. In the magnetic domain $D_{2,1}$, the direction of the magnetic flux lines corresponding to the coil C_2 is the same as that corresponding to the permanent magnet M_1. Therefore, the total magnetic flux in the magnetic domain $D_{2,1}$ is the sum of Φ_{i2} and $\Phi_{M1} = \Phi_m$.

Assuming $i_1 = i_2 = i$, $\Phi_{i1} = \Phi_{i2} = \Phi_i$, and the direction of the magnetic flux lines of the magnet M_1 is positive (the magnetic flux is also positive), then:

$$\Phi_{D1,1} = \Phi_{M1} - \Phi_{i1} = \Phi_m - \Phi_i$$

$$\Phi_{D2,1} = \Phi_{M1} + \Phi_{i2} = \Phi_m + \Phi_i$$

2) For the magnetic flux of the magnetic domain pair $D_i = (D_{1,j}, D_{2,j})$ when j = 2, that is, the magnetic flux of the magnetic domain pair $D_2 = (D_{1,2}, D_{2,2})$.

[0123] In the magnetic domain $D_{1,2}$, only the magnetic flux lines corresponding to the coil C_1 pass through, so the total magnetic flux is only $\Phi_{i1} = \Phi_i$. In the magnetic domain $D_{2,2}$, only the magnetic flux lines corresponding to the coil C_2 pass through, so the total magnetic flux is only $\Phi_{i2} = \Phi_i$.

[0124] Assuming the magnetic resistances of the magnetic circuits formed by the electromagnetic field generated by the current i in the coils C_1 and C_2 are both Z_i, N represents the number of turns of the coils C_1 and C_2, and i is the current intensity, we have:

$$\emptyset_i * Z_i = N * i$$

[0125] Assuming that the magnetic conductance of the magnetic circuit formed by the electromagnetic field generated by the current is G_i, we have:

$$\emptyset_i = \mathrm{G}_i * N * i.$$

[0126] The magnetic flux corresponding to the permanent magnet 3 may also be expressed by the equation of magnetic induction intensity. Assuming that the magnetic induction intensities at the magnetic pole end faces of the permanent magnet M_1 is B_{m1}, the area of the magnetic pole end face is S_m, it follows that $\emptyset_m = B_m S_m$.

[0127] Thus, we have:

$$\begin{cases} \emptyset_{D1,1} = \emptyset_m - \emptyset_i = B_m S_m - \mathrm{G}_i * N * i \\ \emptyset_{D2,1} = \emptyset_m + \emptyset_i = \mathrm{G}_i * N * i + B_m S_m \end{cases}$$

$$\begin{cases} \emptyset_{D1,2} = -\emptyset_i = -\mathrm{G}_i * N * i \\ \emptyset_{D2,2} = \emptyset_i = \mathrm{G}_i * N * i \end{cases}$$

[0128] Referring to FIGS. 13 and 14, FIGS. 13 and 14 show the closed magnetic flux lines of the coils C_1 and C_2, as well as the closed magnetic flux lines of the magnet M_1. In FIGS. 13 and 14, the closed magnetic flux lines generated by the coil C_1 pass through the magnetic gaps $D_{1,1}$, and $D_{2,1}$, the closed magnetic flux lines generated by the coil C_2 pass through the magnetic gaps $D_{2,1}$, *and* $D_{2,2}$, and the closed magnetic flux lines generated by the magnet M_1 sequentially pass through the magnetic gaps $D_{1,1}$ and $D_{2,1}$.

[0129] Referring to FIG. 15, FIG. 15 is a diagram of the relationship between the movable assembly, the magnetic domains $D_{1,1}$, $D_{2,1}$, $D_{1,2}$ and $D_{2,2}$ and the stator assembly. In the magnetic domain $D_{1,1}$, the movable assembly is subjected to a rightward attractive force $F_{1,1}$ from the stator assembly. In the magnetic domain $D_{2,1}$, the movable assembly is subjected to a leftward attractive force $F_{2,1}$ from the stator assembly. In the magnetic domain $D_{1,2}$, the movable assembly is subjected to a leftward attractive force $F_{1,2}$ from the stator assembly; in the magnetic domain $D_{2,2}$, the movable assembly is subjected to a rightward attractive force $F_{2,2}$ from the stator assembly.

[0130] Assuming the resultant force corresponding to the magnetic domain pair $D_j = (D_{1,j}, D_{2,j})$ is F_j (its positive or negative indicates different directions of the force), and taking the rightward direction as positive, the resultant force exerted on the movable assembly by the stator assembly is:

$$F_{moving-magnet} = F_1 + F_2 = \mathrm{F}_{1,1} - \mathrm{F}_{2,1} - \mathrm{F}_{1,2} + \mathrm{F}_{2,2}$$

$$F_{moving-magnet} = F_1 + F_2 = (\mathrm{F}_{1,1} - \mathrm{F}_{2,1}) + (-\mathrm{F}_{1,2} + \mathrm{F}_{2,2})$$

where F_j is the resultant force of the component forces corresponding to the magnetic domain pair $D_j = (D_{1,j}, D_{2,j})$.

[0131] Referring to FIG. 15, FIG. 15 is a force analysis diagram of the isolated movable assembly. The movable assembly is subjected to component forces $F_{1,1}$, $F_{2,1}$, $F_{1,2}$ and $F_{2,2}$ from the stator assembly, and its resultant force is:

$$F_{moving-magnet} = F_1 + F_2 = \left(F_{1,1} - F_{2,1}\right) + (-F_{1,2} + F_{2,2})$$

[0132] The above equation may also be expressed by including the direction of the force through the sign of the component force as:

$$F_{moving-magnet} = \sum_{j=1}^{2} F_j = \sum_{j=1}^{2} (F_{1,j} + F_{2,j})$$

[0133] The various component forces are grouped into two-by-two paired magnetic domain pairs. Each magnetic domain pair corresponds to the resultant force of a different magnetic domain pair D_j, such as $F1 = F_{1,1} - F_{2,1}$ and $F2 = -F_{1,2} + F_{2,2}$, then the total resultant force is calculated.

[0134] Further derive the equation for the electromagnetic force generated by each magnetic domain. The magnitude of the electromagnetic attractive force acting on a magnetized ferromagnetic object is proportional to the total area of the magnetic poles through which the magnetic flux lines passes and the square of the magnetic induction intensity. If the magnetic induction intensity B is uniformly distributed along the surface of the magnetic pole and the calculated air gap length is small, the equation for calculating the electromagnetic attractive force is calculated by the Maxwell formula, expressed as:

$$F = C\,\frac{B^2 \cdot S}{2\mu_0} = C\,\frac{\emptyset^2}{2\mu_0 \cdot S}$$

where:

F: Electromagnetic attractive force
B: Magnetic flux density or magnetic induction intensity
Ø: Magnetic flux passing through the medium
S: Area of the magnetic pole through which the magnetic flux passes
μ_0: Air permeability
C: Coefficient related to the combination type and shape of the magnetic pole end faces, with different values for different scenarios. When the force is generated between permanent magnets, it is denoted as C_{m2m}, usually taking a value of 1, and the accurate value is obtained through actual measurement in the actual design process. When the force is generated between a permanent magnet and a magnetic conductor (yoke iron), it is denoted as C_{m2y}, usually taking a value of 1/2, and the accurate value is obtained through actual measurement in the actual design process. When the force is generated between magnetic conductors (yoke iron), it is denoted as C_{y2y}, usually taking a value of 1/4, and the accurate value is obtained through actual measurement in the actual design process.

1) Calculate F_j when j = 1, corresponding to the magnetic domain pair $D_j = (D_{1,j}, D_{2,j})$ when j = 1.
The resultant force of the component forces corresponding to the magnetic domain pair $D_1 = (D_{1,1}, D_{2,1})$ is $F_1 = F_{1,1} - F_{2,1}$. Applying the above formula to calculate the electromagnetic attractive forces in the magnetic domains $D_{1,1}$ and $D_{2,1}$, we have:

$$\begin{cases} F_{1,1} = C_{y2y}\dfrac{(\emptyset_{D1,1})^2}{2\mu_0 \cdot S_{D1,1}} = C_{y2y}\dfrac{(-\emptyset_i + \emptyset_m)^2}{2\mu_0 \cdot S_{D1,1}} \\ F_{2,1} = C_{y2y}\dfrac{(\emptyset_{D2,1})^2}{2\mu_0 \cdot S_{D2,1}} = C_{y2y}\dfrac{(\emptyset_i + \emptyset_m)^2}{2\mu_0 \cdot S_{D2,1}} \end{cases}$$

where $S_{D1,1}$ and $S_{D2,1}$ represent the areas of the annular end faces corresponding to magnetic domain $D_{1,1}$ and magnetic domain $D_{2,1}$ respectively, and $S_{D1,1} = S_{D2,1} = S_D$, thus:

$$\begin{cases} F_{1,1} = C_{y2y}\dfrac{(\emptyset_m - \emptyset_i)^2}{2\mu_0 \cdot S_{D1,1}} = \dfrac{C_{y2y}}{2\mu_0 \cdot S_D}\,(-\emptyset_i + \emptyset_m)^2 \\ F_{2,1} = C_{y2y}\dfrac{(\emptyset_m + \emptyset_i)^2}{2\mu_0 \cdot S_{D2,1}} = \dfrac{C_{y2y}}{2\mu_0 \cdot S_D}\,(\emptyset_i + \emptyset_m)^2 \end{cases}$$

$$\begin{cases} F_{1,1} = F_{1,1,linear} + F_{1,1,nonlinear} \\ F_{2,1} = F_{2,1,linear} + F_{2,1,nonlinear} \end{cases}$$

where:

$$\begin{cases} F_{1,1,linear} = \dfrac{C_{y2y}}{2\mu_0 \cdot S_D}\,(\emptyset_m^2 - 2\emptyset_m\emptyset_i) \\ F_{1,1,nonlinear} = \dfrac{C_{y2y}}{2\mu_0 \cdot S_D}\,{\emptyset_i}^2 \end{cases}$$

$$\begin{cases} F_{2,1,linear} = \frac{C_{y2y}}{2\mu_0 \cdot S_D} (\emptyset_m^2 + 2\emptyset_m\emptyset_i) \\ F_{2,1,nonlinear} = \frac{C_{y2y}}{2\mu_0 \cdot S_D} {\emptyset_i}^2 \end{cases}$$

Since:

$$F_1 = F_{1,1} - F_{2,1}$$

We obtain

$$F_{1,linear} = F_{1,linear} + F_{1,nonlinear}$$

$$\begin{cases} F_{1,linear} = F_{1,1,linear} - F_{2,1,linear} \\ F_{1,nonlinear} = F_{1,1,nonlinear} - F_{2,1,nonlinear} \end{cases}$$

Substitute $F_{1,1,linear}$, $F_{2,1,linear}$, $F_{1,1,nonlinear}$, $F_{2,1,nonlinear}$ into $F_{1,linear}$ and $F_{1,nonlinear}$ respectively, we obtain:

$$F_{1,linear} = F_{1,1,linear} - F_{2,1,linear}$$
$$= \frac{C_{y2y}}{2\mu_0 \cdot S_D}(\emptyset_m^2 - 2\emptyset_m\emptyset_i) - \frac{C_{y2y}}{2\mu_0 \cdot S_D}(\emptyset_m^2 + 2\emptyset_m\emptyset_i)$$
$$= \frac{C_{y2y}}{2\mu_0 \cdot S_D} (\emptyset_m^2 - 2\emptyset_m\emptyset_i - (\emptyset_m^2 + 2\emptyset_m\emptyset_i)$$
$$= \frac{C_{y2y}}{2\mu_0 \cdot S_D} (-4\emptyset_m\emptyset_i)$$
$$= -\frac{2C_{y2y}\emptyset_m}{\mu_0 \cdot S_D} \emptyset_i$$

Since:

$$\emptyset_m = B_m S_m$$

$$\emptyset_i = G_i N i$$

It follows that:

$$F_{1,linear} = -\frac{2C_{y2y}\emptyset_m}{\mu_0 \cdot S_D} \emptyset_i = -\frac{2C_{y2y}B_m S_m}{\mu_0 \cdot S_D} G_i N i = -\frac{2C_{y2y}B_m S_m G_i N}{\mu_0 \cdot S_D} * i$$

Calculate $F_{1,nonlinear}$ in a similar way as follows:

$$F_{1,nonlinear} = F_{1,1,nonlinear} - F_{2,1,nonlinear}$$
$$= \frac{C_{y2y}}{2\mu_0 \cdot S_D} {\emptyset_i}^2 - \frac{C_{y2y}}{2\mu_0 \cdot S_D} {\emptyset_i}^2 = 0$$

Thus, the resultant force $D_1 = (D_{1,1}, D_{2,1})$ of component forces is:

$$F_1 = F_{1,linear} + F_{1,nonlinear} = -\frac{2C_{y2y}B_m S_m G_i N}{\mu_0 \cdot S_D} * i + 0 = -\frac{2C_{y2y}B_m S_m G_i N}{\mu_0 \cdot S_D} * i$$

2) Calculate F_j when j = 2, corresponding to the magnetic domain pair $D_j = (D_{1,j}, D_{2,j})$ when j = 2.

[0135] The resultant force of the component forces corresponding to the magnetic domain pair $D_2 = (D_{1,2}, D_{2,2})$ is $F_2 = -F_{1,2} + F_{2,2}$. Calculate the electromagnetic attractive forces in the magnetic domains $D_{1,2}$ and $D_{2,2}$, we have:

$$\begin{cases} F_{1,2} = C_{y2y}\dfrac{(\emptyset_{D1,2})^2}{2\mu_0 \cdot S_{D1,2}} = C_{y2y}\dfrac{{\emptyset_i}^2}{2\mu_0 \cdot S_{D1,2}} \\ F_{2,2} = C_{y2y}\dfrac{(\emptyset_{D2,2})^2}{2\mu_0 \cdot S_{D2,2}} = C_{y2y}\dfrac{{\emptyset_i}^2}{2\mu_0 \cdot S_{D2,2}} \end{cases}$$

where $S_{D1,2}$ and $S_{D2,2}$ represent the areas of the annular end faces corresponding to magnetic domain $D_{1,2}$ and magnetic domain $D_{2,2}$ respectively, and $S_{D1,2} = S_{D2,2} = S_D$, thus:

$$\begin{cases} F_{1,2} = C_{y2y}\dfrac{(\emptyset_{D1,2})^2}{2\mu_0 \cdot S_{D1,2}} = C_{y2y}\dfrac{{\emptyset_i}^2}{2\mu_0 \cdot S_D} \\ F_{2,2} = C_{y2y}\dfrac{(\emptyset_{D2,2})^2}{2\mu_0 \cdot S_{D2,2}} = C_{y2y}\dfrac{{\emptyset_i}^2}{2\mu_0 \cdot S_D} \end{cases}$$

Consequently,

$$F_2 = F_{2,linear} + F_{2,nonlinear} = -F_{1,2} + F_{2,2} = -C_{y2y}\frac{{\emptyset_i}^2}{2\mu_0 \cdot S_D} + C_{y2y}\frac{{\emptyset_i}^2}{2\mu_0 \cdot S_D} = 0$$

We obtain:

$$\begin{cases} F_{2,linear} = 0 \\ F_{2,nonlinear} = 0 \end{cases}$$

Since the resultant force on the movable assembly:

$$F_{moving-magnet} = F_1 + F_2$$

$$F_{moving-magnet} = F_{moving-magnet,linear} + F_{moving-magnet,nonlinear}$$

Thus:

$$F_{moving-magnet,linear} = F_{1,linear} + F_{2,linear} = -\frac{2C_{y2y}B_m S_m G_i N}{\mu_0 \cdot S_D} * i + 0 = -\frac{2C_{y2y}B_m S_m G_i N}{\mu_0 \cdot S_D} * i$$

$$F_{moving-magnet,nonlinear} = F_{1,nonlinear} + F_{2,nonlinear} = 0 + 0 = 0$$

[0136] From the above derivation process, the following characteristics may be seen:

1) In the linear term of the resultant force $F_{moving\text{-}magnet,linear}$, the linear terms of the component forces $F_{1,linear}$ and $F_{2,linear}$ are superimposed, so that the linear term of the resultant force $F_{moving\text{-}magnet,linear}$ still has a linear relationship with the coil current.
2) In the nonlinear term of the resultant force $F_{moving\text{-}magnet,nonlinear}$, the nonlinear terms of the component forces $F_{1,nonlinear}$ and $F_{2,nonlinear}$ cancel each other out, so that the nonlinear term of the resultant force $F_{moving\text{-}magnet,nonlinear}$ is zero.

[0137] The above design method is called the design method of the moving-magnet vibrator with nonlinear term cancellation. This method can not only be used to design vibrators, but also be applied to design actuators. The moving-magnet vibrators or actuators obtained by the above method are called moving-magnet vibrator devices or actuators with nonlinear term cancellation.

Embodiment 7

[0138] Referring to FIGS. 17 to 21, a design method of a moving-magnet vibrator with nonlinear term cancellation includes conditions as follows.

(1) A moving-magnet vibrator body 11 is provided. The moving-magnet vibrator body 11 includes an outer cylinder 1, a vibration transmission plate 9, a stator assembly and a movable assembly. The stator assembly includes a coil combination structure, the movable assembly includes a magnet combination structure. The coil combination structure includes a coil 3 and a first magnetic conductor 4, and the magnet combination structure includes a permanent magnet 6 and a second magnetic conductor 5. The stator assembly is fixed inside the outer cylinder 1, the vibration transmission plate 9 is fixed on the outer cylinder 1, and the movable assembly is fixedly connected to the vibration transmission plate 9 through at least one contact point. The movable assembly moves while the stator assembly remains stationary, and the movable assembly is referred to as a moving component.
(2) The movable assembly is simultaneously subjected to paired electromagnetic forces of push and pull, presenting push-pull structural characteristics.

[0139] 2N magnetic domains $D_{1,i}$ and $D_{2,i}$ which are designed as N symmetrical pairs are provided in the moving-magnet vibrator body 11, where N is 1, 2, 3, ..., 100, and i=1, 2, 3, ...

[0140] The number of a permanent magnet in the magnet combination structure and the number of a coil in the coil combination structure are limited, in such a manner that $N_{magnet}>N_{coil}$ or $N_{magnet} < N_{coil}$, where N_{magnet} represents the number of the permanent magnet, and N_{coil} represents the number of the coil, N_{magnet}=1, 2, 3, ..., 100, and N_{coil}=1, 2, 3, ..., 100.

[0141] In the push-pull structural characteristics, linear terms of an electromagnetic force acting on the movable assembly are superimposed so as to be increased, while nonlinear terms of the electromagnetic force acting on the movable assembly are partially or completely canceled so as to be decreased.

[0142] The closed main magnetic flux lines of the coil in the coil combination structure and the closed main magnetic flux lines of the permanent magnet in the magnet combination structure each pass through the magnetic domains $D_{1,i}$ and $D_{2,i}$. The magnetic domain is a spatial region filled with electromagnetic energy, is generally composed of air or a medium with low magnetic permeability (e.g., a relative magnetic permeability<1000), and includes a region where the magnet material is located. In the magnetic domain $D_{1,i}$, a direction of magnetic flux lines of the coil is the same as a direction of magnetic flux lines of the permanent magnet, while in the magnetic domain $D_{2,i}$, the direction of the magnetic flux lines of the coil is opposite to the direction of the magnetic flux lines of the permanent magnet. Alternatively, in the magnetic domain $D_{1,i}$, the direction of the magnetic flux lines of the coil is opposite to the direction of the magnetic flux lines of the permanent magnet, while in the magnetic domain $D_{2,i}$ the direction of the magnetic flux lines of the coil is the same as the direction of the magnetic flux lines of the permanent magnet.

[0143] The number of the permanent magnet 6 and the number of the coil 3 are limited, in which there are two permanent magnets, and three coils.

[0144] Six magnetic domains $D_{1,1}$, $D_{2,1}$, $D_{1,2}$, $D_{2,2}$, $D_{1,3}$, and $D_{2,3}$ which are designed as three symmetrical pairs are provided in the moving-magnet vibrator body, where $D_{1,1}$ is symmetric to $D_{2,1}$, $D_{1,2}$ is symmetric to $D_{2,2}$, and $D_{1,3}$ is symmetric to $D_{2,3}$. The closed magnetic flux lines of the coils 3 and the closed magnetic flux lines of the permanent magnets 6 each pass through the magnetic domains $D_{1,1}$, $D_{2,1}$, $D_{1,2}$, $D_{2,2}$, $D_{1,3}$, and $D_{2,3}$. In the magnetic domain $D_{1,1}$, a direction of magnetic flux lines of the coil 3 is opposite to a direction of magnetic flux lines of the permanent magnet 6. In the magnetic domain $D_{2,1}$, the direction of the magnetic flux lines of the coil 3 is the same as the direction of the magnetic flux lines of the permanent magnet 6. In the magnetic domain $D_{1,2}$, the direction of the magnetic flux lines of the coil 3 is the same as the direction of the magnetic flux lines of the permanent magnet 6. In the magnetic domain $D_{2,2}$, the direction of the magnetic flux lines of the coil 3 is opposite to the direction of the magnetic flux lines of the permanent magnet 6.

[0145] The moving component is subjected to six forces. Each component force includes two parts: one part is a linear term of an excitation current i, and the other part is a nonlinear term of the excitation current i:

$$F_{moving-magnet,n}(i) = F_{moving-magnet,n,linear}(i) + F_{moving-magnet,n,nonlinear}(i),$$

where n = 1, 2, 3, ..., 2N - 1, 2N.

[0146] Accordingly, a resultant force on the moving component also includes two parts: one part is a linear term of the current i, and the other part is a nonlinear term of the current i, which is expressed as:

$$\mathrm{F}_{\text{moving-magnet,resultant force}}(\mathrm{i}) = \mathrm{F}_{\text{moving-magnet,resultant force,linear}}(\mathrm{i}) + \mathrm{F}_{\text{moving-magnet,resultant force,nonlinear}}(\mathrm{i})$$

where:

$$\mathrm{F}_{\text{moving-magnet,resultant force}}(\mathrm{i}) = \sum_{n=1}^{2N} \mathrm{F}_{\text{moving-magnet,n}}(\mathrm{i}) = \sum_{n=1}^{N} (\mathrm{F}_{\text{moving-magnet,n,1}}(\mathrm{i}) + \mathrm{F}_{\text{moving-magnet,n,2}}(\mathrm{i}))$$

$$\mathrm{F}_{\text{moving-magnet,resultant force,linear}}(\mathrm{i}) = \sum_{n=1}^{2N} \mathrm{F}_{\text{moving-magnet,n,linear}}(\mathrm{i}) = \sum_{n=1}^{N} (\mathrm{F}_{\text{moving-magnet,linear,1}}(\mathrm{i}) + \mathrm{F}_{\text{moving-magnet,linear,2}}(\mathrm{i}))$$

$$\mathrm{F}_{\text{moving-magnet,resultant force,nonlinear}}(\mathrm{i}) = \sum_{n=1}^{2N} \mathrm{F}_{\text{moving-magnet,n,nonlinear}}(\mathrm{i}) = \sum_{n=1}^{N} (\mathrm{F}_{\text{moving-magnet,nonlinear,1}}(\mathrm{i}) + \mathrm{F}_{\text{moving-magnet,nonlinear,2}}(\mathrm{i}))$$

[0147] That is, the nonlinear terms in each component force are partially or completely canceled. In the final total resultant force $\sum_i(F_{1,i} + F_{2,i})$, the nonlinear terms of the total resultant force relative to the current are partially or completely canceled, and the linear terms are superimposed to be increased, thereby obtaining the moving-magnet vibrator with nonlinear term cancellation.

[0148] The movable assembly and the stator assembly are in concave-convex shapes and arranged in an interleaved engagement manner. The closed main magnetic flux lines of the coils 3 and the closed main magnetic flux lines of the permanent magnet 6 alternately pass through the movable assembly and the stator assembly.

[0149] The design method further includes conditions as follows.

[0150] (3.1) Looking outward from a center, the coil 3 is located outside and the permanent magnet is located inside.

[0151] (3.2) N_{coil}=3, and N_{magnet}=2.

[0152] (3.3) When $N_{magnet} > 1$, the polarities of the two opposite end faces of the adjacent permanent magnets 6 are the same. When $N_{coil}>1$, the currents in adjacent coils 3 have opposite directions, and the polarities of the electromagnetic fields on the two end faces of two adjacent coils 3 are the same.

[0153] The magnetic conductor is arranged at a position of the outer cylinder 1 close to the coil 3, so as to minimize the magnetic resistance of the magnetic circuit of an electromagnet generated by the coil 3. A yoke iron is arranged around the coil 3 and the permanent magnet 6, or alternatively, for the coil combination structure, a part of outer cylinder a close to the coil is magnetically conductive.

Embodiment 8

[0154] Referring to FIGS. 17 to 21, a moving-magnet vibrator device with nonlinear term cancellation designed by the method of Embodiment 7 includes a moving-magnet vibrator body 11. The moving-magnet vibrator body 11 includes an outer cylinder 1, a vibration transmission plate 9, a stator assembly and a movable assembly. The stator assembly includes a coil combination structure, and the movable assembly includes a magnet combination structure. The coil combination structure includes a coil 3 and a first magnetic conductor 4, the magnet combination structure includes a permanent magnet 6 and a second magnetic conductor 8. The coil combination structure further includes a first magnetic conductor ring 2. When looking from a center outward, the coil 3 is located outside and the permanent magnet 6 is located inside. Two permanent magnets 6 are provided, and polarities of two opposite end faces of adjacent permanent magnets 6 are the same. Three coils 3 are provided, directions of currents in adjacent coils 3 are opposite, and polarities of electromagnetic fields at adjacent end faces of two adjacent coils 3 are the same. Two vibration transmission plates 9 are provided and are respectively fixed on a top surface and a bottom surface of the outer cylinder 1. Two permanent magnets 6 are fixed on two sides of the second magnetic conductor 8. The two permanent magnets are respectively fixed on magnetic conductive sleeves 5, and the magnetic conductive sleeves 5 are respectively fixed on the two vibration transmission plates 9. The three coils are sequentially fixed on an inner side wall of the outer cylinder 1. The first magnetic conductor 4 is fixedly arranged between adjacent coils 3. The first magnetic conductive ring 2 is fixedly arranged on an outer side of the outermost coils 3, and both the first magnetic conductor 4 and the first magnetic conductive ring 2 are fixed on the inner side wall of the outer cylinder 1. The movable assembly and the stator assembly are in concave-convex shapes and arranged in an interleaved engagement manner. Closed magnetic flux lines of the coils 3 and closed magnetic flux lines of the permanent magnets 6 alternately pass through the movable assembly and the stator assembly. Six magnetic domains $D_{1,1}$, $D_{2,1}$, $D_{1,2}$, $D_{2,2}$, $D_{1,3}$, and $D_{2,3}$ which are designed as three symmetrical pairs are provided in the moving-magnet vibrator body 1, where $D_{1,1}$ is symmetric to $D_{2,1}$, $D_{1,2}$ is symmetric to $D_{2,2}$, and $D_{1,3}$ is symmetric to $D_{2,3}$. The closed magnetic flux lines of the coils 3 and the closed magnetic flux lines of the permanent magnets 6 each pass through the magnetic domains $D_{1,1}$, $D_{2,1}$, $D_{1,2}$, $D_{2,2}$, $D_{1,3}$, and $D_{2,3}$. In the magnetic domain $D_{1,1}$, a direction of magnetic flux lines of the coil 3 is opposite to a direction of magnetic flux lines of the permanent magnet 6. In the magnetic domain $D_{2,1}$, the direction of the magnetic flux lines of the coil 3 is the same as the direction of the magnetic flux lines of the permanent magnet 6. In the magnetic domain $D_{1,2}$, the direction of the magnetic flux lines of the coil 3 is the same as the direction of the magnetic flux lines of the permanent magnet 6. In the magnetic domain $D_{2,2}$, the direction of the magnetic flux lines of the coil 3 is opposite to the direction of the magnetic flux lines of the permanent magnet 6.

[0155] Referring to FIG. 18, the magnetic action domains $D_{1,1}$, $D_{2,1}$, $D_{1,2}$, $D_{2,2}$, $D_{1,3}$, and $D_{2,3}$ are formed by 6 air gaps respectively. In the magnetic action domain, the total magnetic flux/magnetic induction intensity generated by the superposition of the magnetic field generated by the permanent magnets and the magnetic field generated by the electromagnet of the coils causes mutual forces between the components around the magnetic domain. The above magnetic domains $D_{1,1}$, $D_{2,1}$, $D_{1,2}$, $D_{2,2}$, $D_{1,3}$, and $D_{2,3}$ are enclosed by the stator assembly and the movable assembly. Therefore, in these magnetic domains, mutual forces are generated between the stator assembly and the movable assembly.

[0156] FIG. 19 illustrates the closed magnetic flux lines of the coils C_1, C_2, and C_3, as well as the closed magnetic flux lines of the magnets M_1 and M_2. The closed magnetic flux lines generated by the coil C_1 pass through the magnetic gaps $D_{1,2}$ and $D_{1,3}$, the closed magnetic flux lines generated by the coil C_2 pass through the magnetic gaps $D_{1,1}$ and $D_{2,1}$, and the closed magnetic flux lines generated by the coil C_3 pass through the magnetic gaps $D_{2,2}$ and $D_{2,3}$. The closed magnetic flux lines generated by the magnet M_1 sequentially pass through the magnetic gaps $D_{1,1}$ and $D_{1,2}$, and the closed magnetic flux lines generated by the magnet M_2 sequentially pass through the magnetic gaps $D_{2,1}$ and $D_{2,2}$.

[0157] Assuming that the currents passing through the coils C_1, C_2, and C_3 are i_1, i_2, and i_3 respectively, and $i_1 = i_2 = i_3 = i$. The corresponding magnetic fluxes of the coils are Φ_{i1}, Φ_{i2} and Φ_{i3} respectively. For the simplicity of derivation, assuming that $\Phi_{i1} = \Phi_{i2} = \Phi_{i3} = \Phi_i$ (another case is $N_1 = N_3 \neq N_2$, where N_1, N_2, N_3 are the number of turns of the coins C_1, C_2, and C_3, respectively; or the magnetic resistance of C_2 is different from that of C_1 and C_3 due to the magnetic circuit structures of C_1, C_2, and C_3, thus $\Phi_{i1} = O_{i3} \neq \Phi_{i2}$. For this case, because of the overall symmetrical design, the conclusion that the nonlinear terms in the resultant force of the paired forces cancel each other still holds). The magnetic fluxes corresponding to the permanent magnets M_1 and M_2 are $\Phi_{M1} = \Phi_{M2} = \Phi_m$.

[0158] The magnetic domains $D_{1,1}$, $D_{2,1}$, $D_{1,2}$, $D_{2,2}$, $D_{1,3}$, and $D_{2,3}$ may be grouped in pairs based on the symmetry. $D_{1,1}$ and $D_{2,1}$ are the first pair of symmetrically arranged magnetic domains, $D_{1,2}$ and $D_{2,2}$ are the second pair of symmetrically arranged magnetic domains, and $D_{1,3}$ and $D_{2,3}$ are the third pair of symmetrically arranged magnetic domains.

1) Magnetic domain pair $D_j = (D_{1,j}, D_{2,j})$ when j=1.

In the magnetic domain $D_{1,1}$, the direction of the magnetic flux lines corresponding to the coil C_2 is opposite to that corresponding to the permanent magnet M_1. Therefore, the total magnetic flux in the magnetic domain $D_{1,1}$ is the difference between Φ_{i1} and $\Phi_{M1} = \Phi_m$. In the magnetic domain $D_{2,1}$, the direction of the magnetic flux lines corresponding to the coil C_2 is the same as that corresponding to the permanent magnet M_2. Therefore, the total magnetic flux in the magnetic domain $D_{2,1}$ is the sum of Φ_{i2} and $\Phi_{M2} = \Phi_m$.

Assuming that $i_1 = i_2 = i_3 = i$, $\Phi_{i1} = \Phi_{i3} \neq \Phi_{i2}$, and in the multiple magnetic domains, the direction of the magnetic flux lines of the permanent magnet is positive, and the magnetic flux is also positive, then:

$$\Phi_{D1,1} = \Phi_{M1} - \Phi_{i2} = \Phi_m - \Phi_{i2}$$

$$\Phi_{D2,1} = \Phi_{M1} + \Phi_{i2} = \Phi_m + \Phi_{i2}$$

2) Magnetic domain pair $D_j = (D_{1,j}, D_{2,j})$ when j=2.

In the magnetic domain $D_{1,2}$, the direction of the magnetic flux lines corresponding to the coil C_1 is the same as that corresponding to the permanent magnet M_1. Therefore, the total magnetic flux in the magnetic domain $D_{1,2}$ is the sum of $\Phi_{11} = \Phi_{i3}$ and $\Phi_{M1} = \Phi_m$. In the magnetic domain $D_{2,2}$, the direction of the magnetic flux lines corresponding to the coil C_3 is opposite to that corresponding to the permanent magnet M_2. Therefore, the total magnetic flux in the magnetic domain $D_{2,2}$ is the difference of $\Phi_{i3} = \Phi_{i1}$ and $\Phi_{M2} = \Phi_m$.

Assuming that $i_1 = i_2 = i_3 = i$, $\Phi_{i1} = \Phi_{i3} \neq \Phi_{i2}$, and in the multiple magnetic domains, the direction of the magnetic flux lines of the permanent magnet is positive, and the magnetic flux is also positive, then:

$$\Phi_{D1,2} = \Phi_{M1} + \Phi_{i1} = \Phi_m + \Phi_{i1}$$

$$\Phi_{D2,1} = \Phi_{M1} - \Phi_{i3} = \Phi_m - \Phi_{i1}$$

3) Magnetic domain pair $D_j = (D_{1,j}, D_{2,j})$ when j=3.

[0159] In the magnetic domain $D_{1,3}$, only the magnetic flux lines corresponding to the coil C_1 pass through, so the total magnetic flux is only Φ_{i1}. In the magnetic domain $D_{2,3}$, only the magnetic flux lines corresponding to the coil C_3 pass through, so the total magnetic flux is only $\Phi_{i3} = \Phi_{i1}$.

[0160] Assuming the magnetic resistances of the magnetic circuits formed by the electromagnetic field generated by the current i in the coils C_1, C_2 and C_3 are Z_i, N represents the number of turns of the coils C_1, C_2 and C_3, and i is the current intensity, we have:

$$\emptyset_i * \mathrm{Z}_i = N * i$$

[0161] Assuming that the magnetic conductance of the magnetic circuit formed by the electromagnetic field generated by the current is G_i, we have:

$$\emptyset_i = \mathrm{G}_i * N * i.$$

[0162] Another case is: $N_1 = N_3 \neq N_2$, where N_1, N_2, N_3 are the number of turns of the coins C_1, C_2, and C_3, respectively, or the magnetic resistance of C_2 is different from the magnetic resistance of C_1 and C_3 due to the magnetic circuit structures of C_1, C_2, and C_3, i.e., $G_{i1} = G_{i3} \neq G_{i2}$, thus $\Phi_{i1} = \Phi_{i3} \neq \Phi_{i2}$. For this case, due to the overall symmetrical design, it still holds the conclusion that the nonlinear terms in the resultant force of the paired forces cancel each other. Thus:

$$\emptyset_{i,1} = \emptyset_{i,3} = \mathrm{G}_{i,1} * \mathrm{N}_{i,1} * i$$

$$\emptyset_{i,2} = \mathrm{G}_{i,2} * \mathrm{N}_{i,2} * i$$

[0163] The magnetic flux corresponding to the permanent magnet may also be expressed by the equation of magnetic induction intensity. Assuming that the magnetic induction intensities at the magnetic pole end faces of the permanent magnets M_1 and M_2 are both B_{m1}, the area of the magnetic pole end face is S_m, it follows that $\emptyset_m = B_m S_m$.

[0164] Thus, we have:

$$\begin{cases}\emptyset_{D1,1} = \emptyset_m - \emptyset_i = B_m S_m - G_i * N * i \\ \emptyset_{D2,1} = \emptyset_m + \emptyset_i = B_m S_m + G_i * N * i\end{cases}$$

$$\begin{cases}\emptyset_{D1,2} = \emptyset_m + \emptyset_i = B_m S_m + G_i * N * i \\ \emptyset_{D2,2} = \emptyset_m - \emptyset_i = B_m S_m - G_i * N * i\end{cases}$$

$$\begin{cases}\emptyset_{D1,3} = \emptyset_i = G_i * N * i \\ \emptyset_{D2,3} = \emptyset_i = G_i * N * i\end{cases}$$

[0165] For another case: the number of turns N_1, N_2, N_3 of the coils C_1, C_2, and C_3 satisfy $N_1 = N_3 \neq N_2$, or the magnetic resistance of C_2 is different from the magnetic resistance of C_1 and C_3 due to the magnetic circuit structures of C_1, C_2, and C_3, $G_{i1} = G_{i3} \neq G_{i2}$, thus $\Phi_{i1} = \Phi_{i3} \neq \Phi_{i2}$. The above formulas become:

$$\begin{cases}\emptyset_{D1,1} = \emptyset_m - \emptyset_i = B_m S_m - G_{i,2} * N_{i,2} * i \\ \emptyset_{D2,1} = \emptyset_m + \emptyset_i = B_m S_m + G_{i,2} * N_{i,2} * i\end{cases}$$

$$\begin{cases}\emptyset_{D1,2} = \emptyset_m + \emptyset_i = B_m S_m + G_{i,1} * N_{i,1} * i \\ \emptyset_{D2,2} = \emptyset_m - \emptyset_i = B_m S_m - G_{i,3} * N_{i,3} * i\end{cases}$$

$$\begin{cases}\emptyset_{D1,3} = \emptyset_i = G_{i,1} * N_{i,1} * i \\ \emptyset_{D2,3} = \emptyset_i = G_{i,3} * N_{i,3} * i\end{cases}$$

[0166] It can be seen from the above formulas that when $N_1 = N_3$ and $G_{i1} = G_{i3}$, the magnetic fluxes in the magnetic domain pair $D_2 = (D_{1,2}, D_{2,2})$, as well as the magnetic domain pairs $D_1 = (D_{1,1}, D_{2,1})$ and $D_3 = (D_{1,3}, D_{2,3})$ still have the property that the nonlinear terms relative to the current in the corresponding component forces can be canceled.

[0167] Referring to FIG. 20, FIG. 20 is a diagram of the relationship between the movable assembly, the magnetic domains $D_{1,1}$, $D_{2,1}$, $D_{1,2}$, $D_{2,2}$, $D_{1,3}$, and $D_{2,3}$ and the stator assembly. In the magnetic domain $D_{1,1}$, the movable assembly is subjected to a leftward attractive force $F_{1,1}$ from the stator assembly. In the magnetic domain $D_{2,1}$, the movable assembly is subjected to a rightward attractive force $F_{2,1}$ from the stator assembly. In the magnetic domain $D_{1,2}$, the movable assembly is subjected to a rightward attractive force $F_{1,2}$ from the stator assembly; in the magnetic domain $D_{2,2}$, the movable assembly is subjected to a leftward attractive force $F_{2,2}$ from the stator assembly. In the magnetic domain $D_{1,3}$, the movable assembly is subjected to a leftward attractive force $F_{1,3}$ from the stator assembly; and in the magnetic domain $D_{2,3}$, the movable assembly is subjected to a rightward attractive force $F_{2,3}$ from the stator assembly. The resultant force corresponding to the magnetic domain pair $D_j = (D_{1,j}, D_{2,j})$ is defined as the resultant force $F_j = (F_{1,j}, F_{2,j})$ corresponding to the magnetic domain pair D_j. Assuming the rightward direction is positive, the sign of $F_{1,j}$ and $F_{2,j}$ is positive when the direction of $F_{1,j}$ and $F_{2,j}$ is rightward, and the sign of $F_{1,j}$ and $F_{2,j}$ is negative when the direction of $F_{1,j}$ and $F_{2,j}$ is leftward. Then, the resultant force exerted on the movable assembly by the stator assembly is:

$$F_{\text{moving-magnet}} = F_1 + F_2 + F_3 = -F_{1,1} + F_{2,1} + F_{1,2} - F_{2,2} - F_{1,3} + F_{2,3}$$

$$F_{\text{moving-magnet}} = F_1 + F_2 + F_3 = (-F_{1,1} + F_{2,1}) + (F_{1,2} - F_{2,2}) + (-F_{1,3} + F_{2,3})$$

where F_j is the resultant force of the component forces generated on the movable assembly in the magnetic domain pair $D_i = (D_{1,j}, D_{2,j})$.

[0168] The above is a force analysis diagram of the isolated movable assembly. The movable assembly is subjected to component forces $F_{1,1}$, $F_{2,1}$, $F_{1,2}$, $F_{2,2}$, $F_{1,3}$, $F_{2,3}$ from the stator assembly. When calculating, first calculate F_1 according to the magnetic domain pair $D_j = (D_{1,j}, D_{2,j})$, then calculate the resultant force of the movable assembly as:

$$F_{\text{moving-magnet}} = F_1 + F_2 + F_3 = (-F_{1,1} + F_{2,1}) + (F_{1,2} - F_{2,2}) + (-F_{1,3} + F_{2,3})$$

[0169] The above can also be expressed by including the direction of the force through the sign of the component force:

$$F_{\text{moving-magnet}} = \sum_{i=1}^{3} F_i = \sum_{i=1}^{3} (F_{1,i} + F_{2,i})$$

[0170] First calculate the resultant force of the component forces generated in the two-by-two paired magnetic domain pairs, i.e., calculate the resultant force $F_1 = -F_{1,1} + F_{2,1}$ in the magnetic domain pair $D_1 = (D_{1,1}, D_{2,1})$, the resultant force $F_2 = F_{1,2} - F_{2,2}$ in the magnetic domain pair $D_2 = (D_{1,2}, D_{2,2})$, and the resultant force $F_2 = -F_{1,3} + F_{2,3}$ in the magnetic domain pair $D_3 = (D_{1,3}, D_{2,3})$, then calculate the total resultant force.

[0171] Further derive the equation for the electromagnetic force generated by each magnetic domain. The magnitude of the electromagnetic attractive force acting on a magnetized ferromagnetic object is proportional to the total area of the magnetic poles through which the magnetic flux lines passes and the square of the magnetic induction intensity. If the magnetic induction intensity B is uniformly distributed along the surface of the magnetic pole and the calculated air gap length is small, the equation for calculating the electromagnetic attractive force is calculated by the Maxwell formula, expressed as:

$$\mathrm{F} = \mathrm{C}\,\frac{\mathrm{B}^2 \cdot \mathrm{S}}{2\mu_0} = \mathrm{C}\,\frac{\varnothing^2}{2\mu_0 \cdot \mathrm{S}}$$

where:

F: Electromagnetic attractive force
B: Magnetic flux density or magnetic induction intensity
Ø: Magnetic flux passing through the medium
S: Area of the magnetic pole through which the magnetic flux passes
μ_0: Air permeability
C: Coefficient related to the combination type and shape of the magnetic pole end faces, with different values for different scenarios. When the force is generated between permanent magnets, it is denoted as C_{m2m}, usually taking a value of 1, and the accurate value is obtained through actual measurement in the actual design process. When the force is generated between a permanent magnet and a magnetic conductor (yoke iron), it is denoted as C_{m2y}, usually taking a value of 1/2, and the accurate value is obtained through actual measurement in the actual design process. When the force is generated between magnetic conductors (yoke iron), it is denoted as C_{y2y}, usually taking a value of 1/4, and the accurate value is obtained through actual measurement in the actual design process.

1) Calculate the resultant force $F_1 = -F_{1,1} + F_{2,1}$, corresponding to the magnetic domain pair $D_i = (D_{1,j}, D_{2,j})$ when j = 1, i.e., $D_1 = (D_{1,1}, D_{2,1})$.
Applying the above formula to calculate the electromagnetic attractive forces in the magnetic domains $D_{1,1}$ and $D_{2,1}$, we have:

$$\begin{cases} F_{1,1} = \mathrm{C_{y2y}}\dfrac{(\varnothing_{\mathrm{D1,1}})^2}{2\mu_0 \cdot S_{D1,1}} = \mathrm{C_{y2y}}\dfrac{(-\varnothing_{i,2} + \varnothing_{\mathrm{m}})^2}{2\mu_0 \cdot S_{D1,1}} \\ F_{2,1} = \mathrm{C_{y2y}}\dfrac{(\varnothing_{\mathrm{D2,1}})^2}{2\mu_0 \cdot S_{D2,1}} = \mathrm{C_{y2y}}\dfrac{(\varnothing_{i,2} + \varnothing_{\mathrm{m}})^2}{2\mu_0 \cdot S_{D2,1}} \end{cases}$$

where $S_{D1,1}$ and $S_{D2,1}$ represent the areas of the annular end faces corresponding to magnetic domain $D_{1,1}$ and magnetic domain $D_{2,1}$ respectively, and $S_{D1,1} = S_{D2,1} = S_{D1}$, thus:

$$\begin{cases} F_{1,1} = \mathrm{C_{y2y}}\dfrac{(\varnothing_{\mathrm{m}} - \varnothing_{i,2})^2}{2\mu_0 \cdot S_{D1,1}} = \dfrac{\mathrm{C_{y2y}}}{2\mu_0 \cdot S_{D1}}\,(-\varnothing_{i,2} + \varnothing_{\mathrm{m}})^2 \\ F_{2,1} = \mathrm{C_{y2y}}\dfrac{(\varnothing_{\mathrm{m}} + \varnothing_{i,2})^2}{2\mu_0 \cdot S_{D2,1}} = \dfrac{\mathrm{C_{y2y}}}{2\mu_0 \cdot S_{D1}}\,(\varnothing_{i,2} + \varnothing_{\mathrm{m}})^2 \end{cases}$$

$$\begin{cases} F_{1,1} = F_{1,1,linear} + F_{1,1,nonlinear} \\ F_{2,1} = F_{2,1,linear} + F_{2,1,nonlinear} \end{cases}$$

where:

$$\begin{cases} F_{1,1,linear} = \frac{C_{y2y}}{2\mu_0 \cdot S_{D1}} \left(\emptyset_m^2 - 2\emptyset_m \emptyset_{i,2}\right) \\ F_{1,1,nonlinear} = \frac{C_{y2y}}{2\mu_0 \cdot S_{D1}} \emptyset_{i,2}{}^2 \end{cases}$$

$$\begin{cases} F_{2,1,linear} = \frac{C_{y2y}}{2\mu_0 \cdot S_{D1}} \left(\emptyset_m^2 + 2\emptyset_m \emptyset_{i,2}\right) \\ F_{2,1,nonlinear} = \frac{C_{y2y}}{2\mu_0 \cdot S_{D1}} \emptyset_{i,2}{}^2 \end{cases}$$

Since:

$$F_1 = -F_{1,1} + F_{2,1}$$

We obtain:

$$F_{1,linear} = F_{1,linear} + F_{1,nonlinear}$$

$$\begin{cases} F_{1,linear} = -F_{1,1,linear} + F_{2,1,linear} \\ F_{1,nonlinear} = -F_{1,1,nonlinear} + F_{2,1,nonlinear} \end{cases}$$

Substitute $F_{1,1,linear}$, $F_{2,1,linear}$, $F_{1,1,nonlinear}$, $F_{2,1,nonlinear}$ into $F_{1,linear}$ and $F_{1,nonlinear}$ respectively, we obtain:

$$F_{1,linear} = -F_{1,1,linear} + F_{2,1,linear}$$

$$= -\frac{C_{y2y}}{2\mu_0 \cdot S_{D1}}\left(\emptyset_m^2 - 2\emptyset_m \emptyset_{i,2}\right) + \frac{C_{y2y}}{2\mu_0 \cdot S_{D1}}\left(\emptyset_m^2 + 2\emptyset_m \emptyset_{i,2}\right)$$

$$= \frac{C_{y2y}}{2\mu_0 \cdot S_{D1}} \left(-\left(\emptyset_m^2 - 2\emptyset_m \emptyset_{i,2}\right) + \left(\emptyset_m^2 + 2\emptyset_m \emptyset_{i,2}\right)\right.$$

$$= \frac{C_{y2y}}{2\mu_0 \cdot S_{D1}} \left(4\emptyset_m \emptyset_{i,2}\right)$$

$$= \frac{2C_{y2y}\emptyset_m}{\mu_0 \cdot S_{D1}} \emptyset_{i,2}$$

Given that:

$$\emptyset_m = B_m S_m$$

$$\emptyset_{i,2} = G_{i,2} N_{i,2} i$$

Hence:

$$F_{1,linear} = \frac{2C_{y2y}\emptyset_m}{\mu_0 \cdot S_{D1}} \emptyset_{i,2} = \frac{2C_{y2y}B_m S_m}{\mu_0 \cdot S_{D1}} G_{i,2}N_{i,2}i = \frac{2C_{y2y}B_m S_m G_{i,2}N_{i,2}}{\mu_0 \cdot S_{D1}} * i$$

Calculate $F_{1,nonlinear}$ in a similar way as follows:

$$F_{1,nonlinear} = -F_{1,1,nonlinear} + F_{2,1,nonlinear}$$
$$= -\frac{C_{y2y}}{2\mu_0 \cdot S_{D1}} {\emptyset_{i,2}}^2 + \frac{C_{y2y}}{2\mu_0 \cdot S_{D1}} {\emptyset_{i,2}}^2 = 0$$

Thus, the resultant force corresponding to the corresponding to the magnetic domain pair $D_{1,1}$ and $D_{2,1}$ is:

$$F_1 = F_{1,linear} + F_{1,nonlinear}$$
$$= \frac{2C_{y2y}B_m S_m G_{i,2}N_{i,2}}{\mu_0 \cdot S_{D1}} * i + 0$$
$$= \frac{2C_{y2y}B_m S_m G_{i,2}N_{i,2}}{\mu_0 \cdot S_{D1}} * i$$

2) Calculate the resultant force $F_2 = F_{1,2} - F_{2,2}$, corresponding to the magnetic domain pair $D_j = (D_{1,j}, D_{2,j})$ when j = 2, i.e., $D_2 = (D_{1,2}, D_{2,2})$.

Applying the above formula to calculate the electromagnetic attractive forces in the magnetic domains $D_{1,2}$ and $D_{2,2}$, we have:

$$\begin{cases} F_{1,2} = C_{y2y}\frac{(\emptyset_{D1,2})^2}{2\mu_0 \cdot S_{D1,1}} = C_{y2y}\frac{(\emptyset_{i,1} + \emptyset_m)^2}{2\mu_0 \cdot S_{D1,1}} \\ F_{2,2} = C_{y2y}\frac{(\emptyset_{D2,2})^2}{2\mu_0 \cdot S_{D2,2}} = C_{y2y}\frac{(-\emptyset_{i,3} + \emptyset_m)^2}{2\mu_0 \cdot S_{D2,1}} \end{cases}$$

where $S_{D1,2}$ and $S_{D2,2}$ represent the areas of the annular end faces corresponding to magnetic domain $D_{1,2}$ and magnetic domain $D_{2,2}$ respectively, and $S_{D1,2} = S_{D2,2} = S_{D1}$, thus:

$$\begin{cases} F_{1,2} = C_{y2y}\frac{(\emptyset_m - \emptyset_{i,1})^2}{2\mu_0 \cdot S_{D1,2}} = \frac{C_{y2y}}{2\mu_0 \cdot S_{D2}} (\emptyset_{i,1} + \emptyset_m)^2 \\ F_{2,2} = C_{y2y}\frac{(\emptyset_m + \emptyset_{i,3})^2}{2\mu_0 \cdot S_{D2,2}} = \frac{C_{y2y}}{2\mu_0 \cdot S_{D2}} (-\emptyset_{i,3} + \emptyset_m)^2 \end{cases}$$

$$\begin{cases} F_{1,2} = F_{1,2,linear} + F_{1,2,nonlinear} \\ F_{2,2} = F_{2,2,linear} + F_{2,2,nonlinear} \end{cases}$$

where:

$$\begin{cases} F_{1,2,linear} = \frac{C_{y2y}}{2\mu_0 \cdot S_{D2}} (\emptyset_m^2 + 2\emptyset_m\emptyset_{i,1}) \\ F_{1,2,nonlinear} = \frac{C_{y2y}}{2\mu_0 \cdot S_{D2}} {\emptyset_{i,1}}^2 \end{cases}$$

$$\begin{cases} F_{2,2,linear} = \frac{C_{y2y}}{2\mu_0 \cdot S_{D2}} (\emptyset_m^2 - 2\emptyset_m\emptyset_{i,3}) \\ F_{2,2,nonlinear} = \frac{C_{y2y}}{2\mu_0 \cdot S_{D2}} \emptyset_{i,3}{}^2 \end{cases}$$

Since:

$$F_2 = F_{1,2} - F_{2,2}$$

We obtain:

$$F_{2,linear} = F_{2,linear} + F_{2,nonlinear}$$

$$\begin{cases} F_{2,linear} = F_{1,2,linear} - F_{2,2,linear} \\ F_{2,nonlinear} = F_{1,2,nonlinear} - F_{2,2,nonlinear} \end{cases}$$

Substitute $F_{1,1,linear}$, $F_{2,2,linear}$, $F_{1,2,nonlinear}$, $F_{2,2,nonlinear}$ into $F_{2,linear}$ and $F_{2,nonlinear}$ respectively, we obtain:

$$F_{2,linear} = F_{1,2,linear} - F_{2,2,linear}$$

$$= \frac{C_{y2y}}{2\mu_0 \cdot S_{D2}} \left(\emptyset_m^2 + 2\emptyset_m\emptyset_{i,1}\right) - \frac{C_{y2y}}{2\mu_0 \cdot S_{D2}} (\emptyset_m^2 - 2\emptyset_m\emptyset_{i,3})$$

$$= \frac{C_{y2y}}{2\mu_0 \cdot S_{D2}} \left(\emptyset_m^2 + 2\emptyset_m\emptyset_{i,1}\right) - (\emptyset_m^2 - 2\emptyset_m\emptyset_{i,3})$$

$$= \frac{C_{y2y}}{2\mu_0 \cdot S_{D2}} (4\emptyset_m\emptyset_{i,1})$$

$$= \frac{2C_{y2y}\emptyset_m}{\mu_0 \cdot S_{D2}} \emptyset_{i,1}$$

Given that:

$$\emptyset_m = B_m S_m$$

$$\emptyset_{i,1} = \emptyset_{i,3=} G_{i,1} N_{i,1} i$$

Hence:

$$F_{2,linear} = \frac{2C_{y2y}\emptyset_m}{\mu_0 \cdot S_{D2}} \emptyset_{i,1} = \frac{2C_{y2y} B_m S_m}{\mu_0 \cdot S_{D2}} G_{i,1} N_{i,1} i = \frac{2C_{y2y} B_m S_m G_{i,1} N_{i,1}}{\mu_0 \cdot S_{D2}} * i$$

Calculate $F_{2,nonlinear}$ in a similar way as follows:

$$F_{2,nonlinear} = -F_{1,2,nonlinear} + F_{2,2,nonlinear}$$

$$= \frac{C_{y2y}}{2\mu_0 \cdot S_{D2}} \emptyset_{i,1}{}^2 - \frac{C_{y2y}}{2\mu_0 \cdot S_{D2}} \emptyset_{i,3}{}^2 = 0$$

Thus, the resultant force corresponding to the corresponding to the magnetic domain pair $D_{1,2}$ and $D_{2,2}$ is:

$$F_2 = F_{2,linear} + F_{2,nonlinear} = \frac{2C_{y2y}B_m S_m G_{i,1} N_{i,1}}{\mu_0 \cdot S_{D2}} * i + 0 = \frac{2C_{y2y}B_m S_m G_{i,1} N_{i,1}}{\mu_0 \cdot S_{D2}} * i$$

3) Calculate the resultant force $F_3 = -F_{1,3} + F_{2,3}$, corresponding to the magnetic domain pair $D_j = (D_{1,j}, D_{2,j})$ when j = 3, i.e., $D_3 = (D_{1,3}, D_{2,3})$.

Applying the above formula to calculate the electromagnetic attractive forces in the magnetic domains $D_{1,3}$ and $D_{2,3}$, we have:

$$\begin{cases} F_{1,3} = C_{y2y}\dfrac{(\emptyset_{D1,3})^2}{2\mu_0 \cdot S_{D1,3}} = C_{y2y}\dfrac{{\emptyset_i}^2}{2\mu_0 \cdot S_{D1,3}} \\ F_{2,3} = C_{y2y}\dfrac{(\emptyset_{D2,3})^2}{2\mu_0 \cdot S_{D2,3}} = C_{y2y}\dfrac{{\emptyset_i}^2}{2\mu_0 \cdot S_{D2,3}} \end{cases}$$

where $S_{D1,3}$ and $S_{D2,3}$ represent the areas of the annular end faces corresponding to magnetic domain $D_{1,3}$ and magnetic domain $D_{2,3}$ respectively, and $S_{D1,3} = S_{D2,3} = S_{D3}$, thus:

$$\begin{cases} F_{1,3} = C_{y2y}\dfrac{(\emptyset_{D1,3})^2}{2\mu_0 \cdot S_{D1,3}} = C_{y2y}\dfrac{{\emptyset_{i,1}}^2}{2\mu_0 \cdot S_{D3}} \\ F_{2,3} = C_{y2y}\dfrac{(\emptyset_{D2,3})^2}{2\mu_0 \cdot S_{D2,3}} = C_{y2y}\dfrac{{\emptyset_{i,3}}^2}{2\mu_0 \cdot S_{D3}} \end{cases}$$

Thus:

$$F_3 = F_{3,linear} + F_{3,nonlinear} = F_{1,3} - F_{2,3} = C_{y2y}\frac{{\emptyset_{i,1}}^2}{2\mu_0 \cdot S_{D3}} - C_{y2y}\frac{{\emptyset_{i,3}}^2}{2\mu_0 \cdot S_{D3}} = 0$$

We obtain:

$$\begin{cases} F_{2,linear} = 0 \\ F_{2,nonlinear} = 0 \end{cases}$$

4) Calculate the resultant force on the movable assembly:

$$F_{moving-magnet} = F_1 + F_2 + F_3$$

$$F_{moving-magnet} = F_{moving-magnet,linear} + F_{moving-magnet,nonlinear}$$

Thus:

$$F_{moving-magnet,linear} = F_{1,linear} + F_{2,linear} + F_{3,linear}$$
$$= \frac{2C_{y2y}B_mS_mG_{i2}N_{i2}}{\mu_0 \cdot S_{D1}} * i + \frac{2C_{y2y}B_mS_mG_{i1}N_{i1}}{\mu_0 \cdot S_{D2}} * i + 0$$
$$= \frac{2C_{y2y}B_mS_m}{\mu_0}\left(\frac{G_{i2}N_{i2}}{S_{D1}} + \frac{G_{i1}N_{i1}}{S_{D2}}\right) * i$$

$$F_{moving-magnet,nonlinear} = F_{1,nonlinear} + F_{2,nonlinear} + F_{3,nonlinear} = 0 + 0 + 0 = 0$$

[0172] From the above derivation process, the following characteristics may be seen:

1) In the linear term of the resultant force $F_{moving\text{-}magnet,linear}$, the linear terms of the component forces $F_{1,linear}$, $F_{2,linear}$ and $F_{3,linear}$ are superimposed, so that the linear term of the resultant force $F_{moving\text{-}magnet,linear}$ still has a linear relationship with the coil current.
2) In the nonlinear term of the resultant force $F_{moving\text{-}magnet,nonlinear}$, the nonlinear terms of the component forces $F_{1,nonlinear}$, $F_{2,nonlinear}$ and $F_{3,nonlinear}$ cancel each other out, so that the nonlinear term of the resultant force $F_{moving\text{-}magnet,nonlinear}$ is zero.

[0173] The above design method is called the design method of the moving-magnet vibrator with nonlinear term cancellation. This method can not only be used to design vibrators, but also be applied to design actuators. The moving-magnet vibrators or actuators obtained by the above method are called moving-magnet vibrator devices or actuators with nonlinear term cancellation.

Embodiment 9

[0174] In the moving-magnet vibrator with nonlinear term cancellation described in Embodiments 1 to 8, the permanent magnet or magnet may be replaced with a magnet component, and the coil may be replaced with a coil component, which shall fall within the protection scope of the disclosure.
[0175] The magnet component: the magnet component is a single magnet or an assembly of multiple magnets (n_{magnet}>1), the assembly of multiple magnets generates an overall magnetic field equivalent to a magnetic field generated by a certain single magnet. Directions of magnetic fields generated by the multiple magnets in the assembly are the same as a direction of a certain dominant magnetic field/ (when magnetic field intensities generated by the multiple magnets are significantly different from each other, the directions of the magnetic fields generated by the multiple magnets may be opposite, but a direction of the overall magnetic field is the same as the direction of the dominant magnetic field), so that the overall magnetic field generated by the multiple magnets is equivalently regarded as being generated by a single magnet component. The multiple magnets are connected through a rigid structural component, or a flexible structural component (arranged between the magnets, at edges of the magnets, or around the magnets), or a manner without a structural component, including bonding, welding, embedding, screws, spirals, riveting, bolts, buckles, clamping jaws, brackets, sleeves, glands, or other manners.
[0176] The coil component: the coil component is a single coil or an assembly of multiple coils (n_{coil} > 1), the assembly of multiple coils generates an overall magnetic field equivalent to a magnetic field generated by a certain single coil. Directions of magnetic fields generated by the multiple coils in the assembly are the same as a direction of a magnetic field generated by a certain dominant coil/(when magnetic field intensities generated by the multiple coils in the assembly are significantly different from each other, the directions of the magnetic fields generated by the multiple coils may be opposite, but a direction of the overall magnetic field is the same as the direction of the magnetic field generated by the dominant coil), so that the overall magnetic field generated by the assembly is equivalently regarded as being generated by a current in a single coil component. The multiple coils are connected through a rigid structural component, or a flexible structural component (arranged between the coils, at edges of the coils, or around the coils), or a manner without a structural component, including bonding, welding, embedding, screws, spirals, riveting, bolts, buckles, clamping jaws, brackets, sleeves, glands, or other manners.
[0177] To describe the magnet component and the coil component in detail, the following embodiments are provided for specific description.
[0178] The magnet components 201 during use includes the embodiments as follows.
[0179] Embodiment 1 of magnet component 201.
[0180] Referring to FIG. 24, permanent magnets are connected in series along the magnetic field direction without a

structural component therebetween, and $n_{magnet} = 2$.

[0181] Permanent magnet 1 and permanent magnet 2 are connected via bonding, welding, riveting, bolts, clamping jaws, brackets, sleeves or other manners. The magnetic field generated by each of permanent magnet 1 and permanent magnet 2 is directed toward the Y+ axis direction, thus the magnetic fields have the same direction. Therefore, the combination of permanent magnet 1 and permanent magnet 2, when viewed from the direction of the overall external magnetic field, may be regarded as substantially equivalent (indicated by the "=" sign in the figure) to the single magnet on the right. The combination of permanent magnet 1 and permanent magnet 2 may be considered as one magnet component 201.

[0182] Embodiment 2 of magnet component 201.

[0183] Referring to FIG. 25, permanent magnets are connected in series along the magnetic field direction without a structural component therebetween, and $N_{magnet} = 3$.

[0184] Permanent magnet 1, permanent magnet 2 and permanent magnet 3 are connected via bonding, welding, riveting, bolts, clamping jaws, brackets, sleeves or other manners. The magnetic field generated by each of permanent magnet 1, permanent magnet 2 and permanent magnet 3 is directed toward the Y+ axis direction, thus the magnetic fields have the same direction. Therefore, the combination of permanent magnet 1, permanent magnet 2 and permanent magnet 3, when viewed from the direction of the overall external magnetic field, may be regarded as substantially equivalent (indicated by the "=" sign in the figure) to the single magnet on the right. The combination of permanent magnet 1, permanent magnet 2 and permanent magnet 3 may be considered as one magnet component 201.

[0185] Embodiment 3 of the magnet component 201.

[0186] Referring to FIG. 26, permanent magnets are connected in series along the magnetic field direction with a structural component therebetween, and $n_{magnet} = 2$.

[0187] A magnetic conductor is provided between permanent magnet 1 and permanent magnet 2 to provide spacing therebetween. Permanent magnet 1 and the magnetic conductor, as well as permanent magnet 2 and the magnetic conductor, are connected via bonding, welding, riveting, bolts, clamping jaws, brackets, sleeves or other manners. The magnetic field generated by each of permanent magnet 1 and permanent magnet 2 is directed toward the Y+ axis direction, thus the magnetic fields have the same direction. Therefore, the combination of permanent magnet 1, the magnetic conductor and permanent magnet 2, when viewed from the direction of the overall external magnetic field, may be regarded as equivalent (indicated by the "=" sign in the figure) to the single magnet on the right. The combination of permanent magnet 1, the magnetic conductor and permanent magnet 2 may be considered as one magnet component 201.

[0188] The magnetic conductor may also be replaced with a non-magnetic material or a magnet with a significantly weaker magnetic field oriented in the opposite direction, which does not affect the overall equivalence to a single permanent magnet. Therefore, these configurations are also included in this case.

[0189] Embodiment 4 of the magnet component 201.

[0190] Referring to FIG. 27, permanent magnets are connected in series along the magnetic field direction without a structural component therebetween, and $n_{magnet} = 2$.

[0191] Permanent magnet 1 and permanent magnet 2, where permanent magnet 1 is larger than permanent magnet 2, are connected via bonding, welding, riveting, bolts, clamping jaws, brackets, sleeves or other manners. The magnetic field generated by each of permanent magnet 1 and permanent magnet 2 is directed toward the Y+ axis direction, thus the magnetic fields have the same direction. Therefore, the combination of permanent magnet 1 and permanent magnet 2, when viewed from the direction of the overall external magnetic field, may be regarded as substantially equivalent (indicated by the "=" sign in the figure) to the single magnet on the right. The combination of permanent magnet 1 and permanent magnet 2 may be considered as one magnet component 201.

[0192] Embodiment 5 of the magnet component 201.

[0193] Referring to FIG. 28, permanent magnets are connected in series along the magnetic field direction with a structural component therebetween, and $n_{magnet} = 2$.

[0194] Permanent magnet 1 and permanent magnet 2, where permanent magnet 1 is larger than permanent magnet 2, are connected via bonding, welding, riveting, bolts, clamping jaws, brackets, sleeves or other manners. The magnetic field generated by each of permanent magnet 1 and permanent magnet 2 is directed toward the Y+ axis direction, thus the magnetic fields have the same direction. Therefore, the combination of permanent magnet 1 and permanent magnet 2, when viewed from the direction of the overall external magnetic field, may be regarded as substantially equivalent (indicated by the "=" sign in the figure) to the single magnet on the right. The combination of permanent magnet 1 and permanent magnet 2 may be considered as one magnet component 201.

[0195] Embodiment 6 of the magnet component 201.

[0196] Referring to FIG. 29, permanent magnets are connected in parallel along the magnetic field direction without a structural component therebetween, and $n_{magnet} = 2$.

[0197] Permanent magnet 1 and permanent magnet 2 are connected via bonding, welding, riveting, bolts, clamping jaws, brackets, sleeves or other manners. The magnetic field generated by each of permanent magnet 1 and permanent magnet 2 is directed toward the Y+ axis direction, thus the magnetic fields have the same direction. Therefore, the combination of permanent magnet 1 and permanent magnet 2, when viewed from the direction of the overall external magnetic field, may be regarded as substantially equivalent (indicated by the "=" sign in the figure) to the single magnet on the right. The combination of permanent magnet 1 and permanent magnet 2 may be considered as one magnet component 201.

[0198] Embodiment 7 of the magnet component 201.

[0199] Referring to FIG. 30, permanent magnets are connected in parallel along the magnetic field direction without a structural component therebetween, and n_{magnet} = 3.

[0200] Permanent magnet 1, permanent magnet 2 and permanent magnet 3 are connected via bonding, welding, riveting, bolts, clamping jaws, brackets, sleeves or other manners. The magnetic field generated by each of permanent magnet 1, permanent magnet 2 and permanent magnet 3 is directed toward the Y+ axis direction, thus the magnetic fields have the same direction. Therefore, the combination of permanent magnet 1, permanent magnet 2 and permanent magnet 3, when viewed from the direction of the overall external magnetic field, may be regarded as substantially equivalent (indicated by the "=" sign in the figure) to the single magnet on the right. The combination of permanent magnet 1, permanent magnet 2 and permanent magnet 3 may be considered as one magnet component 201.

[0201] Embodiment 8 of the magnet component 201.

[0202] Referring to FIG. 31, permanent magnets are connected in in a series-parallel hybrid configuration along the magnetic field direction without a structural component therebetween, and n_{magnet} = 3.

[0203] Permanent magnet 1, permanent magnet 2, permanent magnet 3, magnetic conductive plate 1 and magnetic conductive plate 2 are connected via bonding, welding, riveting, bolts, clamping jaws, brackets, sleeves or other manners. The magnetic field generated by each of permanent magnet 1, permanent magnet 2 and permanent magnet 3 is directed toward the Y+ axis direction, and the magnetic fields of magnetic conductive plate 1 and magnetic conductive plate 2 after magnetization are also directed toward the Y+ axis direction, thus all the magnetic fields have the same direction. Therefore, the combination of permanent magnet 1, permanent magnet 2, permanent magnet 3, magnetic conductive plate 1 and magnetic conductive plate 2, when viewed from the direction of the overall external magnetic field, may be regarded as substantially equivalent (indicated by the "=" sign in the figure) to the single magnet on the right. The combination of permanent magnet 1, permanent magnet 2, permanent magnet 3, magnetic conductive plate 1 and magnetic conductive plate 2 may be considered as one magnet component 201.

[0204] The magnetic conductive plate may also be replaced with a non-magnetic plate or a magnet with a significantly weaker magnetic field oriented in the opposite direction, which does not affect the overall equivalence to a single permanent magnet. Therefore, these configurations are also included in this case.

[0205] Embodiment 9 of the magnet component 201.

[0206] Referring to FIG. 32, permanent magnets are connected in parallel along the magnetic field direction with a structural component therebetween, and n_{magnet} = 2.

[0207] A magnetic conductor is provided between permanent magnet 1 and permanent magnet 2 to provide spacing therebetween. Permanent magnet 1 and the magnetic conductor, as well as permanent magnet 2 and the magnetic conductor, are connected via bonding, welding, riveting, bolts, clamping jaws, brackets, sleeves or other manners. The magnetic field generated by each of permanent magnet 1 and permanent magnet 2 is directed toward the Y+ axis direction, thus the magnetic fields have the same direction. Therefore, the combination of permanent magnet 1, the magnetic conductor and permanent magnet 2, when viewed from the direction of the overall external magnetic field, may be regarded as equivalent (indicated by the "=" sign in the figure) to the single magnet on the right. The combination of permanent magnet 1, the magnetic conductor and permanent magnet 2 may be considered as one magnet component 201.

[0208] The magnetic conductive plate may also be replaced with a non-magnetic material or a magnet with a significantly weaker magnetic field oriented in the opposite direction, which does not affect the overall equivalence to a single permanent magnet. Therefore, these configurations are also included in this case.

[0209] Embodiment 10 of the magnet component 201.

[0210] Referring to FIG. 33, permanent magnets are connected in parallel along the magnetic field direction without a structural component therebetween, and N_{magnet} = 2.

[0211] Permanent magnet 1 and permanent magnet 2 are connected via bonding, welding, riveting, bolts, clamping jaws, brackets, sleeves or other manners. The magnetic field generated by each of permanent magnet 1 and permanent magnet 2 is directed toward the Y+ axis direction, thus the magnetic fields have the same direction. Therefore, the combination of permanent magnet 1 and permanent magnet 2, when viewed from the direction of the overall external magnetic field, may be regarded as substantially equivalent (indicated by the "=" sign in the figure) to the single magnet on the right. The combination of permanent magnet 1 and permanent magnet 2 may be considered as one magnet component 201.

[0212] Embodiment 11 of the magnet component 201.

[0213] Referring to FIG. 34, permanent magnets are connected in parallel along the magnetic field direction with a structural component therebetween, and n_{magnet} = 2.

[0214] A magnetic conductor is provided between permanent magnet 1 and permanent magnet 2 to provide spacing therebetween. Permanent magnet 1 and the magnetic conductor, as well as permanent magnet 2 and the magnetic conductor, are connected via bonding, welding, riveting, bolts, clamping jaws, brackets, sleeves or other manners. The magnetic field generated by each of permanent magnet 1 and permanent magnet 2 is directed toward the Y+ axis direction, thus the magnetic fields have the same direction. Therefore, the combination of permanent magnet 1, the magnetic conductor and permanent magnet 2, when viewed from the direction of the overall external magnetic field, may be regarded as equivalent (indicated by the "=" sign in the figure) to the single magnet on the right. The combination of permanent magnet 1, the magnetic conductor and permanent magnet 2 may be considered as one magnet component 201.

[0215] The magnetic conductive plate may also be replaced with a non-magnetic material or a magnet with a significantly weaker magnetic field oriented in the opposite direction, which does not affect the overall equivalence to a single permanent magnet. Therefore, these configurations are also included in this case.

[0216] Embodiment 12 of the magnet component 201.

[0217] Referring to FIG. 35, permanent magnets are connected in parallel along the magnetic field direction without a structural component therebetween, and n_{magnet} = 2.

[0218] Permanent magnet 1 (shaped as a ring, circular ring, square ring, rectangular ring, etc.) and permanent magnet 2 (shaped as a cylinder, circular column, square column, rectangular column, etc.) are connected via bonding, welding, riveting, bolts, clamping jaws, brackets, sleeves or other manners. The magnetic field generated by each of permanent magnet 1 and permanent magnet 2 is directed toward the Y+ axis direction, thus the magnetic fields have the same direction. Therefore, the combination of permanent magnet 1 and permanent magnet 2, when viewed from the direction of the overall external magnetic field, may be regarded as substantially equivalent (indicated by the "=" sign in the figure) to the single magnet on the right. The combination of permanent magnet 1 and permanent magnet 2 may be considered as one magnet component 201.

[0219] Embodiment 13 of the magnet component 201.

[0220] Referring to FIG. 36, permanent magnets are connected in parallel along the magnetic field direction with a structural component therebetween, and n_{magnet} = 2.

[0221] Magnetic conductive ring 104 is provided between permanent magnet 1 (shaped as a ring, circular ring, square ring, rectangular ring, etc.) and permanent magnet 2 (shaped as a cylinder, circular column, square column, rectangular column, etc.) to provide spacing therebetween. Permanent magnet 1 and the magnetic conductor, as well as permanent magnet 2 and the magnetic conductor, are connected via bonding, welding, riveting, bolts, clamping jaws, brackets, sleeves or other manners. The magnetic field generated by each of permanent magnet 1 and permanent magnet 2 is directed toward the Y+ axis direction, thus the magnetic fields have the same direction. Therefore, the combination of permanent magnet 1, the magnetic conductor and permanent magnet 2, when viewed from the direction of the overall external magnetic field, may be regarded as equivalent (indicated by the "=" sign in the figure) to the single magnet on the right. The combination of permanent magnet 1, the magnetic conductor and permanent magnet 2 may be considered as one magnet component 201.

[0222] The magnetic conductive ring may also be replaced with a non-magnetic ring or a magnetic ring with a significantly weaker magnetic field oriented in the opposite direction, which does not affect the overall equivalence to a single permanent magnet. Therefore, these configurations are also included in this case.

[0223] Embodiment 14 of the magnet component 201.

[0224] Referring to FIG. 37, permanent magnets are connected in parallel along the magnetic field direction without a structural component therebetween, and n_{magnet} = 2.

[0225] Permanent magnet 1 (shaped as a ring, circular ring, square ring, rectangular ring, etc.) and permanent magnet 2 (shaped as a ring, circular column, square column, rectangular column, etc.) are connected via bonding, welding, riveting, bolts, clamping jaws, brackets, sleeves or other manners. The magnetic field generated by each of permanent magnet 1 and permanent magnet 2 is directed toward the Y+ axis direction, thus the magnetic fields have the same direction. Therefore, the combination of permanent magnet 1 and permanent magnet 2, when viewed from the direction of the overall external magnetic field, may be regarded as substantially equivalent (indicated by the "=" sign in the figure) to the single magnet on the right. The combination of permanent magnet 1 and permanent magnet 2 may be considered as one magnet component 201. The core part in the figure may be air, a non-magnetic material or a weakly magnetic material (e.g., a weakly magnetic conductive bolt).

[0226] Embodiment 15 of the magnet component 201.

[0227] Referring to FIG. 38, permanent magnets are connected in parallel along the magnetic field direction with a structural component therebetween, and n_{magnet} = 2.

[0228] Magnetic conductive ring 104 is provided between permanent magnet 1 (shaped as a ring, circular ring, square ring, rectangular ring, etc.) and permanent magnet 2 (shaped as a cylinder, circular column, square column, rectangular column, etc.) to provide spacing therebetween. Permanent magnet 1 and the magnetic conductor, as well as permanent magnet 2 and the magnetic conductor, are connected via bonding, welding, riveting, bolts, clamping jaws, brackets, sleeves or other manners. The magnetic field generated by each of permanent magnet 1 and permanent magnet 2 is directed toward the Y+ axis direction, thus the magnetic fields have the same direction. Therefore, the combination of permanent magnet 1, the magnetic conductor and permanent magnet 2, when viewed from the direction of the overall external magnetic field, may be regarded as equivalent (indicated by the "=" sign in the figure) to the single magnet on the right. The combination of permanent magnet 1, the magnetic conductor and permanent magnet 2 may be considered as one magnet component 201.

[0229] The magnetic conductive connection ring may also be replaced with a non-magnetic ring or a magnetic ring with a significantly weaker magnetic field oriented in the opposite direction, which does not affect the overall equivalence to a single permanent magnet. Therefore, these configurations are also included in this case.

[0230] Embodiment 16 of the magnet component 201.

[0231] Referring to FIG. 39, permanent magnets are connected in in a series-parallel hybrid configuration along the magnetic field direction without a structural component therebetween, and n_{magnet} = 5.

[0232] Permanent magnet 1, permanent magnet 2 and permanent magnet 3 are connected in parallel via bonding, welding, riveting, bolts, clamping jaws, brackets, sleeves or other manners to obtain an equivalent magnet (magnet 1 | magnet 2 | magnet 3). This equivalent magnet (magnet 1 | magnet 2 | magnet 3) is then connected in series with permanent magnet 4 and permanent magnet 5 to obtain an equivalent magnet (magnet 4 - (magnet 1 | magnet 2 | magnet 3) - magnet 5). The magnetic field generated by each of the equivalent magnet (magnet 1 | magnet 2 | magnet 3), permanent magnet 4 and permanent magnet 5 is directed toward the Y+ axis direction, thus the magnetic fields have the same direction. Therefore, the magnet combination (magnet 4 - (magnet 1 | magnet 2 | magnet 3) - magnet 5), when viewed from the direction of the overall external magnetic field, may be regarded as substantially equivalent (indicated by the "=" sign in the figure) to the single magnet on the right. The magnet combination (magnet 4 - (magnet 1 | magnet 2 | magnet 3) - magnet 5) may be considered as one magnet component 201.

[0233] Embodiment 17 of the magnet component 201.

[0234] Referring to FIG. 40, permanent magnets are connected in in a series-parallel hybrid configuration along the magnetic field direction without a structural component therebetween, and n_{magnet} = 5.

[0235] Permanent magnet 1, permanent magnet 2 and permanent magnet 3 are connected in series via bonding, welding, riveting, bolts, clamping jaws, brackets, sleeves or other manners to obtain an equivalent magnet (magnet 1 - magnet 2 - magnet 3). This equivalent magnet (magnet 1 - magnet 2 - magnet 3) is then connected in parallel with permanent magnet 4 and permanent magnet 5 to obtain an equivalent magnet (magnet 4 | (magnet 1 - magnet 2 - magnet 3) | magnet 5). The magnetic field generated by each of the equivalent magnet (magnet 1 - magnet 2 - magnet 3), permanent magnet 4 and permanent magnet 5 is directed toward the Y+ axis direction, thus the magnetic fields have the same direction. Therefore, the magnet combination (magnet 4 | (magnet 1 - magnet 2 - magnet 3) | magnet 5), when viewed from the direction of the overall external magnetic field, may be regarded as substantially equivalent (indicated by the "=" sign in the figure) to the single magnet on the right. The magnet combination (magnet 4 | (magnet 1 - magnet 2 - magnet 3) | magnet 5) may be considered as one magnet component 201.

[0236] Embodiment 18 of the magnet component 201.

[0237] Referring to FIG. 40a, permanent magnets are connected in series along the magnetic field direction without a structural component therebetween, and n_{magnet} = 2.

[0238] Permanent magnet 1 and permanent magnet 2, where permanent magnet 1 is larger than permanent magnet 2, are connected via bonding, welding, embedding, screws, spirals, riveting, bolts, buckles, clamping jaws, brackets, sleeves, glands; or other manners. The magnetic field of permanent magnet 1 points is directed toward the Y+ axis direction, and the magnetic field of permanent magnet 2 points is directed toward the Y- axis direction (the negative direction of the Y-axis). However, since the magnetic field intensity of permanent magnet 2 is less than the magnetic field intensity of permanent magnet 1, the combination of permanent magnet 1 and permanent magnet 2, when viewed from the direction of the overall external magnetic field, may still be regarded as substantially equivalent (indicated by the "=" sign in the figure) to the single magnet on the right. The combination of permanent magnet 1 and permanent magnet 2 may be considered as one magnet component 201.

[0239] The coil component 102 during use includes embodiments as follows.

[0240] Embodiment 1 of the coil component 102.

[0241] Referring to FIG. 41, coils are connected in series along the magnetic field direction without a structural component therebetween, and n_{coil} = 2.

[0242] Coil 1 and coil 2 are connected via bonding, brackets, sleeves, riveting, clamping jaws, welding or other manners. The magnetic field generated by each of coil 1 and coil 2 is directed toward the Y+ axis direction, thus the magnetic fields have the same direction. Therefore, the combination of coil 1 and coil 2 generates an overall magnetic field whose direction, when viewed from the outside, may be considered equivalent (as indicated by the "=" sign in the diagram) to the magnetic field of the single coil on the right. The combination of coil 1 and coil 2 may be considered as one coil component 102.

[0243] In the aforementioned embodiment, whether there is an iron core in the middle of the coils or not has no effect on the direction of the magnetic field generated by the coil current. Thus, it does not affect the conclusion that the two coils are connected in series to form one coil component 102.

[0244] In the figures, according to standard coil current labeling conventions, the circle-cross icon ⊗ indicates current flowing perpendicular to the screen toward the inside, and the circle-dot icon ⊙ indicates current flowing perpendicular to the screen toward the outside.

[0245] Embodiment 2 of the coil component 102.

[0246] Referring to FIG. 42, coils are connected in series along the magnetic field direction with a sleeve surrounding the coils, and n_{coil} = 2.

[0247] Coil 1 and coil 2 are connected via a sleeve (preferably made of magnetic conductive material, or weak magnetic conductive material, non-magnetic conductive material, etc.). The magnetic field generated by each of coil 1 and coil 2 is directed toward the Y+ axis direction, thus the magnetic fields have the same direction. Therefore, the combination of coil 1 and coil 2 generates an overall magnetic field whose direction, when viewed from the outside, may be considered equivalent (as indicated by the "=" sign in the diagram) to the magnetic field of the single coil on the right. The combination of coil 1 and coil 2 may be considered as one coil component 102.

[0248] Embodiment 3 of the coil component 102.

[0249] Referring to FIG. 43, coils are connected in series along the magnetic field direction without a structural component therebetween, and n_{coil} = 3.

[0250] Coil 1, coil 2 and coil 3 are connected via bonding, brackets, sleeves, riveting, clamping jaws, welding or other manners. The magnetic field generated by each of coil 1, coil 2 and coil 3 is directed toward the Y+ axis direction, thus the magnetic fields have the same direction. Therefore, the combination of coil 1, coil 2 and coil 3 generates an overall magnetic field whose direction, when viewed from the outside, may be considered equivalent (as indicated by the "=" sign in the diagram) to the magnetic field of the single coil on the right. The combination of coil 1, coil 2 and coil 3 may be considered as one coil component 102.

[0251] Embodiment 4 of the coil component 102.

[0252] Referring to FIG. 44, coils are connected in series along the magnetic field direction with a structural component therebetween, and n_{coil} = 2.

[0253] A magnetic conductor is provided between coil 1 and coil 2 to provide spacing therebetween. Coil 1 and magnetic conductive ring 104, as well as coil 2 and magnetic conductive ring 104, are connected via bonding, brackets, sleeves, riveting, clamping jaws, welding or other manners. The magnetic field generated by each of coil 1 and coil 2 is directed toward the Y+ axis direction, thus the magnetic fields have the same direction. Therefore, the combination of coil 1, magnetic conductive ring 104, and coil 2 generates an overall magnetic field whose direction, when viewed from the outside, may be considered equivalent (as indicated by the "=" sign in the diagram) to the magnetic field of the single coil on the right. The combination of coil 1, magnetic conductive ring 104, and coil 2 may be considered as one coil component 102.

[0254] The magnetic conductive ring may also be replaced with a non-magnetic ring or a coil with a significantly weaker magnetic field oriented in the opposite direction, which does not affect the overall equivalence to a single coil. Therefore, these configurations are also included in this case.

[0255] Embodiment 5 of the coil component 102.

[0256] Referring to FIG. 45, coils are connected in series along the magnetic field direction without a structural component therebetween, and n_{coil} = 2.

[0257] Coil 1 and coil 2, where coil 1 is larger than coil 2, are connected via bonding, brackets, sleeves, riveting, clamping jaws, welding or other manners. The magnetic field generated by each of coil 1 and coil 2 is directed toward the Y+ axis direction, thus the magnetic fields have the same directions. Therefore, the combination of coil 1 and coil 2 generates an overall magnetic field whose direction, when viewed from the outside, may be considered equivalent (as indicated by the "=" sign in the diagram) to the magnetic field of the single coil on the right. The combination of coil 1 and coil 2 may be considered as one coil component 102.

[0258] Embodiment 6 of the coil component 102.

[0259] Referring to FIG. 46, coils are connected in series along the magnetic field direction with a structural component therebetween, and n_{coil} = 2.

[0260] Coil 1 and coil 2, where coil 1 is larger than coil 2, are connected via bonding, brackets, sleeves, riveting, clamping jaws, welding or other manners. The magnetic field generated by each of coil 1 and coil 2 is directed toward the Y+ axis direction, thus the magnetic fields have the same directions. Therefore, the combination of coil 1 and coil 2 generates an overall magnetic field whose direction, when viewed from the outside, may be considered equivalent (as indicated by the "=" sign in the diagram) to the magnetic field of the single coil on the right. The combination of coil 1 and coil 2 may be considered as one coil component 102.

[0261] The magnetic conductive ring may also be replaced with a non-magnetic ring or a coil with a significantly weaker magnetic field oriented in the opposite direction, which does not affect the overall equivalence to a single coil. Therefore, these configurations are also included in this case.

[0262] Embodiment 7 of the coil component 102.

[0263] Referring to FIG. 47, coils are connected in parallel along the magnetic field direction without a structural component therebetween, and $n_{coil} = 2$.

[0264] Coil 1 (outer coil) and coil 2 (inner coil) are connected via bonding, brackets, sleeves, riveting, clamping jaws, welding or other manners. The magnetic field generated by each of coil 1 and coil 2 is directed toward the Y+ axis direction, thus the magnetic fields have the same directions. Therefore, the combination of coil 1 and coil 2 generates an overall magnetic field whose direction, when viewed from the outside, may be considered equivalent (as indicated by the "=" sign in the diagram) to the magnetic field of the single coil on the right. The combination of coil 1 and coil 2 may be considered as one coil component 102.

[0265] Embodiment 8 of the coil component 102.

[0266] Referring to FIG. 48, coils are connected in parallel along the magnetic field direction without a structural component therebetween, and $N_{coil} = 2$.

[0267] Coil 1 (outer coil), coil 2 (inner coil) and an iron core are connected via bonding, brackets, sleeves, riveting, clamping jaws, welding or other manners. The magnetic field generated by each of coil 1 and coil 2 is directed toward the Y+ axis direction, thus the magnetic fields have the same directions. Therefore, the combination of coil 1, coil 2, and the iron core generates an overall magnetic field whose direction, when viewed from the outside, may be considered equivalent (as indicated by the "=" sign in the diagram) to the magnetic field of the single coil on the right. The combination of coil 1, coil 2, and the iron core may be considered as one coil component 102.

[0268] Embodiment 9 of the coil component 102.

[0269] Referring to FIG. 49, coils are connected in parallel along the magnetic field direction without a structural component therebetween, and $n_{coil} = 3$.

[0270] Coil 1, coil 2 and coil 3 are connected via bonding, brackets, sleeves, riveting, clamping jaws, welding or other manners. The magnetic field generated by each of coil 1, coil 2 and coil 3 is directed toward the Y+ axis direction, thus the magnetic fields have the same directions. Therefore, the combination of coil 1, coil 2 and coil 3 generates an overall magnetic field whose direction, when viewed from the outside, may be considered equivalent (as indicated by the "=" sign in the diagram) to the magnetic field of the single coil on the right. The combination of coil 1, coil 2 and coil 3 may be considered as one coil component 102.

[0271] Embodiment 10 of the coil component 102.

[0272] Referring to FIG. 50, coils are connected in parallel along the magnetic field direction without a structural component therebetween, and $n_{coil} = 3$.

[0273] Coil 1, coil 2, coil 3, magnetic conductive plate 1 and magnetic conductive plate 2 are connected via bonding, brackets, sleeves, riveting, clamping jaws, welding or other manners. The magnetic field generated by each of coil 1, coil 2 and coil 3 is directed toward the Y+ axis direction, and the magnetic fields of magnetic conductive plate 1 and magnetic conductive plate 2 after magnetization are also directed toward the Y+ axis direction, thus all having the same directions. Therefore, the combination of coil 1, coil 2, coil 3, magnetic conductive plate 1 and magnetic conductive plate 2 generates an overall magnetic field whose direction, when viewed from the outside, may be considered equivalent (as indicated by the "=" sign in the diagram) to the magnetic field of the single coil on the right. The combination of coil 1, coil 2, coil 3, magnetic conductive plate 1 and magnetic conductive plate 2 may be considered as one coil component 102.

[0274] The magnetic conductive plate may also be replaced with a non-magnetic plate or a magnet with a significantly weaker magnetic field oriented in the opposite direction, which does not affect the overall equivalence to a single coil. Therefore, these configurations are also included in this case.

[0275] Embodiment 11 of the coil component 102.

[0276] Referring to FIG. 51, coils are connected in parallel along the magnetic field direction with a structural component therebetween, and $n_{coil} = 2$.

[0277] Coil 1 and coil 2 are separated by an isolating ring (preferably made of magnetic material, though it may also be made of weakly magnetic or non-magnetic material). Coil 1 and the isolating ring, as well as coil 2 and the isolating ring, are connected via bonding, brackets, sleeves, riveting, clamping jaws, welding, or other manners. The magnetic field generated by each of coil 1 and coil 2 is directed toward the positive Y-axis direction, thus having the same orientation. Therefore, the combination of coil 1, coil 2, and the isolating ring generates an overall magnetic field whose direction, when viewed from the outside, may be considered equivalent (as indicated by the "=" sign in the diagram) to the magnetic field of the single coil on the right. The combination of coil 1, the magnetic conductor, and coil 2 may be considered as one coil component 102.

[0278] Embodiment 12 of the coil component 102.

[0279] Referring to FIG. 52, coils are connected in a series-parallel hybrid manner along the magnetic field direction without a structural component therebetween, and $n_{coil} = 4$.

[0280] Coil 1 and coil 2 are connected in parallel via bonding, brackets, sleeves, riveting, clamping jaws, welding or other manners to obtain one equivalent coil (coil 1 | coil 2). The equivalent coil (coil 1 | coil 2) is then connected in series with coil 3 and coil 4 to obtain one equivalent coil (coil 3 - (coil 1 | coil 2) - coil 4). The magnetic field generated by each of the equivalent coil (coil 1 | coil 2), coil 3 and coil 4 is directed toward the Y+ axis direction, thus the magnetic fields have the same direction. Therefore, the coil combination (coil 3 - (coil 1 | coil 2) - coil 4) generates an overall magnetic field whose direction, when viewed from the outside, may be considered equivalent (as indicated by the "=" sign in the diagram) to the magnetic field of the single coil on the right. The coil combination (coil 3 - (coil 1 | coil 2) - coil 4) may be considered as one coil component 102.

[0281] Embodiment 13 of the coil component 102.

[0282] Referring to FIG. 53, coils are connected in a series-parallel hybrid manner along the magnetic field direction without a structural component therebetween, and $n_{coil} = 4$.

[0283] Coil 1, coil 2 and coil 3 are connected in series via bonding, brackets, sleeves, riveting, clamping jaws, welding or other manners to obtain one equivalent coil (coil 1 - coil 2 - coil 3). The equivalent coil (coil 1 - coil 2 - coil 3) is then connected in parallel with coil 4 to obtain one equivalent coil ((coil 1 - coil 2 - coil 3) | coil 4). The magnetic field generated by each of the equivalent coil (coil 1 - coil 2 - coil 3) and coil 4 is directed toward the Y+ axis direction, thus the magnetic fields have the same direction. Therefore, the coil assembly ((coil 1 - coil 2 - coil 3) | coil 4) generates an overall magnetic field whose direction, when viewed from the outside, may be considered equivalent (as indicated by the "=" sign in the diagram) to the magnetic field of the single coil on the right. The coil combination ((coil 1 - coil 2 - coil 3) | coil 4) may be considered as one coil component 102.

Embodiment 10

[0284] Referring to FIGS. 1 to 53, the moving-magnet vibrator device with nonlinear term cancellation obtained by using the design method of moving-magnet vibrator device with nonlinear term cancellation according to embodiment 1, embodiment 3, embodiment 5, and embodiment 7, is applied to a device such as a bone conduction headphone, bone conduction glasses, a wired headphone, a wireless headphone, AR glasses, VR glasses, a smart watch, a smart bracelet, a head-mounted device, a wearable device, a smartphone, a game controller, a game headphone, a game steering wheel, a game pedal, a mouse, a keyboard, a touch screen, an electrical control panel, a touch device, a screen sound-generating device, a vehicle-mounted haptic feedback device, a smart cockpit, a game chair, a massage chair, a massager, a haptic feedback vest, a haptic feedback glove, a haptic feedback belt, a haptic feedback leg device, a hearing aid, a sleep-aiding device, or a haptic feedback network interconnection device. When the moving-magnet vibrator device with nonlinear term cancellation is used in the aforementioned products, it can convert electrical energy into mechanical energy, such as vibration or mechanical motion.

[0285] Compared with the relating technologies, the embodiments of the disclosure provide the improved design method, device and use of a moving-magnet vibrator with nonlinear term cancellation, which have the improvements and advantages as follows.

[0286] The embodiments of the disclosure provide the design method that enables the nonlinear terms in the driving force acting on the magnet combination structure, or in the acceleration of the movable assembly relative to the vibrator coil current, to be fully or partially cancelled in the final resultant force through paired or unpaired configurations. This significantly reduces the distortion of the vibrator and improves the fidelity of the original audio signal or haptic feedback signal.

[0287] The embodiments of the disclosure provide the moving-magnet vibrator with nonlinear term cancellation, which enables the total harmonic distortion in the low-frequency band to be reduced from the original peak value of 99% to below 15%. The reduction of the distortion curve is equivalently interpreted as the reduction of the resonant frequency of the vibrator system, thereby achieving better low-frequency sound quality. In addition, the reduction of the distortion curve may be further equivalently interpreted as the improvement of the sensitivity of the vibrator system and the reduction of power consumption.

[0288] The design method of the moving-magnet vibrator with nonlinear term cancellation according to the embodiments of the disclosure achieves uniform and balanced force on the vibrator, realizing the overall translational vibration of the vibrator, thereby enabling a good vibration performance.

[0289] The foregoing description enables those skilled in the art to practice or use the disclosure. Various modifications to these embodiments will be apparent to those skilled in the art, and the general principles defined herein may be implemented in other embodiments without departing from the spirit or scope of the disclosure. Therefore, the application shall not be limited to the embodiments disclosed herein, but is intended to conform to the broadest scope consistent with the principles and novel features disclosed herein.

Claims

1. A moving-magnet vibrator with nonlinear term cancellation, comprising:

a moving-magnet vibrator body; wherein the moving-magnet vibrator body comprises an outer cylinder, a vibration transmission plate, a stator assembly and a movable assembly, the stator assembly comprises a coil combination structure, and the movable assembly comprises a magnet combination structure; the stator assembly is fixed inside the outer cylinder, the vibration transmission plate is fixed on the outer cylinder, and the movable assembly is fixedly connected to the vibration transmission plate through at least one contact point; the movable assembly moves while the stator assembly remains stationary, and the movable assembly is referred to as a moving component; and

the movable assembly is configured to be simultaneously subjected to paired electromagnetic forces of push and pull, thereby presenting push-pull structural characteristics.

2. The moving-magnet vibrator with nonlinear term cancellation as claimed in claim 1, wherein in the moving-magnet vibrator body, 2N magnetic domains $D_{1,i}$ and $D_{2,i}$ are designed as N symmetrical pairs, where N=1, 2, 3, ..., 100, and i=1, 2, 3, ...

3. The moving-magnet vibrator with nonlinear term cancellation as claimed in claim 2, wherein the magnet combination structure comprise a permanent magnet, the coil combination structure comprises a coil, and the number of the permanent magnet in the magnet combination structure and the number of the coil in the coil combination structure are limited by $N_{magnet}>N_{coil}$ or $N_{magnet} < N_{coil}$, where N_{magnet} represents the number of the permanent magnet, N_{coil} represents the number of the coil, N_{magnet}=1, 2, 3, ...,100, and N_{coil}=1, 2, 3, ..., 100.

4. The moving-magnet vibrator with nonlinear term cancellation as claimed in claim 3, wherein in the push-pull structural characteristics, linear terms of the electromagnetic force acting on the movable assembly are superimposed to be increased, and nonlinear terms of the electromagnetic force acting on the movable assembly are partially or completely canceled to be decreased.

5. The moving-magnet vibrator with nonlinear term cancellation as claimed in claim 2, wherein closed main magnetic flux lines of a coil in the coil combination structure and closed main magnetic flux lines of a permanent magnet in the magnet combination structure each pass through magnetic domains $D_{1,i}$ and $D_{2,i}$; the magnetic domain is a spatial region filled with electromagnetic energy, the magnetic domain is composed of air or a medium with a relative magnetic permeability less than 1000, and comprises a region where a magnet material is located;

in the magnetic domain $D_{1,i}$, a direction of magnetic flux lines of the coil is the same as a direction of magnetic flux lines of the permanent magnet, and in the magnetic domain $D_{2,i}$, the direction of the magnetic flux lines of the coil is opposite to the direction of the magnetic flux lines of the permanent magnet; alternatively, in the magnetic domain $D_{1,i}$, the direction of the magnetic flux lines of the coil is opposite to the direction of the magnetic flux lines of the permanent magnet, and in the magnetic domain $D_{2,i}$, the direction of the magnetic flux lines of the coil is the same as the direction of the magnetic flux lines of the permanent magnet.

6. The moving-magnet vibrator with nonlinear term cancellation as claimed in claim 5, wherein the moving component is subjected to 2N forces, where N=1, 2, 3, ..., 100; each component force comprises two parts: one part is a linear term of an excitation current i, and another part is a nonlinear term of the excitation current i:

$$F_{moving-magnet,n}(i) = F_{moving-magnet,n,linear}(i) + F_{moving-magnet,n,nonlinear}(i),$$

where n = 1, 2, 3, ..., 2N - 1, 2N;

a resultant force on the moving component comprises two parts: one part is a linear term of the excitation current i, and another part is a nonlinear term of the excitation current i:

$$F_{moving-magnet,resultant\ force}(i) = F_{moving-magnet,resultant\ force,linear}(i) + F_{moving-magnet,resultant\ force,nonlinear}(i);$$

where:

$$F_{moving-magnet,resultant\ force}(i) = \sum_{n=1}^{2N} F_{moving-magnet,n}(i) = \sum_{n=1}^{N} \left(F_{moving-magnet,n,1}(i) + F_{moving-magnet,n,2}(i)\right);$$

$$F_{moving-magnet,resultant\ force,linear}(i) = \sum_{n=1}^{2N} F_{moving-magnet,n,linear}(i) = \sum_{n=1}^{N}(F_{moving-magnet,linear,1}(i) + F_{moving-magnet,linear,2}(i));\ \text{and}$$

$$F_{moving-magnet,resultant\ force,nonlinear}(i) = \sum_{n=1}^{2N} F_{moving-magnet,n,nonlinear}(i) = \sum_{n=1}^{N} \left(F_{moving-magnet,nonlinear,1}(i) + F_{moving-magnet,nonlinear,2}(i)\right);$$

the nonlinear terms in each component force are partially or completely canceled, and in a final total resultant force $\Sigma_i(F_{1,i} + F_{2,i})$, the nonlinear terms of the total resultant force relative to the excitation current are partially or completely canceled, and the linear terms are superimposed to be increased, thereby obtaining the moving-magnet vibrator with nonlinear term cancellation.

7. The moving-magnet vibrator with nonlinear term cancellation as claimed in claim 1, wherein the coil combination structure comprises a coil and a first magnetic conductor, and the magnet combination structure comprises a permanent magnet and a second magnetic conductor.

8. The moving-magnet vibrator with nonlinear term cancellation as claimed in claim 1, wherein the magnet combination structure comprises a magnet component and a second magnetic conductor; the magnet component is a single magnet or an assembly of a plurality of magnets, the assembly of plurality of magnets generating an overall magnetic field equivalent to a magnetic field generated by a certain single magnet, directions of magnetic fields generated by the plurality of magnets of the assembly are the same as a direction of a certain dominant magnetic field; the plurality of magnets are connected through a rigid structural component, or a flexible structural component arranged between the magnets, at edges of the magnets, or around the magnets, or connected through a manner without a structural component, including bonding, welding, embedding, screws, spirals, riveting, bolts, buckles, clamping jaws, brackets, sleeves, or glands.

9. The moving-magnet vibrator with nonlinear term cancellation as claimed in claim 1, wherein the coil combination structure comprises a coil component and a first magnetic conductor, the coil component is a single coil or an assembly of a plurality of coils, the assembly of plurality of coils generating an overall magnetic field equivalent to a magnetic field generated by a certain single coil, directions of magnetic fields generated by the plurality of coils of the assembly are the same as a direction of a magnetic field generated by a certain dominant coil; the plurality of coils are connected through a rigid structural component, or a flexible structural component arranged between the coils, at edges of the coils, or around the coils, or a manner without a structural component, including bonding, welding, embedding, screws, spirals, riveting, bolts, buckles, clamping jaws, brackets, sleeves, or glands.

10. The moving-magnet vibrator with nonlinear term cancellation as claimed in claim 7, wherein the movable assembly and the stator assembly are in concave-convex shapes and arranged in an interleaved engagement manner, and closed main magnetic flux lines of the coil and closed main magnetic flux lines of a permanent magnet alternately pass through the movable assembly and the stator assembly.

11. The moving-magnet vibrator with nonlinear term cancellation as claimed in claim 3, wherein:

looking outward from a center, the permanent magnet is located inside and the coil is located outside;

$$N_{magnet} = (N_{coil} + 1) \times n,$$

where n is a natural number, n = 1, 2, 3...; and
when $N_{magnet}>1$, polarities of two opposite end faces of adjacent permanent magnets are the same; when $N_{coil}>1$, directions of currents in adjacent coils are opposite, and polarities of electromagnetic fields at adjacent end faces

of two adjacent coils are the same.

12. The moving-magnet vibrator with nonlinear term cancellation as claimed in claim 3, wherein:

looking outward from a center, the permanent magnet is located inside and the coil is located outside;

$$N_{magnet} = (N_{coil} - 1) \times n,$$

where n is a natural number, n = 1, 2, 3...; and
when $N_{magnet}>1$, polarities of two opposite end faces of adjacent permanent magnets are the same; when $N_{coil}>1$, directions of currents in adjacent coils are opposite, and polarities of electromagnetic fields at adjacent end faces of two adjacent coils are the same.

13. The moving-magnet vibrator with nonlinear term cancellation as claimed in claim 3, wherein:

looking outward from a center, the coil is located inside and the permanent magnet is located outside;

$$N_{magnet} = (N_{coil} + 1) \times n,$$

where n is a natural number, n = 1, 2, 3...; and
when $N_{magnet}>1$, polarities of two opposite end faces of adjacent permanent magnets are the same; when $N_{coil}>1$, directions of currents in adjacent coils are opposite, and polarities of electromagnetic fields at adjacent end faces of two adjacent coils are the same.

14. The moving-magnet vibrator with nonlinear term cancellation as claimed in claim 3, wherein:

looking outward from a center, the coil is located inside and the permanent magnet is located outside;

$$N_{magnet} = (N_{coil} - 1) \times n,$$

where n is a natural number, n = 1, 2, 3...; and
when $N_{magnet}>1$, polarities of two opposite end faces of adjacent permanent magnets are the same; when $N_{coil}>1$, directions of currents in adjacent coils are opposite, and polarities of electromagnetic fields at adjacent end faces of two adjacent coils are the same.

15. The moving-magnet vibrator with nonlinear term cancellation as claimed in claim 10, wherein a magnetic conductor is provided at a position of the outer cylinder close to the coil to minimize a magnetic resistance of a magnetic circuit of an electromagnet generated by the coil; the permanent magnet in the magnet assembly is isolated by a magnetic conductor; a yoke iron is used around the coil and the permanent magnet, or for the coil combination structure, a part of the outer cylinder close to the coil is magnetically conductive.

16. The moving-magnet vibrator device with nonlinear term cancellation as claimed in claim 12, wherein:

the coil combination structure further comprises a first magnetic conductor and a first magnetic conductor ring, the magnet combination structure further comprises a second magnetic conductor; the permanent magnet comprises one permanent magnet and the coil comprises two coils; the vibration transmission plate comprises two vibration transmission plates fixed on a top surface and a bottom surface of the outer cylinder respectively; the permanent magnet is fixed in the second magnetic conductor, two ends of the second magnetic conductor are respectively fixed on the two vibration transmission plates; the first magnetic conductor is fixed in middle of an inner side wall of the outer cylinder, and the two coils are respectively fixed on two sides of the first magnetic conductor; the first magnetic conductive ring is fixedly arranged on outer sides of the two coils, and the coils and the first magnetic conductive ring are fixed on the inner side wall of the outer cylinder;
the movable assembly and the stator assembly are in concave-convex shapes and arranged in an interleaved engagement manner; closed magnetic flux lines of the coils and closed magnetic flux lines of the permanent magnet alternately pass through the movable assembly and the stator assembly; two magnetic domains $D_{1,1}$ and $D_{2,1}$ which are designed as a symmetrical pair are provided in the moving-magnet vibrator body, the closed

magnetic flux lines of the coil and the closed magnetic flux lines of the permanent magnet each pass through the magnetic domains $D_{1,1}$ and $D_{2,1}$; in the magnetic domain $D_{1,1}$, a direction of magnetic flux lines of one coil is the same as a direction of magnetic flux lines of the permanent magnet, and in the magnetic domain $D_{2,1}$, the direction of the magnetic flux lines of another coil is opposite to the direction of the magnetic flux lines of the permanent magnet.

17. The moving-magnet vibrator device with nonlinear term cancellation as claimed in claim 13, wherein:

the coil combination structure further comprises a first magnetic conductor and a first magnetic conductor ring, the magnet combination structure further comprises a second magnetic conductor and a second magnetic conductive ring, and the permanent magnet comprises two permanent magnets and the coil comprises one coil; the vibration transmission plate comprises one vibration transmission plate fixed on a top surface of the outer cylinder, an end of the first magnetic conductor is fixed on a bottom surface of the outer cylinder, the coil is wound around and fixed on the first magnetic conductor, and the first magnetic conductive ring is fixed at an end of the first magnetic conductor;

the moving-magnet vibrator device with nonlinear term cancellation further comprises an L-shaped vibration transmission bracket, a horizontal part of the vibration transmission bracket is parallel to a vibration direction, the second magnetic conductor is fixed on the horizontal part of the vibration transmission bracket, the two permanent magnets are fixedly arranged on two sides of the second magnetic conductor, and the two permanent magnets are fixed on the horizontal part of the vibration transmission bracket; and

the movable assembly and the stator assembly are in concave-convex shapes and arranged in an interleaved engagement manner; closed magnetic flux lines of the coil and closed magnetic flux lines of the permanent magnets alternately pass through the movable assembly and the stator assembly; two magnetic domains $D_{1,1}$ and $D_{2,1}$ which are designed as a symmetrical pair are provided in the moving-magnet vibrator body, the closed magnetic flux lines of the coil and the closed magnetic flux lines of the permanent magnet each pass through the magnetic domains $D_{1,1}$ and $D_{2,1}$; in the magnetic domain $D_{1,1}$, a direction of magnetic flux lines of the coil is opposite to a direction of magnetic flux lines of one permanent magnet, and in the magnetic domain $D_{2,1}$, the direction of the magnetic flux lines of the coil is the same as the direction of the magnetic flux lines of another permanent magnet.

18. The moving-magnet vibrator device with nonlinear term cancellation as claimed in claim 14, wherein:

the magnet combination structure further comprises a second magnetic conductor, the coil combination structure further comprises a first magnetic conductor, a first magnetic conductor ring and a second magnetic conductor ring; the permanent magnet comprises one permanent magnet and the coil comprises two coils; the vibration transmission plate comprises one vibration transmission plate fixed on a top surface of the outer cylinder, an end of the first magnetic conductor is fixed on a bottom surface of the outer cylinder, the two coils are wound around and fixed on the first magnetic conductor, the second magnetic conductive ring is fixed at an end of the first magnetic conductor, and the first magnetic conductive ring is wound around and fixed on a middle part of the first magnetic conductor and located between the two coils;

wherein the moving-magnet vibrator device with nonlinear term cancellation further comprises an L-shaped vibration transmission bracket, a horizontal part of the vibration transmission bracket is parallel to a vibration direction, the permanent magnet is fixed in middle of the horizontal part of the vibration transmission bracket, and the second magnetic conductor is located on two sides of the permanent magnet and fixed on the horizontal part of the vibration transmission bracket; and

the movable assembly and the stator assembly are in concave-convex shapes and arranged in an interleaved engagement manner; closed magnetic flux lines of the coils and closed magnetic flux lines of the permanent magnet alternately pass through the movable assembly and the stator assembly; four magnetic domains $D_{1,1}$, $D_{2,1}$, $D_{1,2}$ and $D_{2,2}$ which are designed as two symmetrical pairs are provided in the moving-magnet vibrator body, where $D_{1,1}$ is symmetric to $D_{2,1}$, and $D_{1,2}$ is symmetric to $D_{2,2}$; the closed magnetic flux lines of the coil and the closed magnetic flux lines of the permanent magnet each pass through the magnetic domains $D_{1,1}$, $D_{2,1}$, $D_{1,2}$ and $D_{2,2}$; in the magnetic domain $D_{1,1}$, a direction of magnetic flux lines of one coil is opposite to a direction of magnetic flux lines of the permanent magnet; and in the magnetic domain $D_{2,1}$, the direction of the magnetic flux lines of another coil is the same as the direction of the magnetic flux lines of the permanent magnet.

19. The moving-magnet vibrator device with nonlinear term cancellation as claimed in claim 12, wherein:

the magnet combination structure further comprises a second magnetic conductor, and the coil combination structure further comprises a first magnetic conductor and a first magnetic conductor ring; the permanent magnet comprises two permanent magnets; the coil comprises three coils; the vibration transmission plate comprises two vibration transmission plates respectively fixed on a top surface and a bottom surface of the outer cylinder; the two permanent magnets are fixed on two sides of the second magnetic conductor, the two permanent magnets are respectively fixed on magnetic conductive sleeves, and the magnetic conductive sleeves are respectively fixed on the two vibration transmission plates; the three coils are sequentially fixed on an inner side wall of the outer cylinder, the first magnetic conductor is fixedly arranged between adjacent coils, the first magnetic conductive ring is fixedly arranged on an outer side of the outermost coils, and both the first magnetic conductor and the first magnetic conductive ring are fixed on the inner side wall of the outer cylinder; and

the movable assembly and the stator assembly are in concave-convex shapes and arranged in an interleaved engagement manner; closed magnetic flux lines of the coils and closed magnetic flux lines of the permanent magnets alternately pass through the movable assembly and the stator assembly; six magnetic domains $D_{1,1}$, $D_{2,1}$, $D_{1,2}$, $D_{2,2}$, $D_{1,3}$, and $D_{2,3}$ which are designed as three symmetrical pairs are provided in the moving-magnet vibrator body, where $D_{1,1}$ is symmetric to $D_{2,1}$, $D_{1,2}$ is symmetric to $D_{2,2}$, and $D_{1,3}$ is symmetric to $D_{2,3}$; the closed magnetic flux lines of the coils and the closed magnetic flux lines of the permanent magnets each pass through the magnetic domains $D_{1,1}$, $D_{2,1}$, $D_{1,2}$, $D_{2,2}$, $D_{1,3}$, and $D_{2,3}$; in the magnetic domain $D_{1,1}$, a direction of magnetic flux lines of one coil is opposite to a direction of magnetic flux lines of one permanent magnet; in the magnetic domain $D_{2,1}$, the direction of the magnetic flux lines of the one coil is the same as the direction of the magnetic flux lines of another permanent magnet; in the magnetic domain $D_{1,2}$, the direction of the magnetic flux lines of another coil is the same as the direction of the magnetic flux lines of the one permanent magnet; and in the magnetic domain $D_{2,2}$, the direction of the magnetic flux lines of a further coil is opposite to the direction of the magnetic flux lines of the another permanent magnet.

20. The moving-magnet vibrator device with nonlinear term cancellation as claimed in claim 1 is configured to be applied to a bone conduction headphone, bone conduction glasses, a wired headphone, a wireless headphone, AR glasses, VR glasses, a smart watch, a smart bracelet, a head-mounted device, a wearable device, a smartphone, a game controller, a game headphone, a game steering wheel, a game pedal, a mouse, a keyboard, a touch screen, an electrical control panel, a touch device, a screen sound-generating device, a vehicle-mounted haptic feedback device, a smart cockpit, a game chair, a massage chair, a massager, a haptic feedback vest, a haptic feedback glove, a haptic feedback belt, a haptic feedback leg device, a hearing aid, a sleep-aiding device, or a haptic feedback network interconnection device.

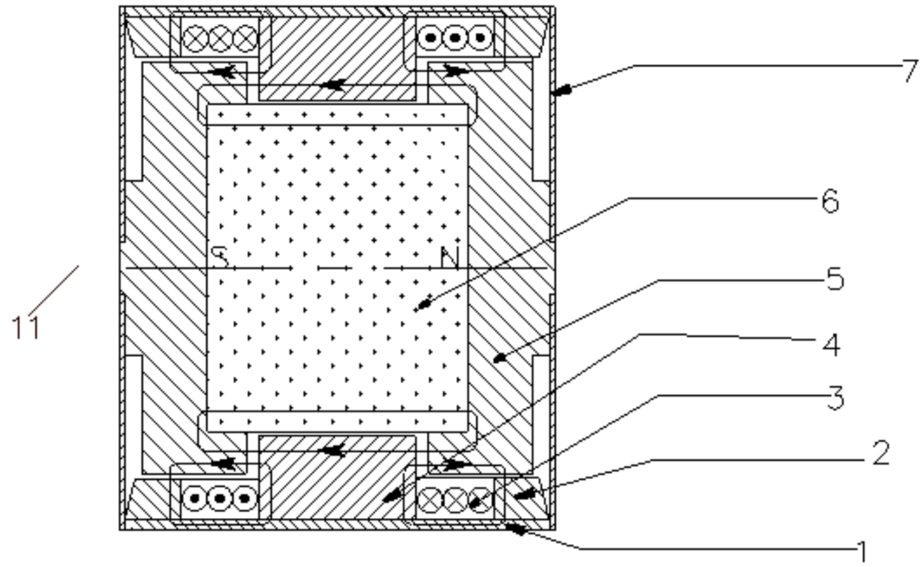

7
6
5
4
3
2
1
11
S
N

FIG. 1

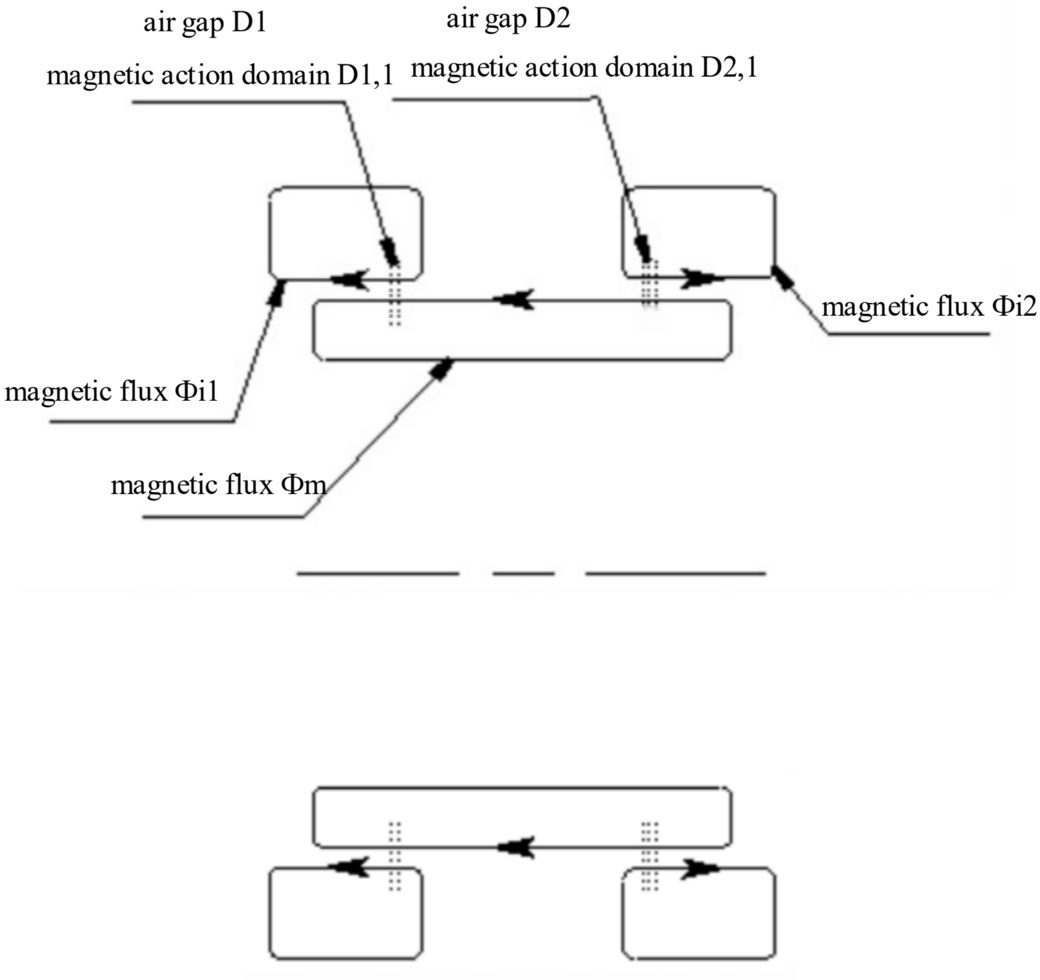

air gap D1
air gap D2
magnetic action domain D1,1
magnetic action domain D2,1
magnetic flux Φi2
magnetic flux Φi1
magnetic flux Φm

FIG. 2

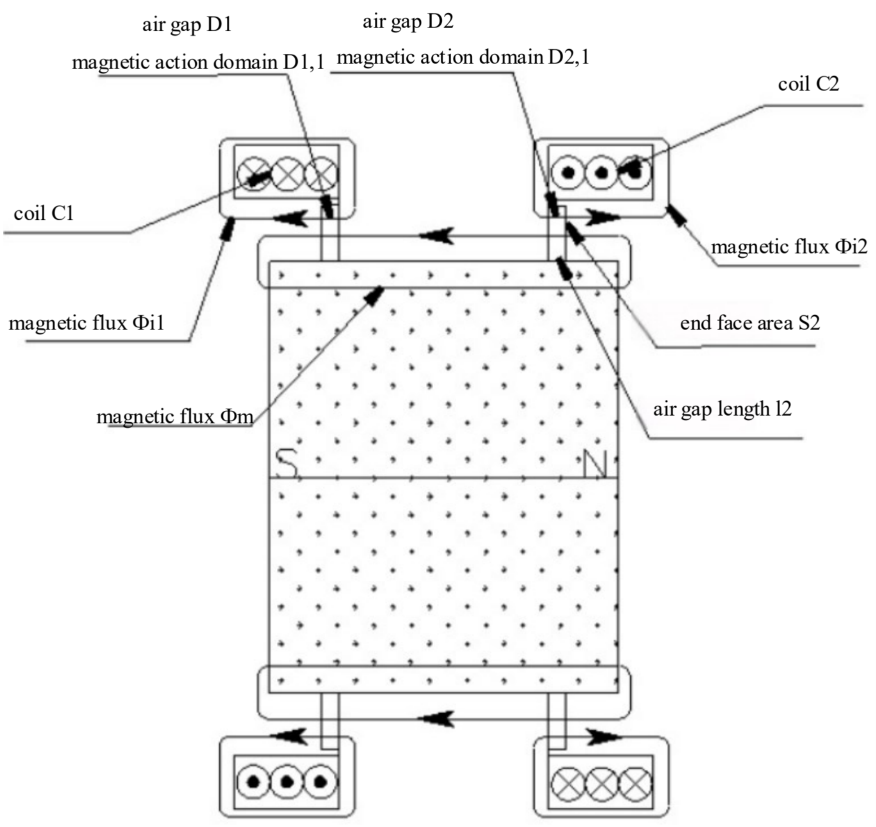

air gap D1
magnetic action domain D1,1
air gap D2
magnetic action domain D2,1
coil C2
coil C1
magnetic flux Φi2
magnetic flux Φi1
end face area S2
magnetic flux Φm
air gap length l2
S
N

FIG. 3

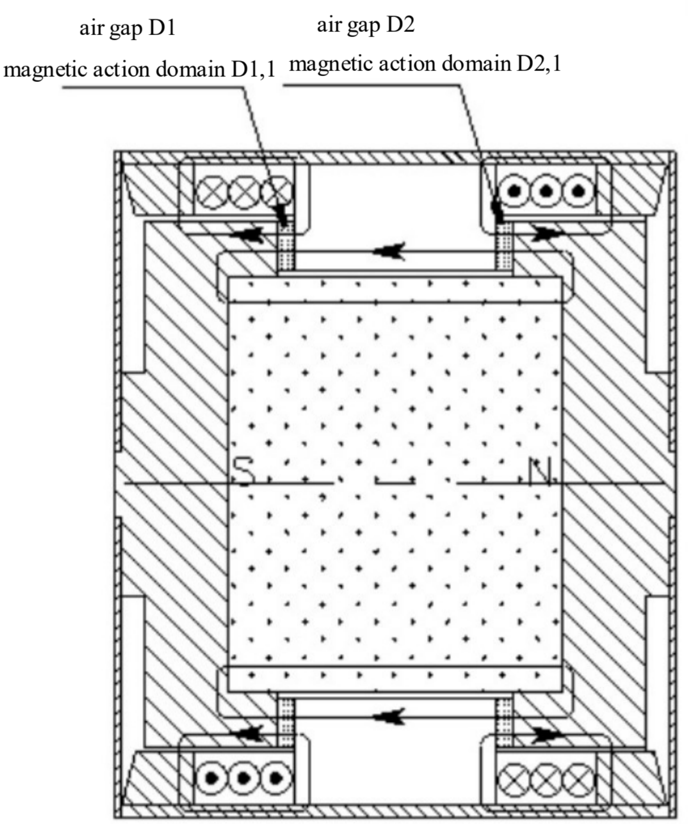

air gap D1
magnetic action domain D1,1
air gap D2
magnetic action domain D2,1
S
N

FIG. 4

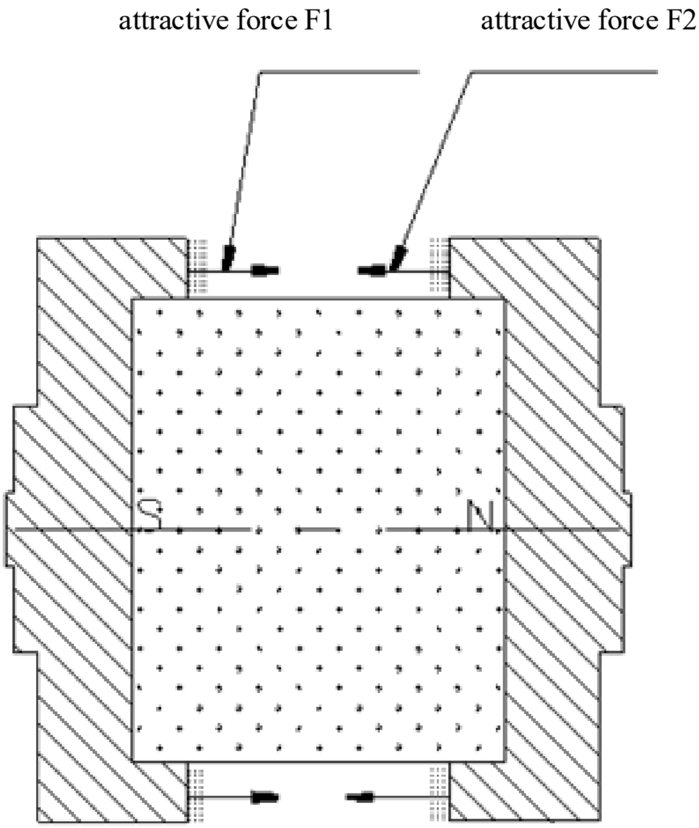

attractive force F1
attractive force F2
S
N

FIG. 5

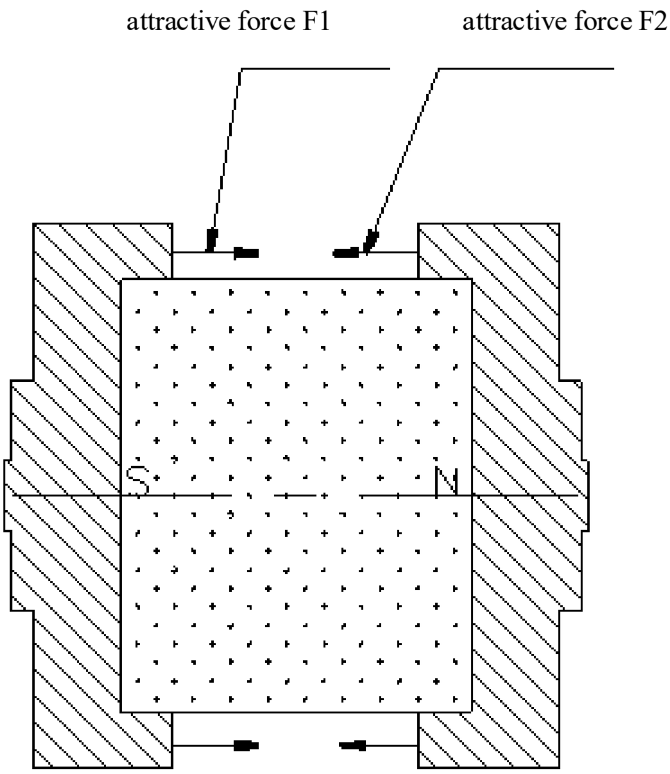

attractive force F1
attractive force F2
S
N

FIG. 6

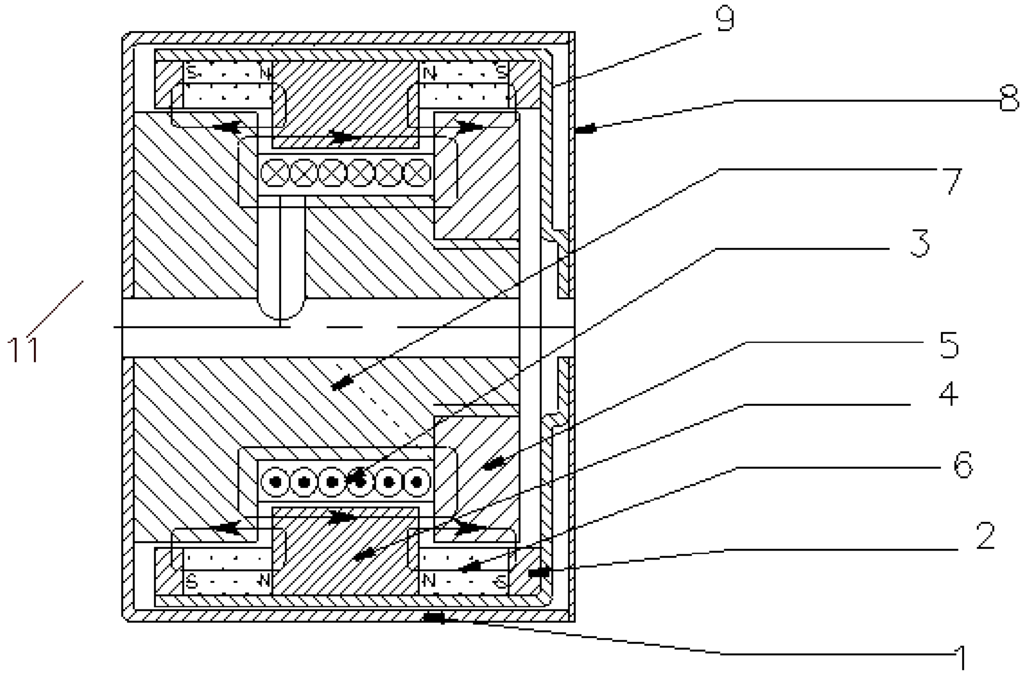

9
8
7
3
5
4
6
2
1
11
S
N
N
S

FIG. 7

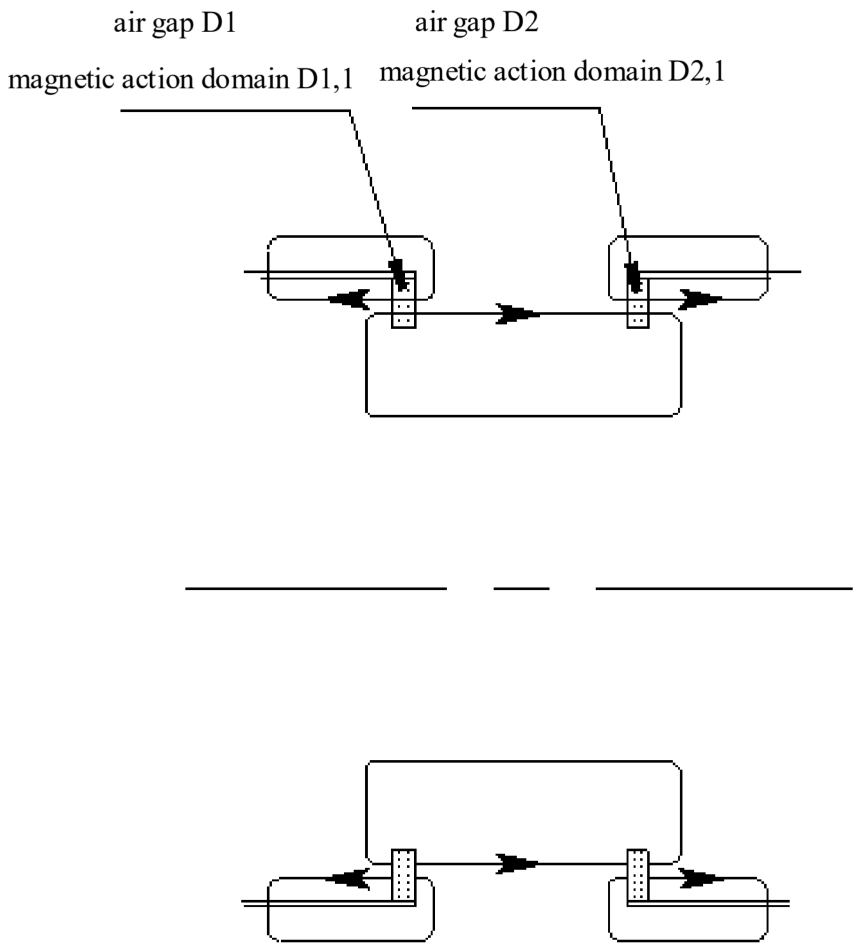

air gap D1
magnetic action domain D1,1
air gap D2
magnetic action domain D2,1

FIG. 8

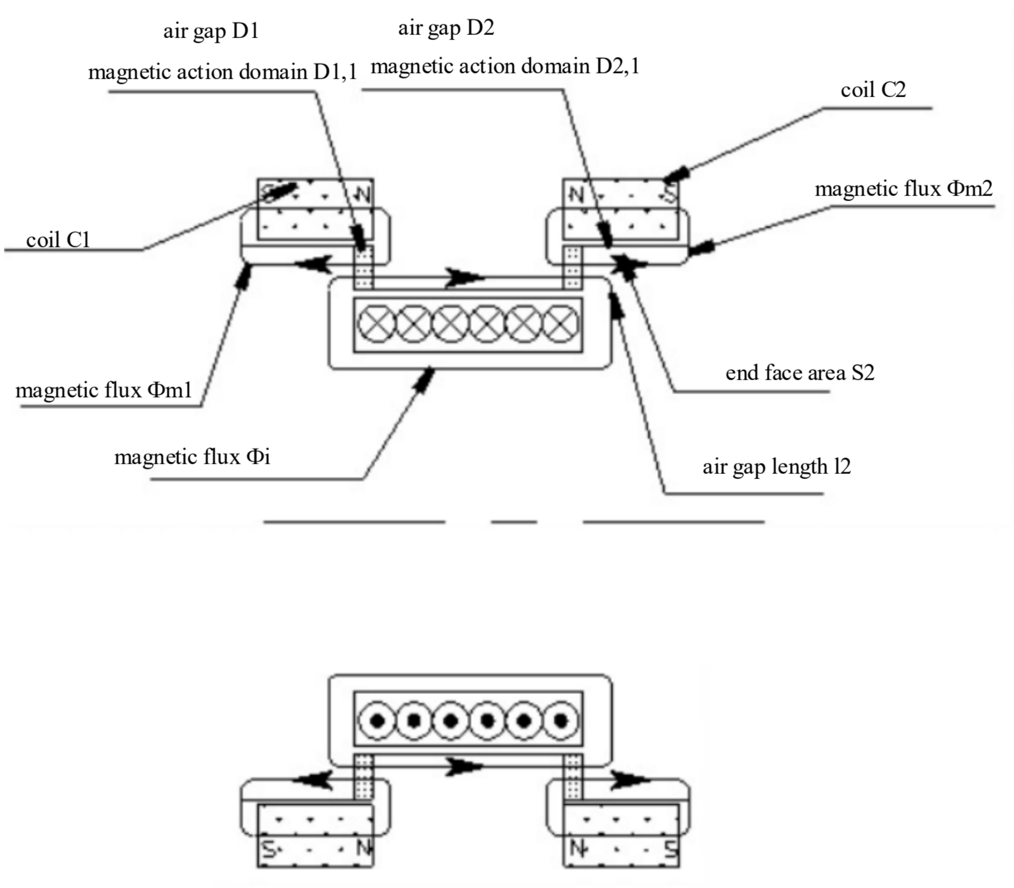

air gap D1
magnetic action domain D1,1
air gap D2
magnetic action domain D2,1
coil C2
magnetic flux Φm2
coil C1
end face area S2
magnetic flux Φm1
magnetic flux Φi
air gap length l2
S
N
N
S

FIG. 9

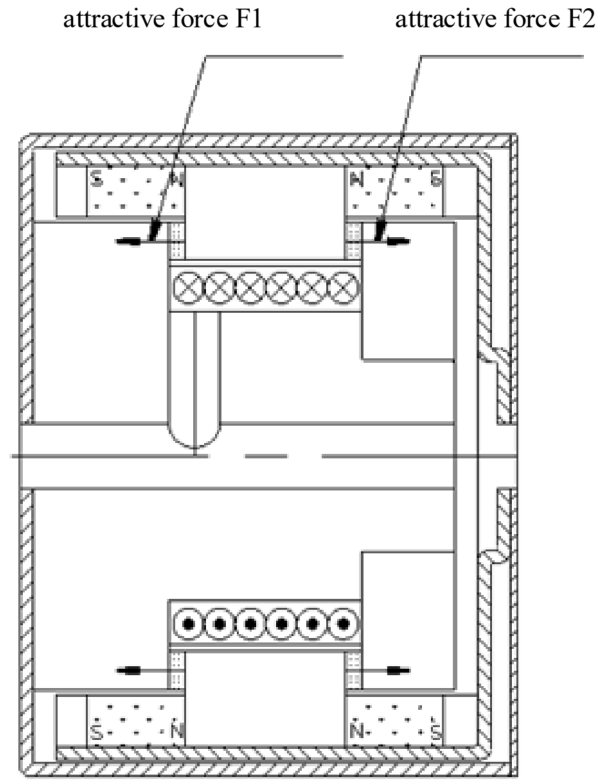

attractive force F1
attractive force F2
S
N
N
S

FIG. 10

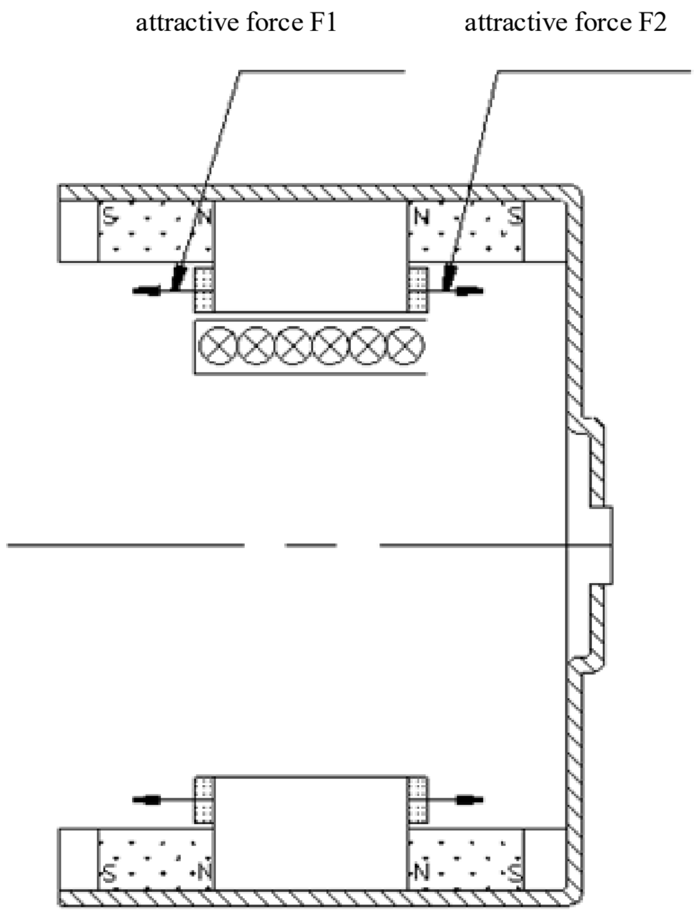

attractive force F1
attractive force F2
S
N
N
S
S
N
N
S

FIG. 11

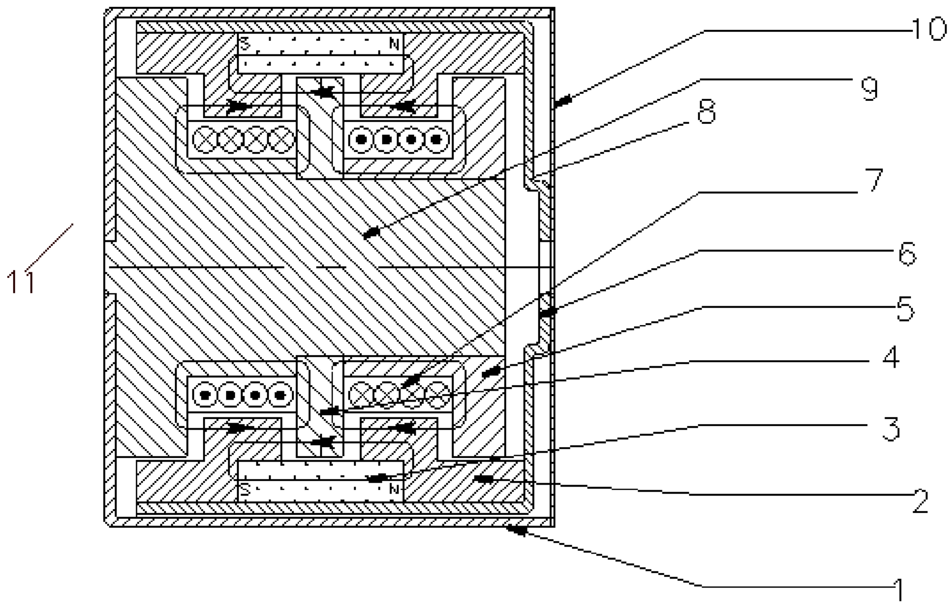

10
9
8
7
6
5
4
3
2
1
11
S
N
S
N

FIG. 12

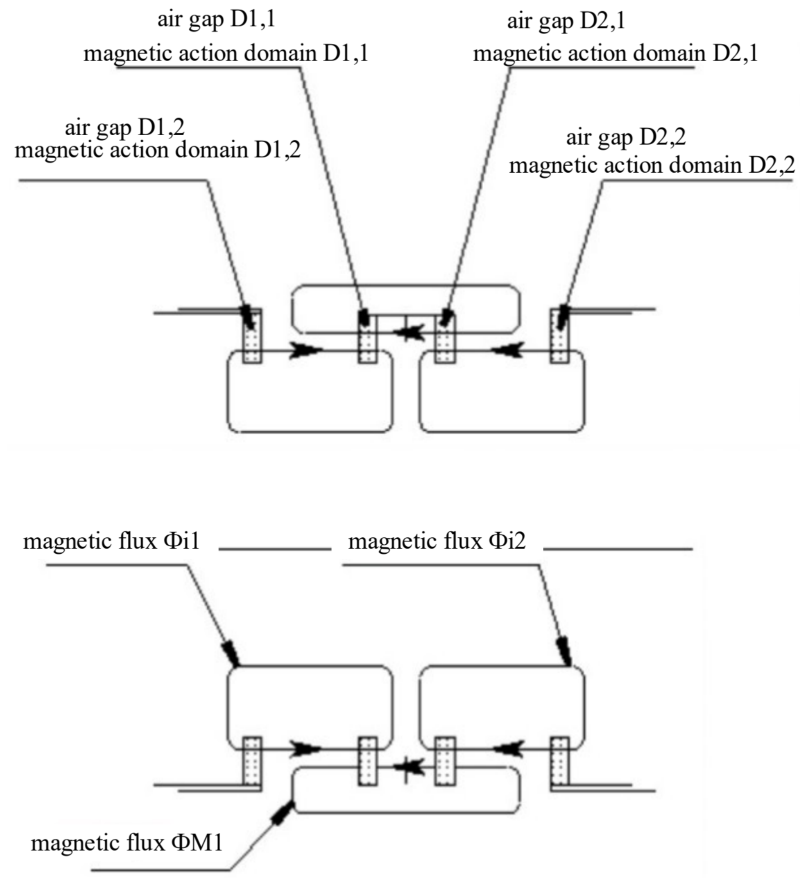

air gap D1,1
magnetic action domain D1,1
air gap D2,1
magnetic action domain D2,1
air gap D1,2
magnetic action domain D1,2
air gap D2,2
magnetic action domain D2,2
magnetic flux Φi1
magnetic flux Φi2
magnetic flux ΦM1

FIG. 13

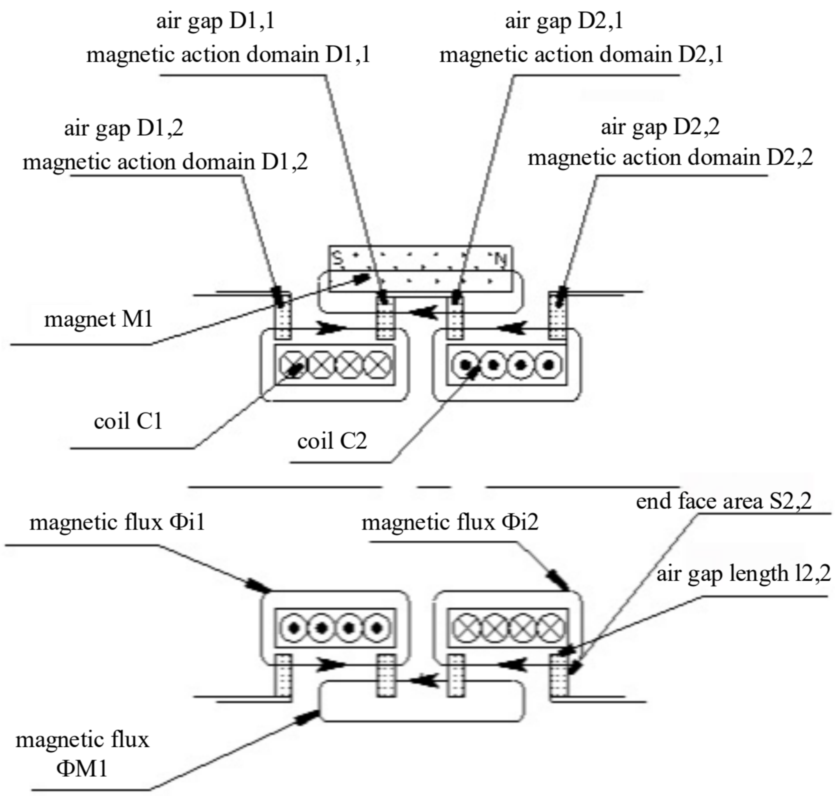

air gap D1,1
magnetic action domain D1,1
air gap D2,1
magnetic action domain D2,1
air gap D1,2
magnetic action domain D1,2
air gap D2,2
magnetic action domain D2,2
S
N
magnet M1
coil C1
coil C2
magnetic flux Φi1
magnetic flux Φi2
end face area S2,2
air gap length l2,2
magnetic flux
ΦM1

FIG. 14

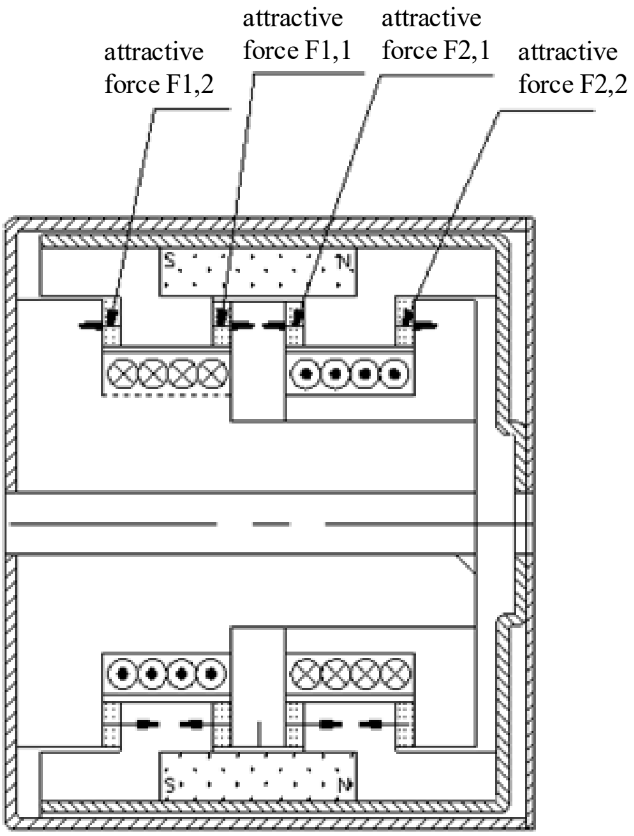

attractive
force F1,2
attractive
force F1,1
attractive
force F2,1
attractive
force F2,2
S
N
S
N

FIG. 15

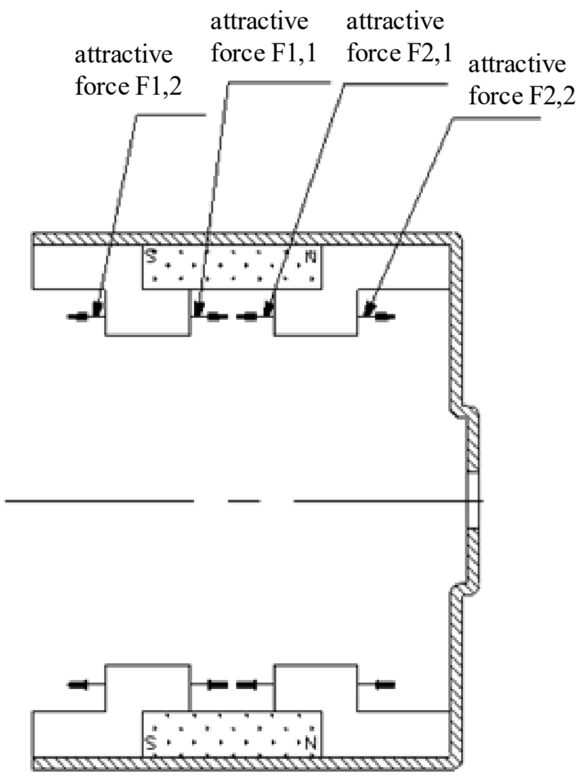

attractive
force F1,2
attractive
force F1,1
attractive
force F2,1
attractive
force F2,2
S
N
S
N

FIG. 16

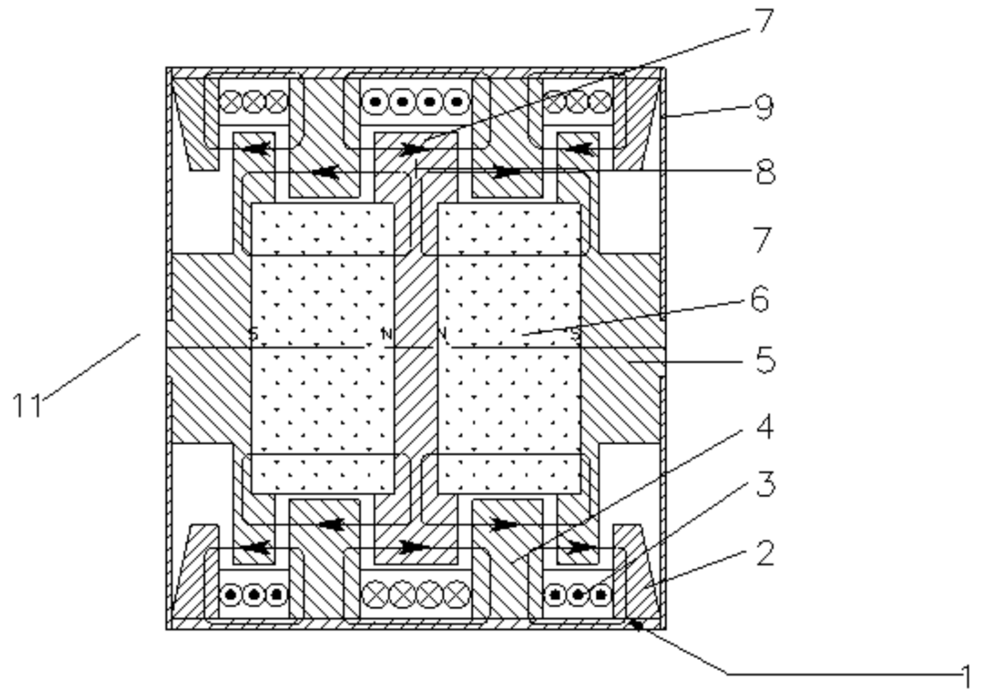

7
9
8
7
6
5
4
3
2
1
11
S
N
N
S

FIG. 17

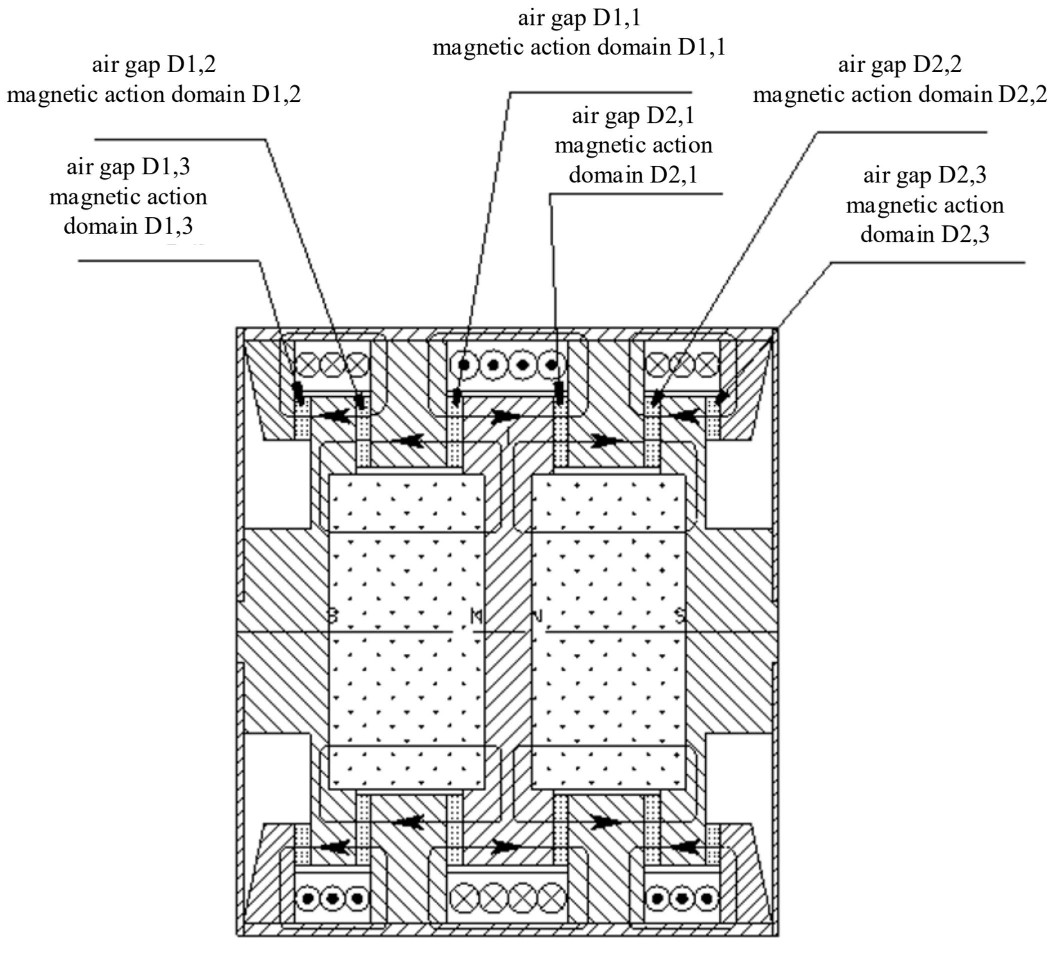

air gap D1,1
magnetic action domain D1,1
air gap D1,2
magnetic action domain D1,2
air gap D2,2
magnetic action domain D2,2
air gap D2,1
magnetic action
domain D2,1
air gap D1,3
magnetic action
domain D1,3
air gap D2,3
magnetic action
domain D2,3
S
N
N
S

FIG. 18

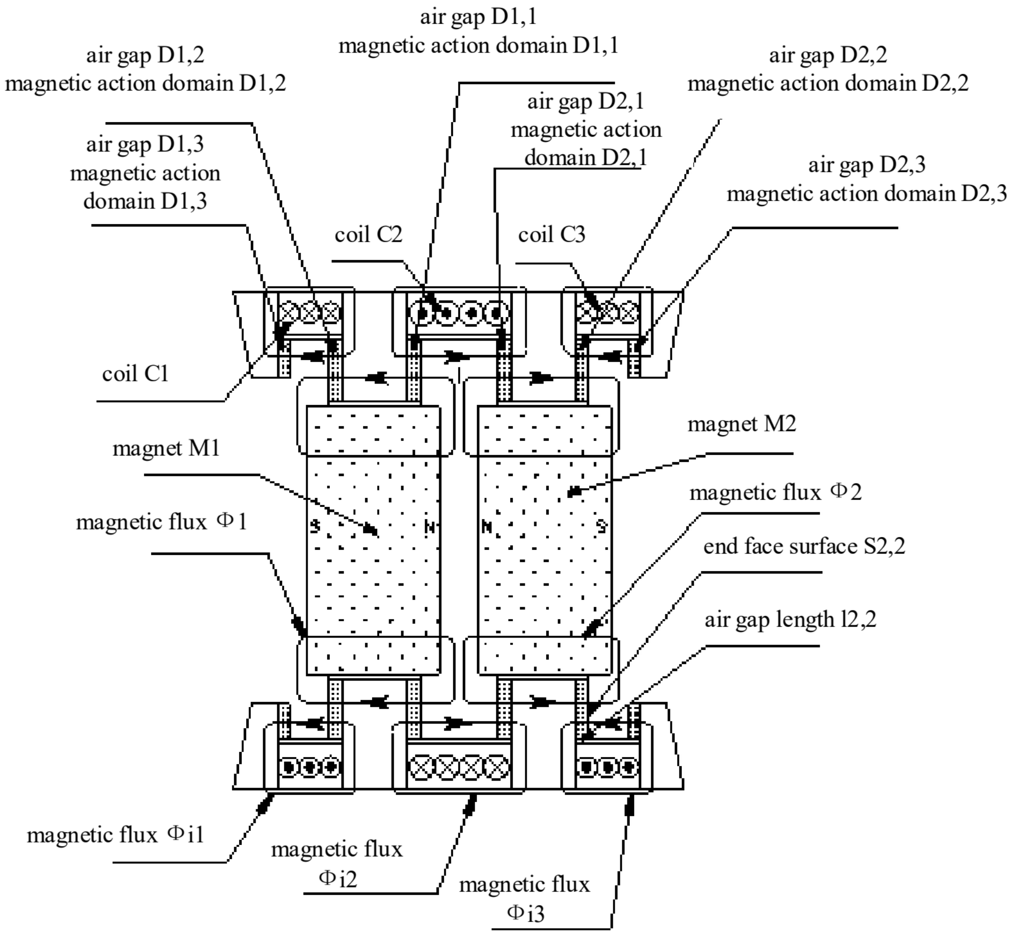

air gap D1,1
magnetic action domain D1,1
air gap D1,2
magnetic action domain D1,2
air gap D2,2
magnetic action domain D2,2
air gap D2,1
magnetic action
domain D2,1
air gap D1,3
magnetic action
domain D1,3
air gap D2,3
magnetic action domain D2,3
coil C2
coil C3
coil C1
magnet M2
magnet M1
magnetic flux Φ2
magnetic flux Φ1
end face surface S2,2
air gap length l2,2
magnetic flux Φi1
magnetic flux
Φi2
magnetic flux
Φi3

FIG. 19

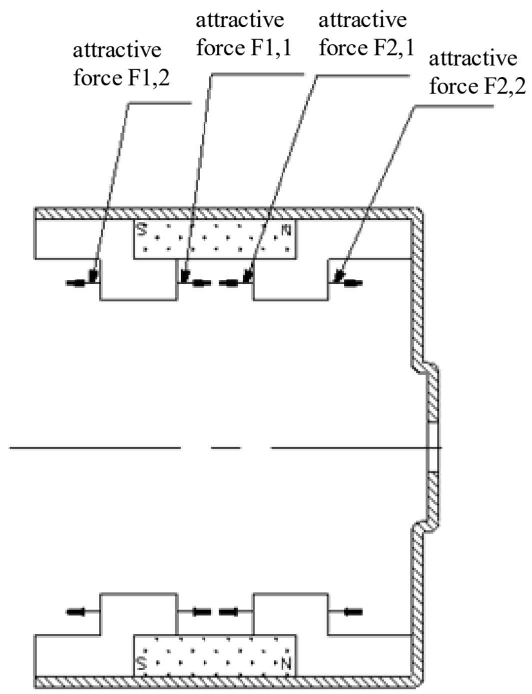

attractive
force F1,1
attractive
force F2,1
attractive
force F1,2
attractive
force F2,2

FIG. 20

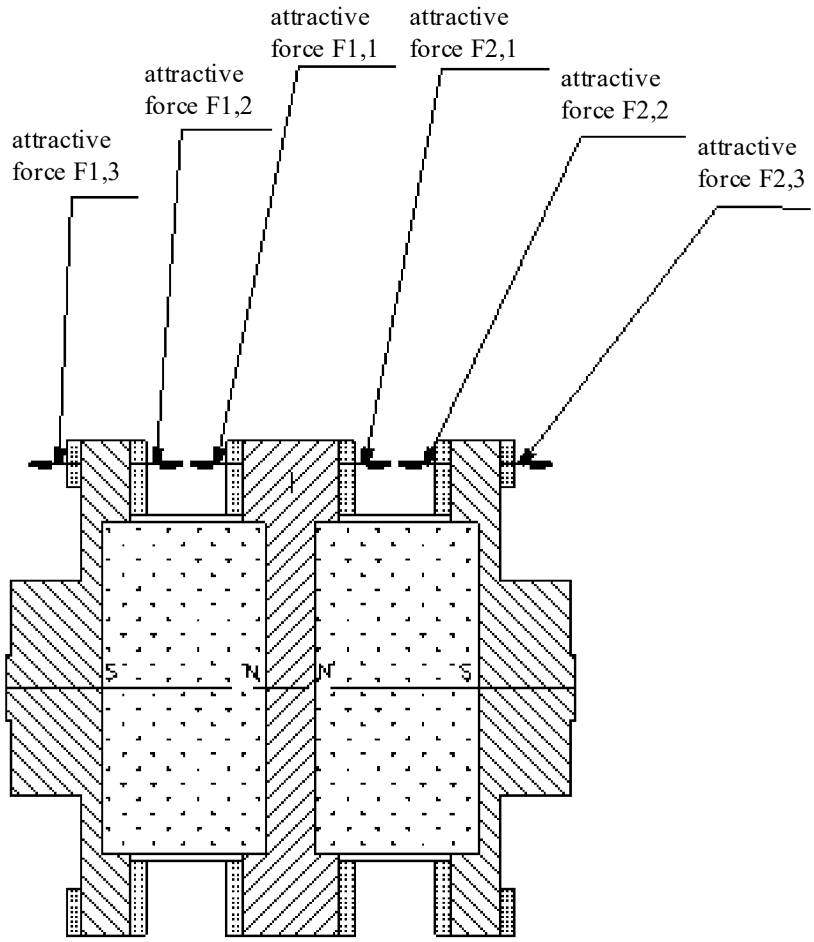

attractive force F1,1
attractive force F2,1
attractive force F1,2
attractive force F2,2
attractive force F1,3
attractive force F2,3
S
N
N
S

FIG. 21

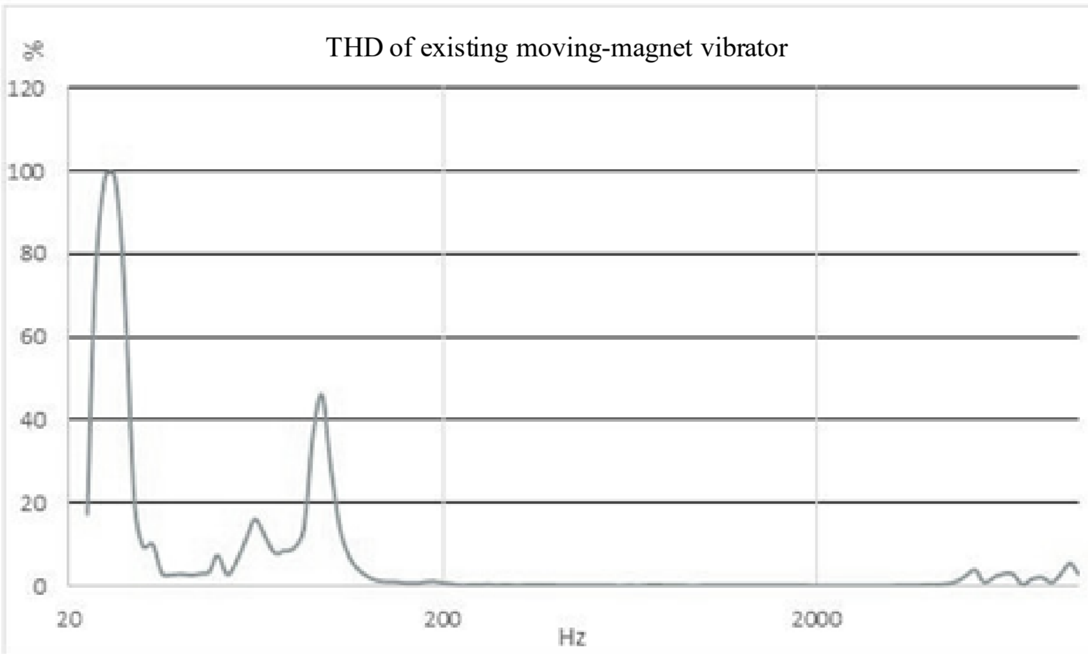

THD of existing moving-magnet vibrator
%
120
100
80
60
40
20
0
20
200
2000
Hz

FIG. 22

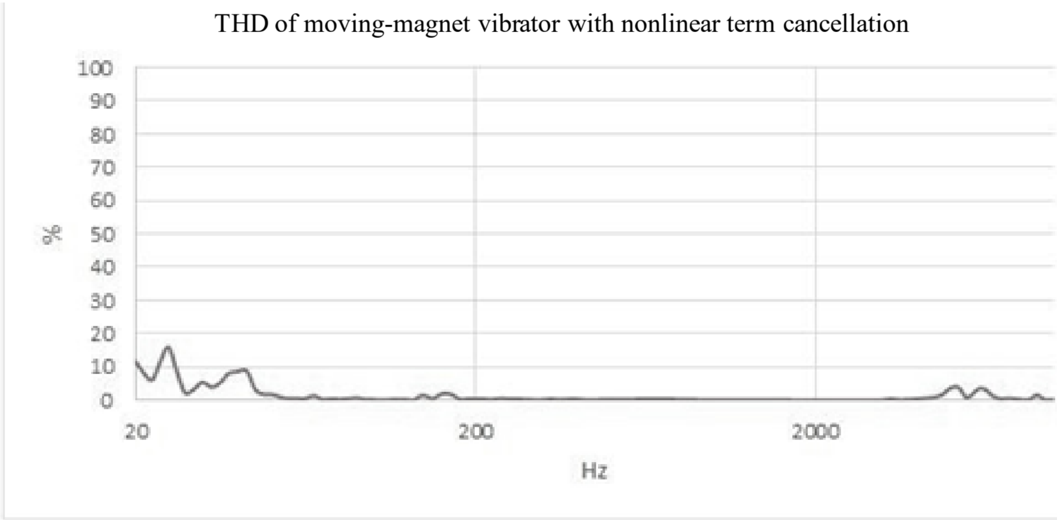


FIG. 23

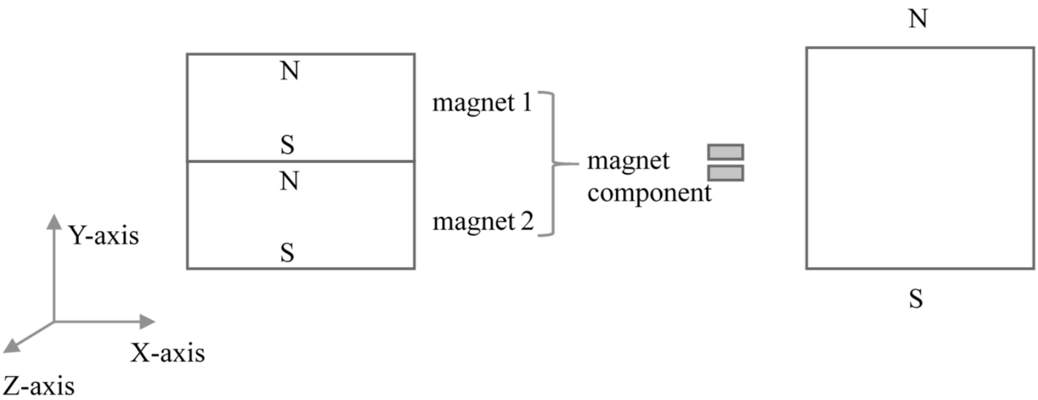


FIG. 24

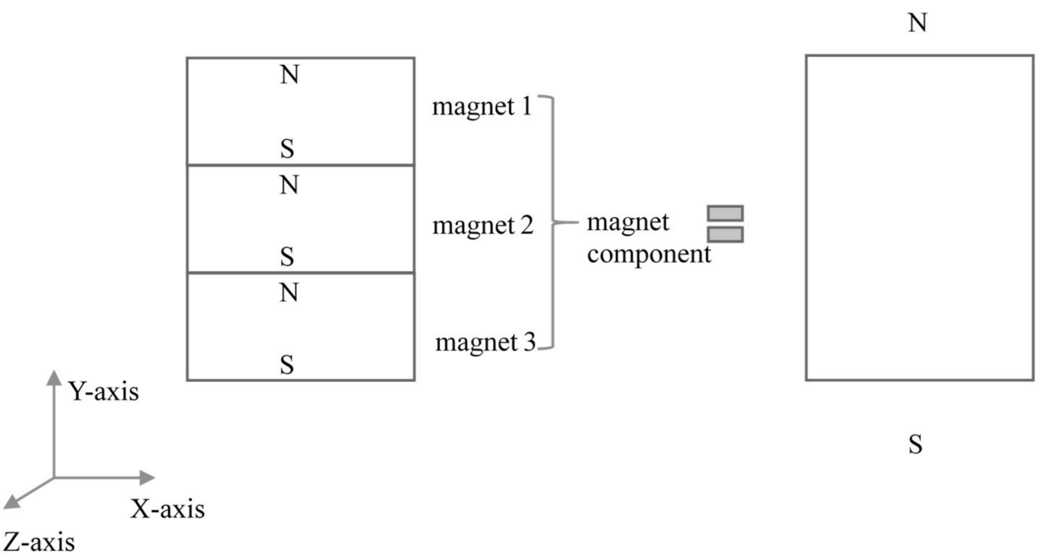


FIG. 25

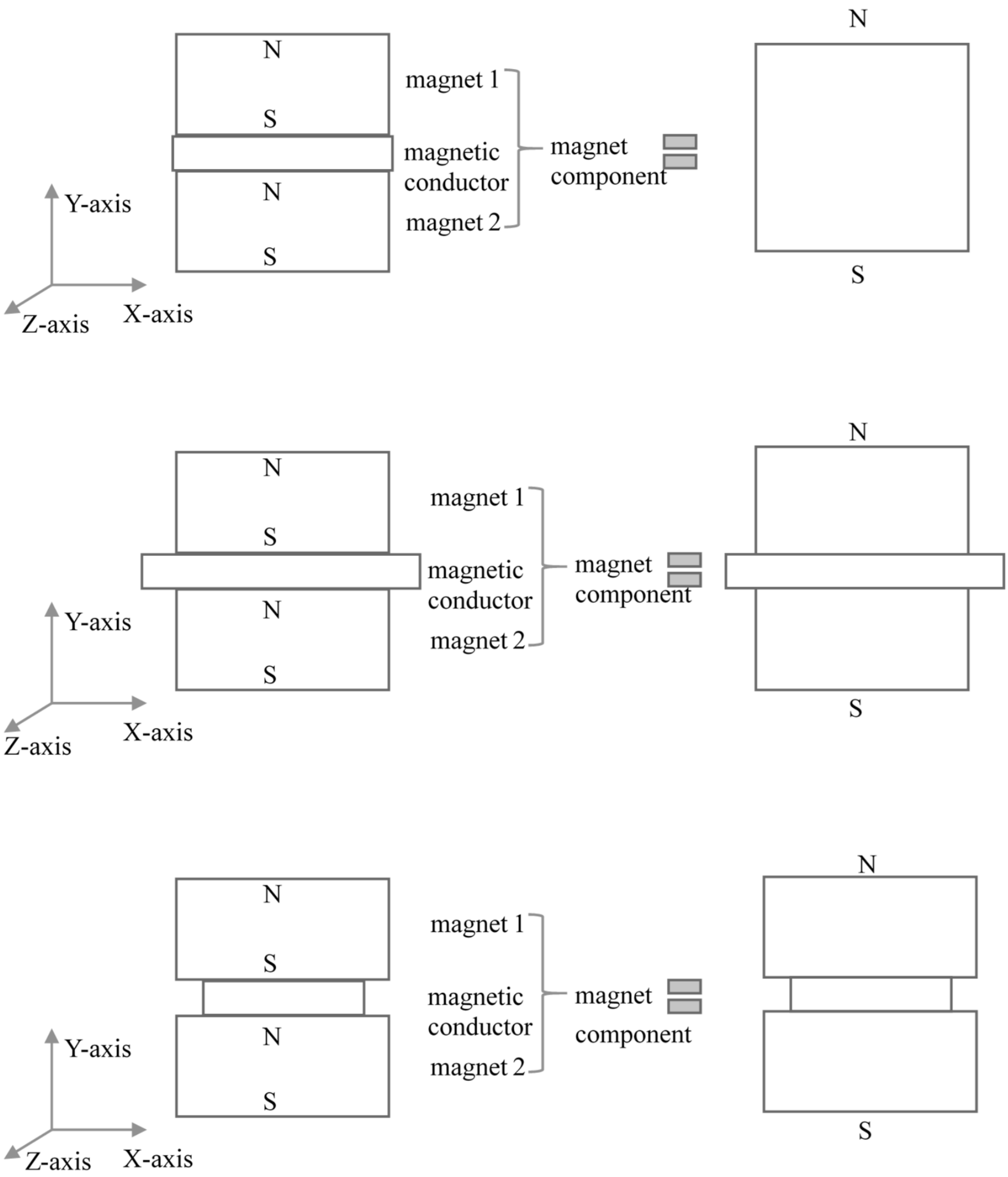

N
S
N
S
magnet 1
magnetic
conductor
magnet 2
magnet
component
N
S
Y-axis
Z-axis
X-axis
N
S
N
S
magnet 1
magnetic
conductor
magnet 2
magnet
component
N
S
Y-axis
Z-axis
X-axis
N
S
N
S
magnet 1
magnetic
conductor
magnet 2
magnet
component
N
S
Y-axis
Z-axis
X-axis

FIG. 26

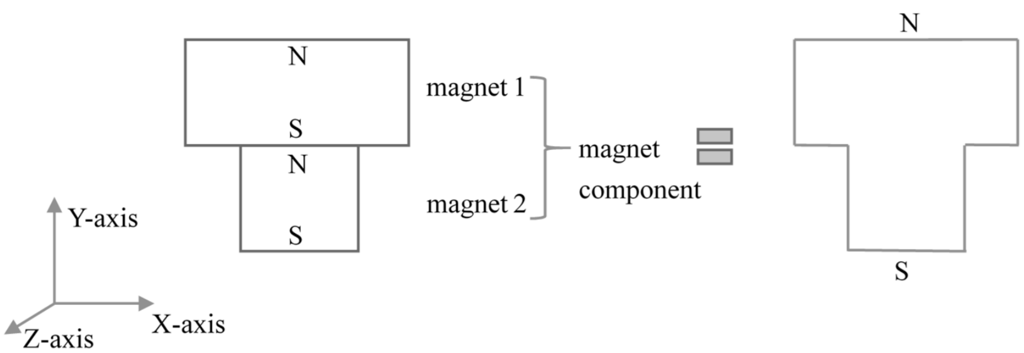

N
S
N
S
magnet 1
magnet 2
magnet
component
N
S
Y-axis
Z-axis
X-axis

FIG. 27

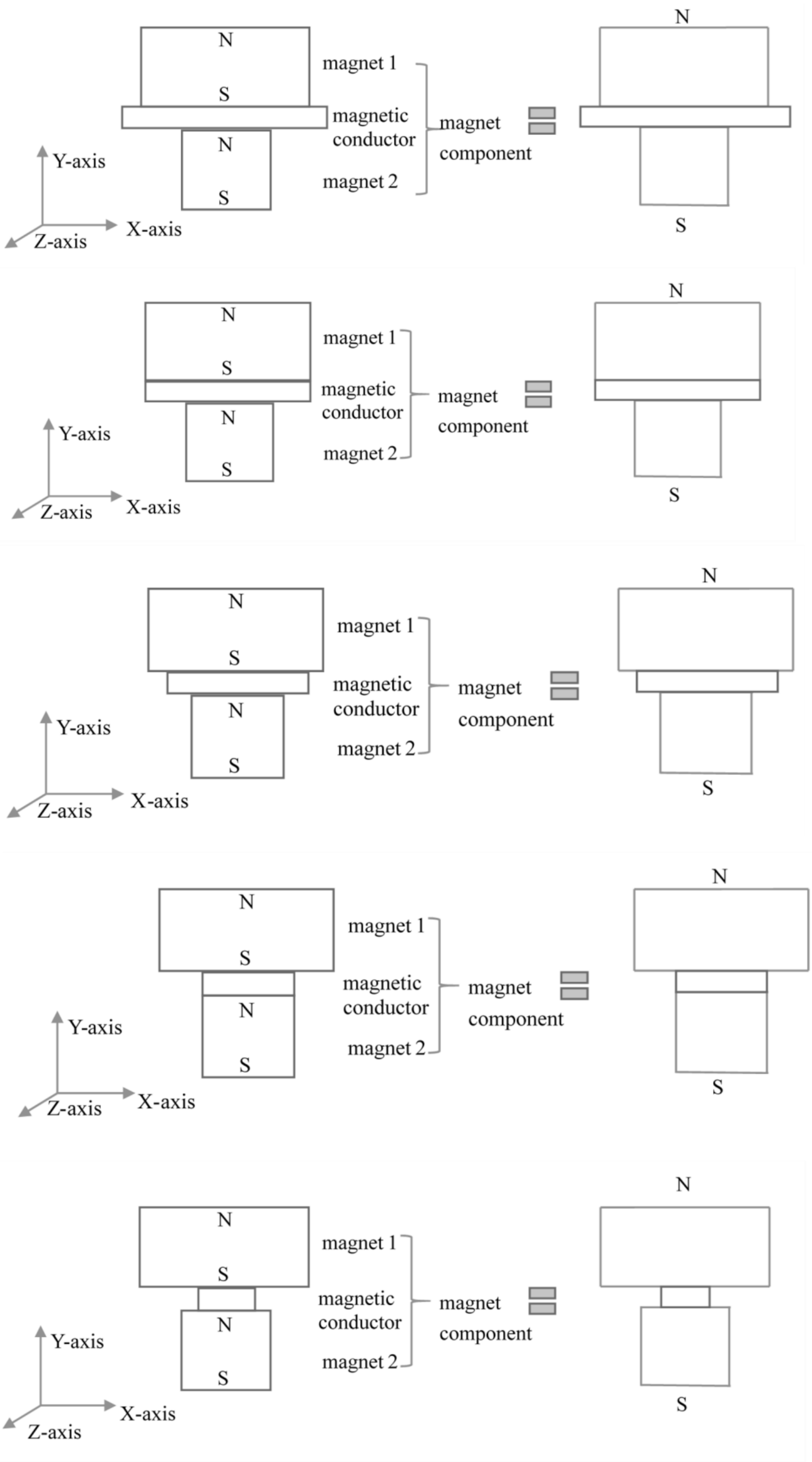

N
S
N
S
magnet 1
magnetic conductor
magnet 2
magnet component
N
S
Y-axis
X-axis
Z-axis
N
S
N
S
magnet 1
magnetic conductor
magnet 2
magnet component
N
S
Y-axis
X-axis
Z-axis
N
S
N
S
magnet 1
magnetic conductor
magnet 2
magnet component
N
S
Y-axis
X-axis
Z-axis
N
S
N
S
magnet 1
magnetic conductor
magnet 2
magnet component
N
S
Y-axis
X-axis
Z-axis
N
S
N
S
magnet 1
magnetic conductor
magnet 2
magnet component
N
S
Y-axis
X-axis
Z-axis

FIG. 28

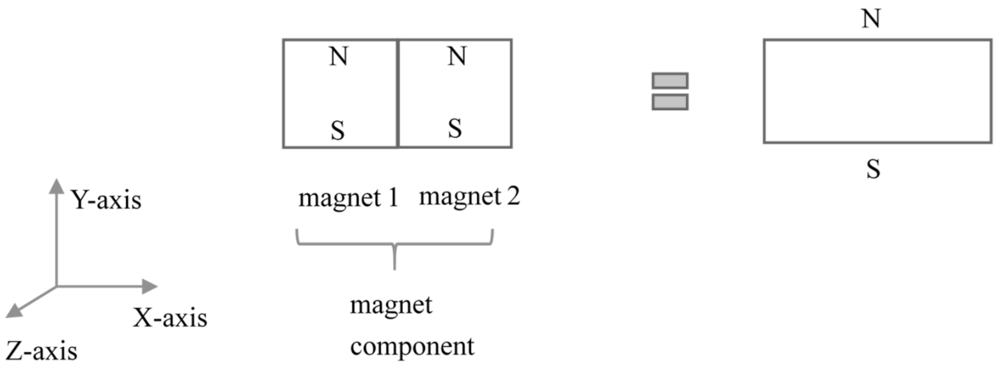


FIG. 29

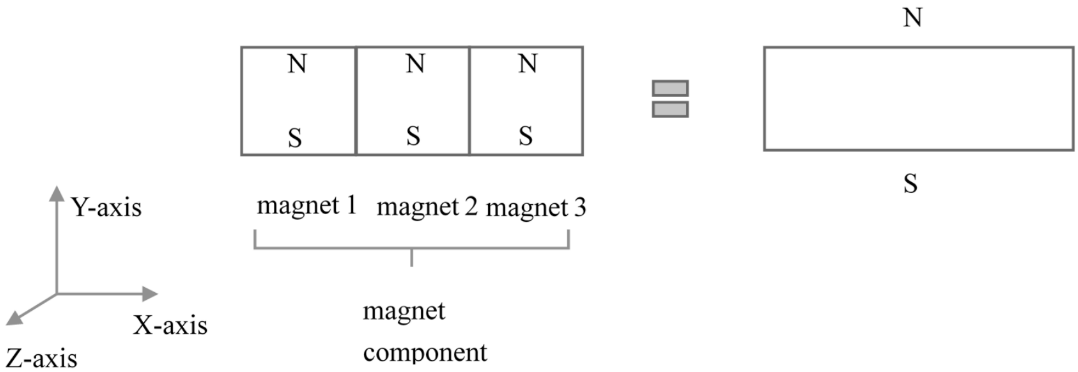


FIG. 30

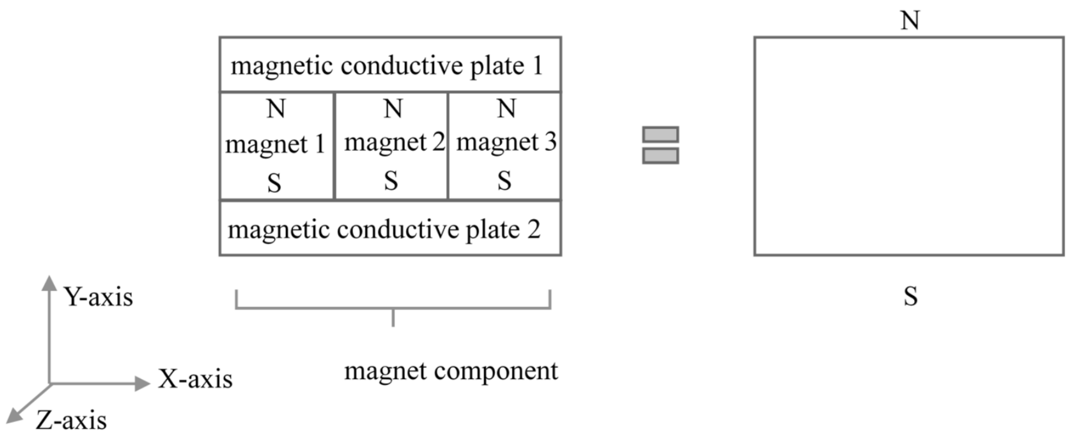


FIG. 31

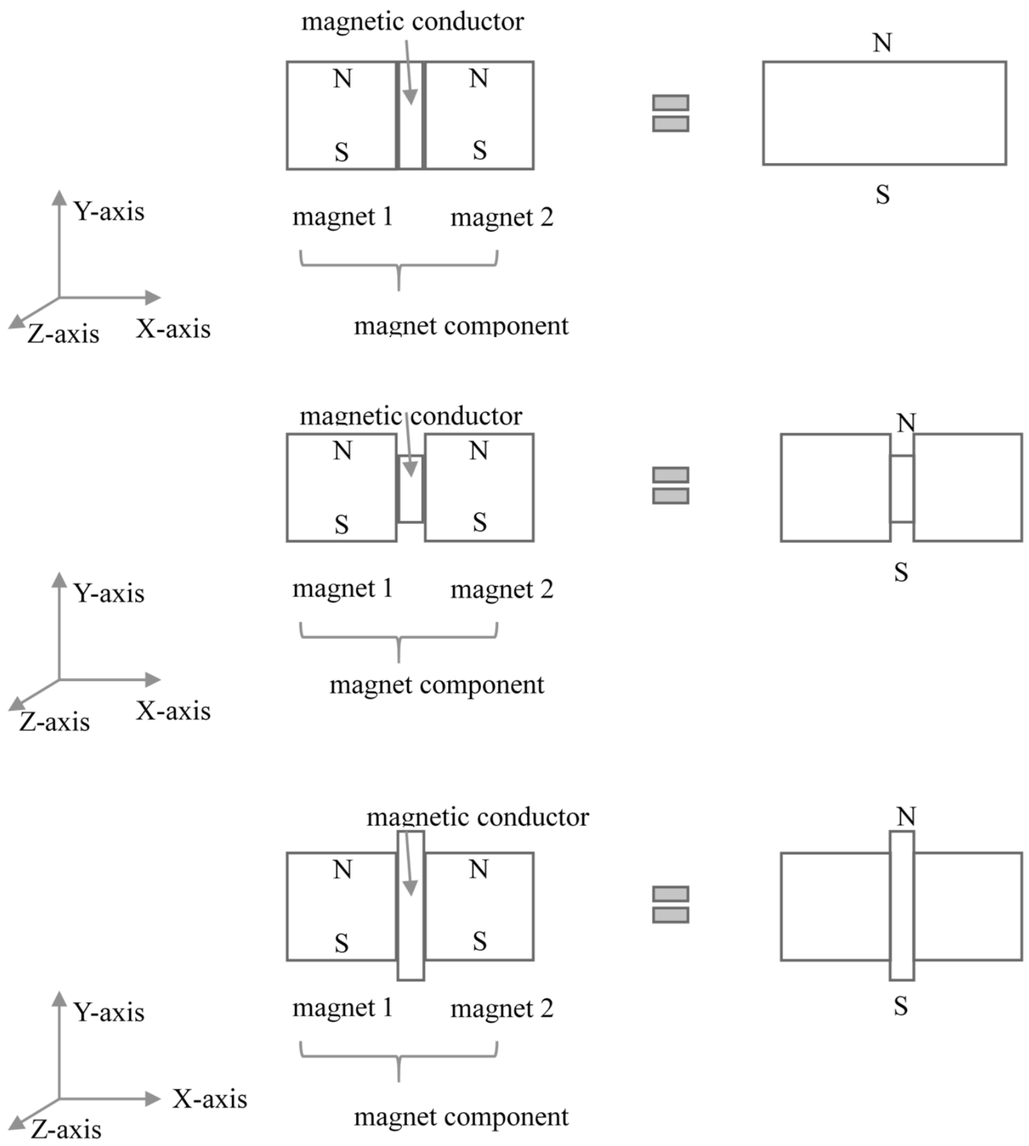

magnetic conductor
N
N
S
S
N
S
Y-axis
magnet 1
magnet 2
magnet component
Z-axis
X-axis
magnetic conductor
N
N
S
S
N
S
Y-axis
magnet 1
magnet 2
magnet component
Z-axis
X-axis
magnetic conductor
N
N
S
S
N
S
Y-axis
magnet 1
magnet 2
magnet component
Z-axis
X-axis

FIG. 32

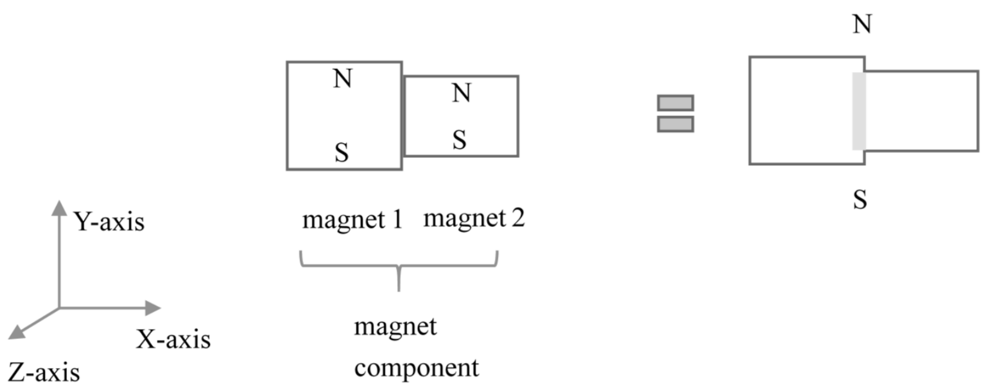

N
N
S
N
S
S
Y-axis
magnet 1
magnet 2
magnet component
X-axis
Z-axis

FIG. 33

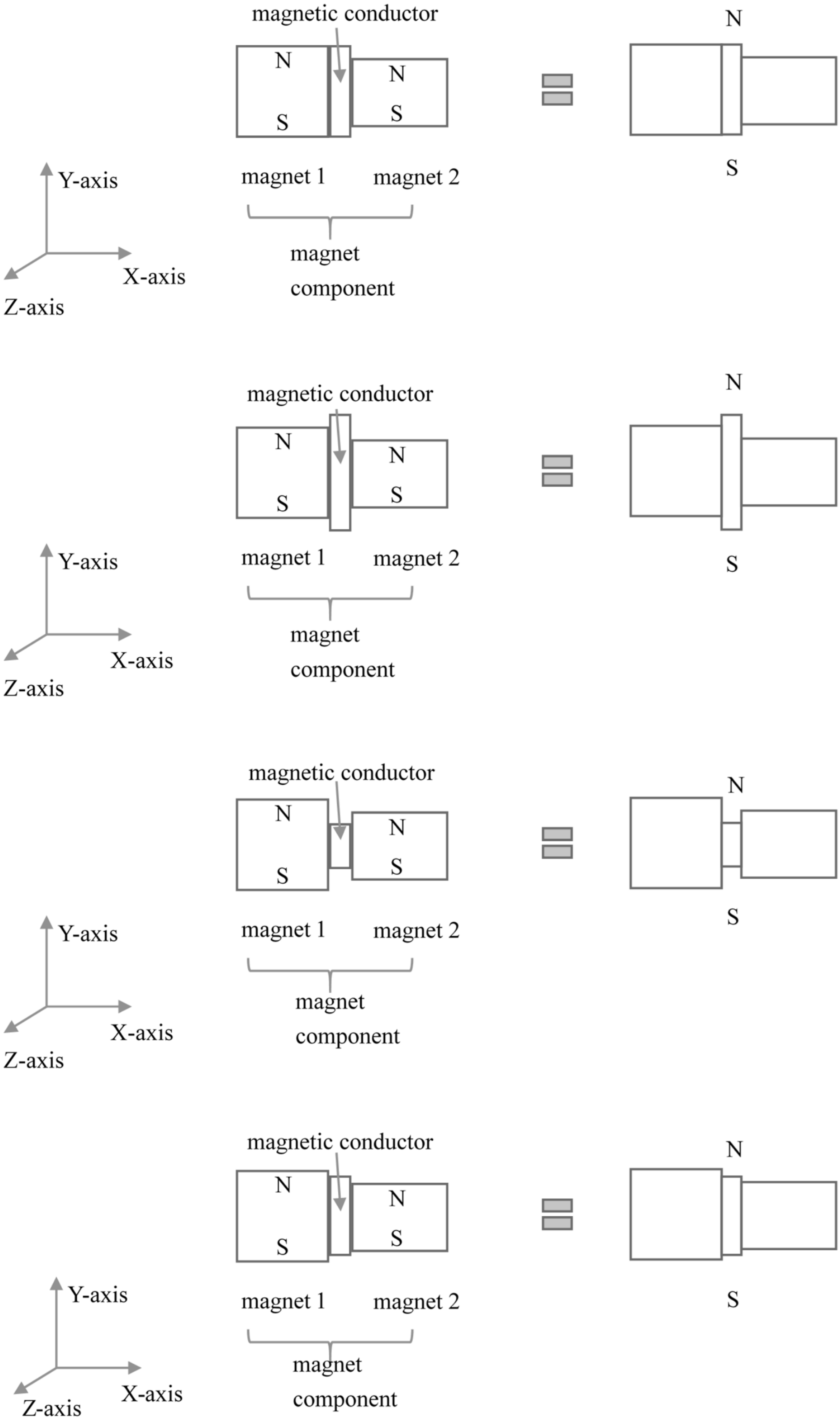

magnetic conductor
N
S
N
S
N
S
magnet 1
magnet 2
magnet component
Y-axis
X-axis
Z-axis
magnetic conductor
N
S
N
S
N
S
magnet 1
magnet 2
magnet component
Y-axis
X-axis
Z-axis
magnetic conductor
N
S
N
S
N
S
magnet 1
magnet 2
magnet component
Y-axis
X-axis
Z-axis
magnetic conductor
N
S
N
S
N
S
magnet 1
magnet 2
magnet component
Y-axis
X-axis
Z-axis

FIG. 34

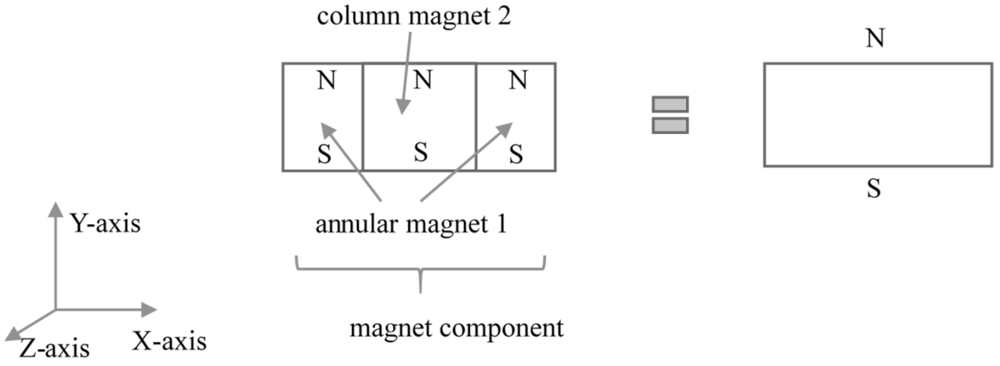

column magnet 2
N
N
N
S
S
S
annular magnet 1
magnet component
N
S
Y-axis
X-axis
Z-axis

FIG. 35

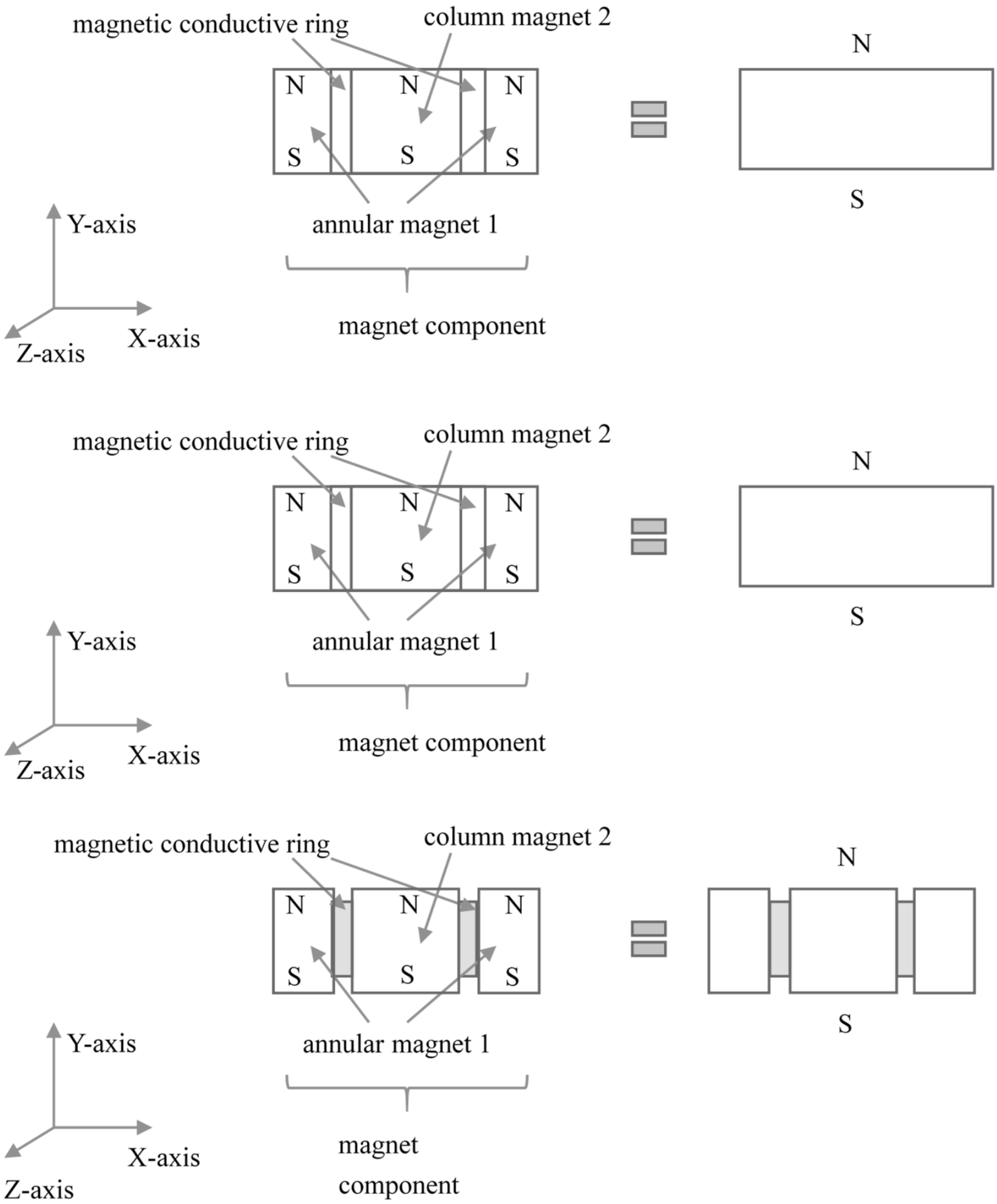

magnetic conductive ring
column magnet 2
N
N
N
S
S
S
annular magnet 1
magnet component
N
S
Y-axis
X-axis
Z-axis
magnetic conductive ring
column magnet 2
N
N
N
S
S
S
annular magnet 1
magnet component
N
S
Y-axis
X-axis
Z-axis
magnetic conductive ring
column magnet 2
N
N
N
S
S
S
annular magnet 1
magnet
component
N
S
Y-axis
X-axis
Z-axis

FIG. 36

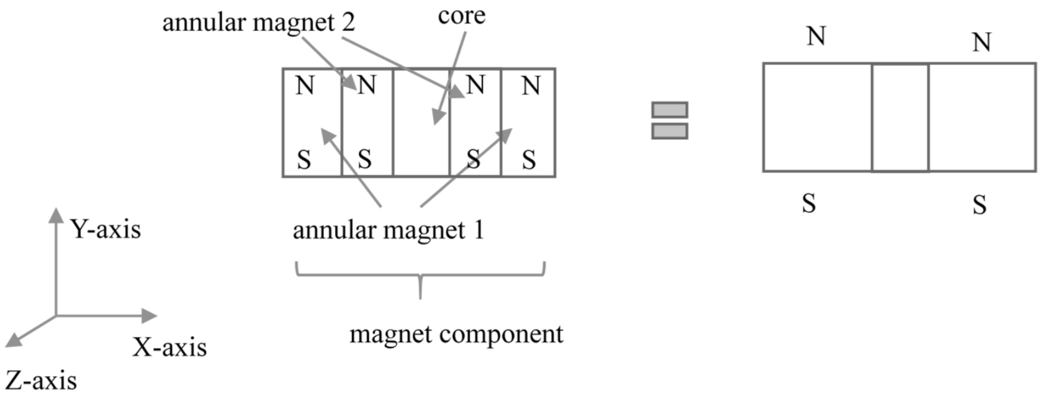
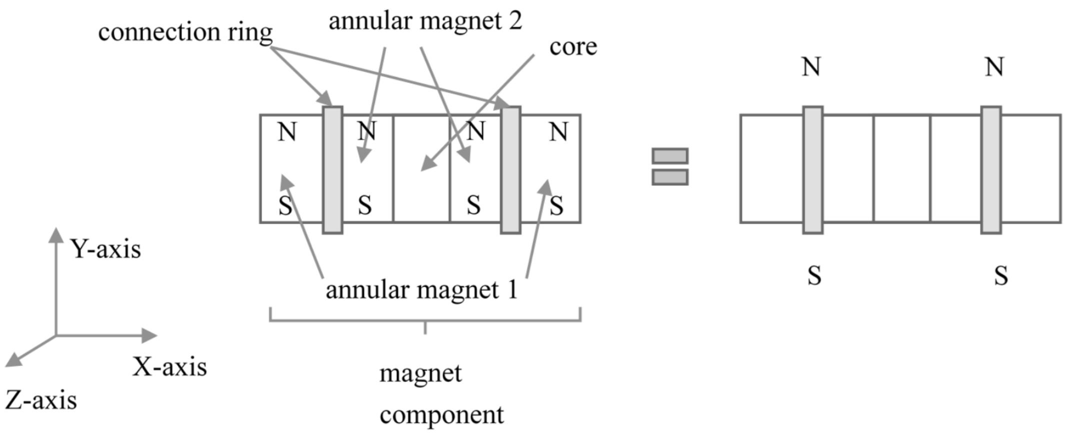

annular magnet 2
core
N
N
N
N
S
S
S
S
N
N
S
S
Y-axis
annular magnet 1
X-axis
Z-axis
magnet component

FIG. 37


connection ring
annular magnet 2
core
N
N
N
N
S
S
S
S
N
N
S
S
Y-axis
annular magnet 1
X-axis
Z-axis
magnet
component

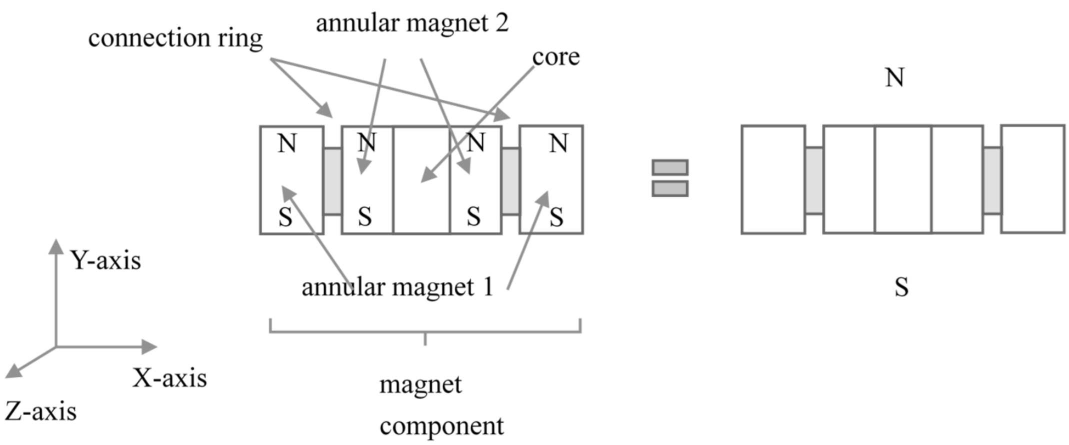

connection ring
annular magnet 2
core
N
N
N
N
S
S
S
S
N
S
Y-axis
annular magnet 1
X-axis
Z-axis
magnet
component

FIG. 38

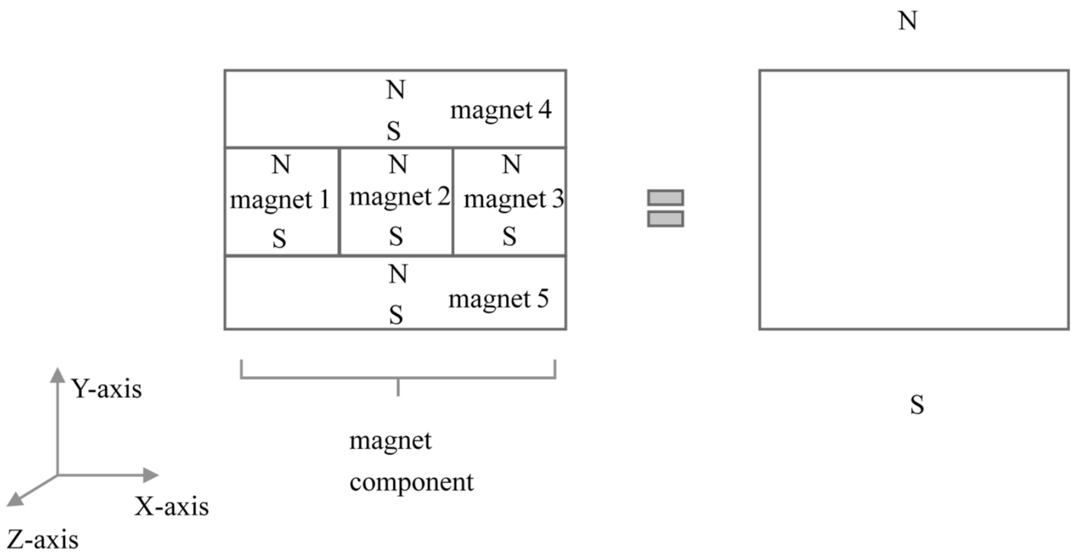


FIG. 39

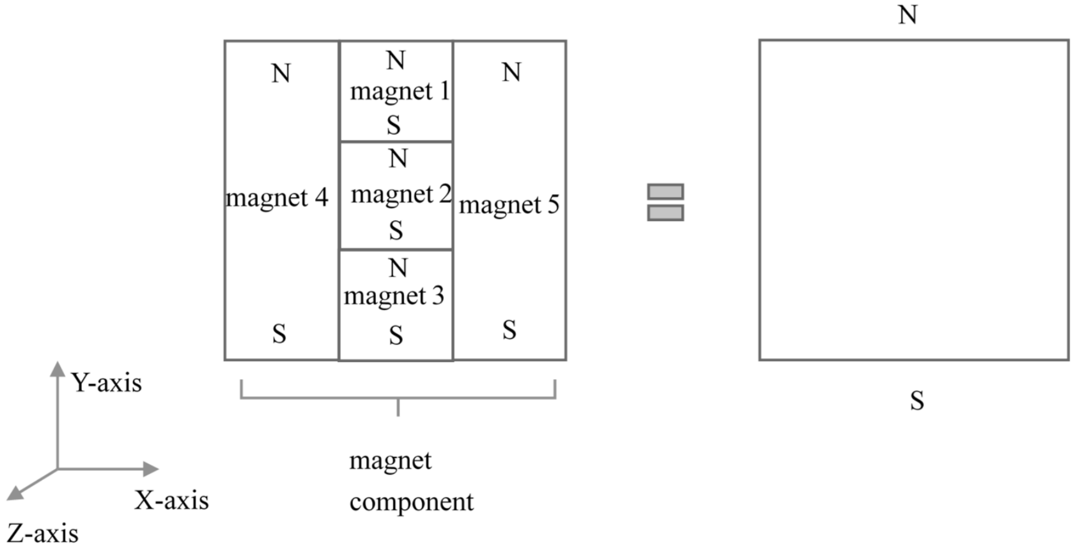


FIG. 40

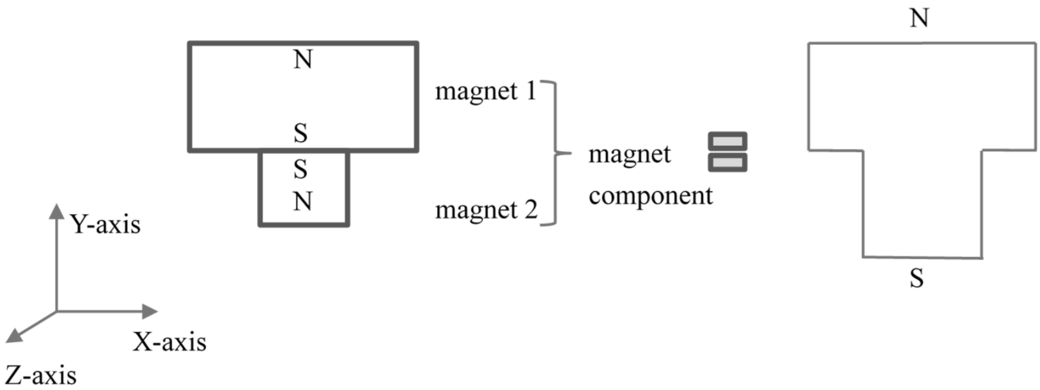


FIG. 40a

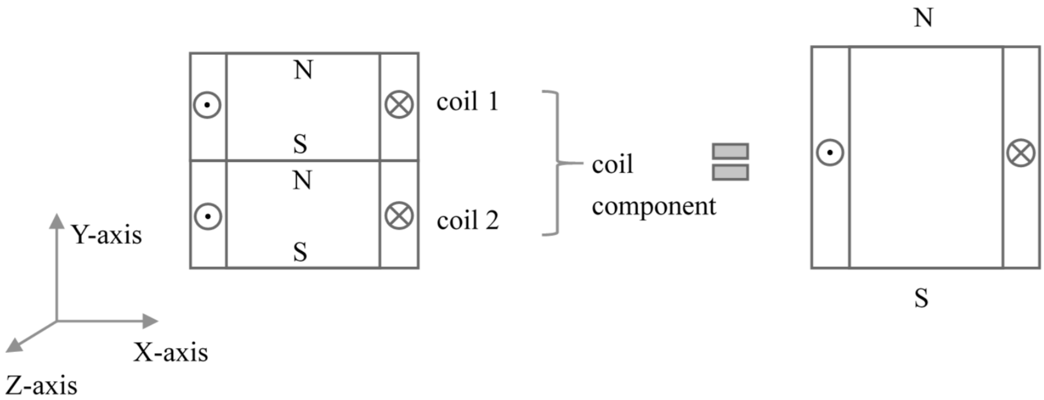


FIG. 41

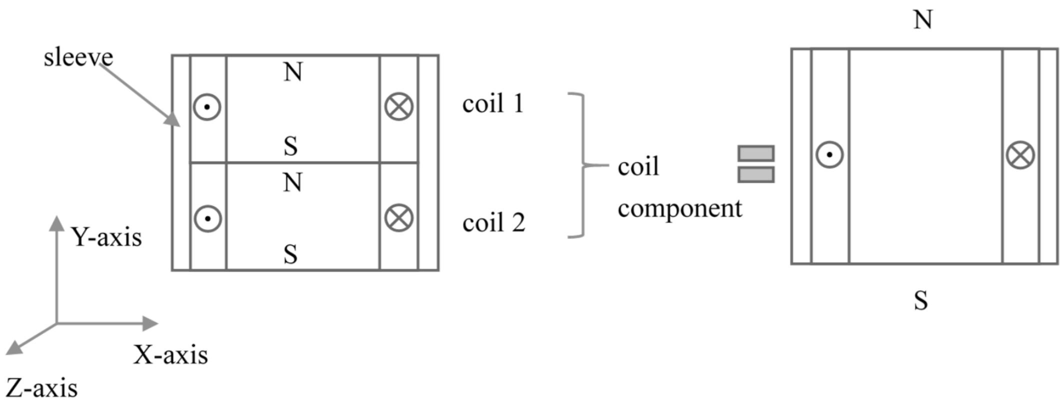


FIG. 42

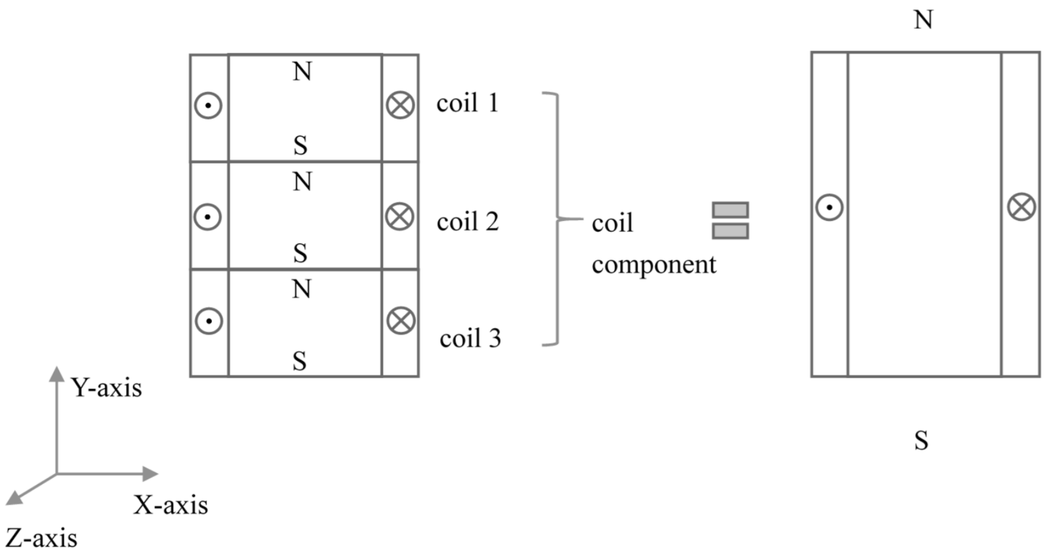


FIG. 43

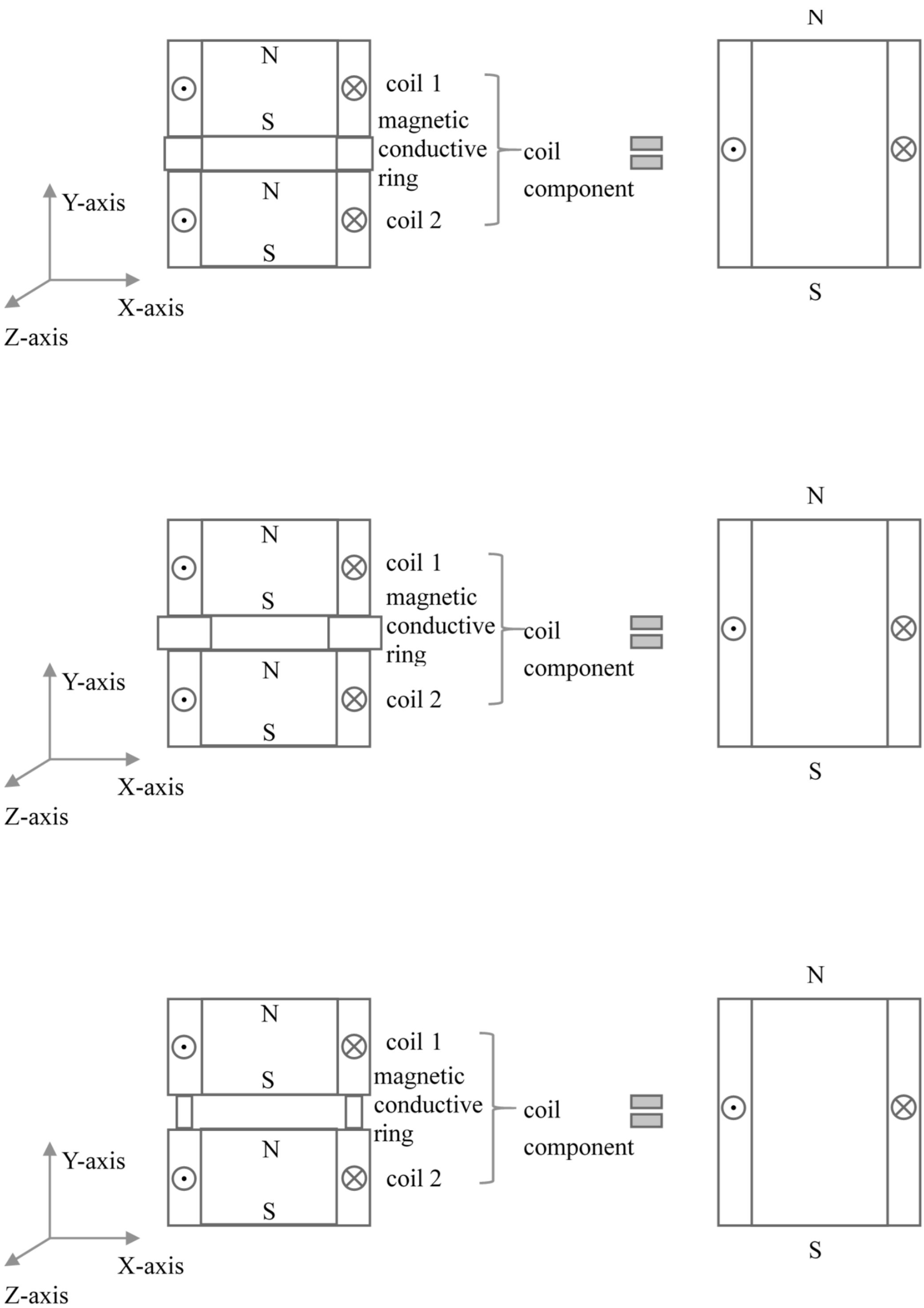

N
S
N
S
coil 1
magnetic conductive ring
coil 2
coil component
N
S
Y-axis
X-axis
Z-axis
N
S
N
S
coil 1
magnetic conductive ring
coil 2
coil component
N
S
Y-axis
X-axis
Z-axis
N
S
N
S
coil 1
magnetic conductive ring
coil 2
coil component
N
S
Y-axis
X-axis
Z-axis

FIG. 44

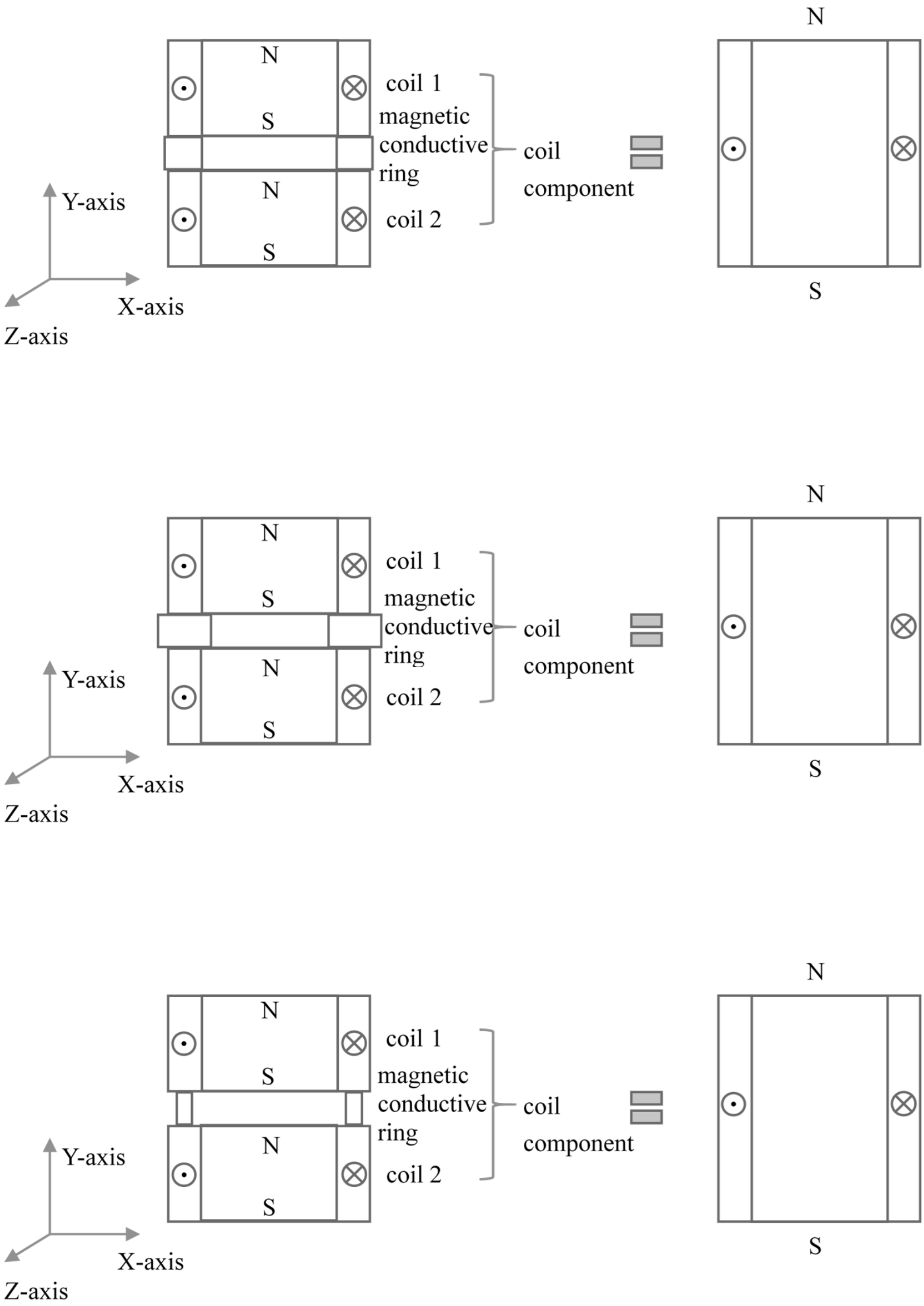

N
S
N
S
coil 1
magnetic
conductive
ring
coil 2
coil
component
N
S
Y-axis
X-axis
Z-axis
N
S
N
S
coil 1
magnetic
conductive
ring
coil 2
coil
component
N
S
Y-axis
X-axis
Z-axis
N
S
N
S
coil 1
magnetic
conductive
ring
coil 2
coil
component
N
S
Y-axis
X-axis
Z-axis

FIG. 45

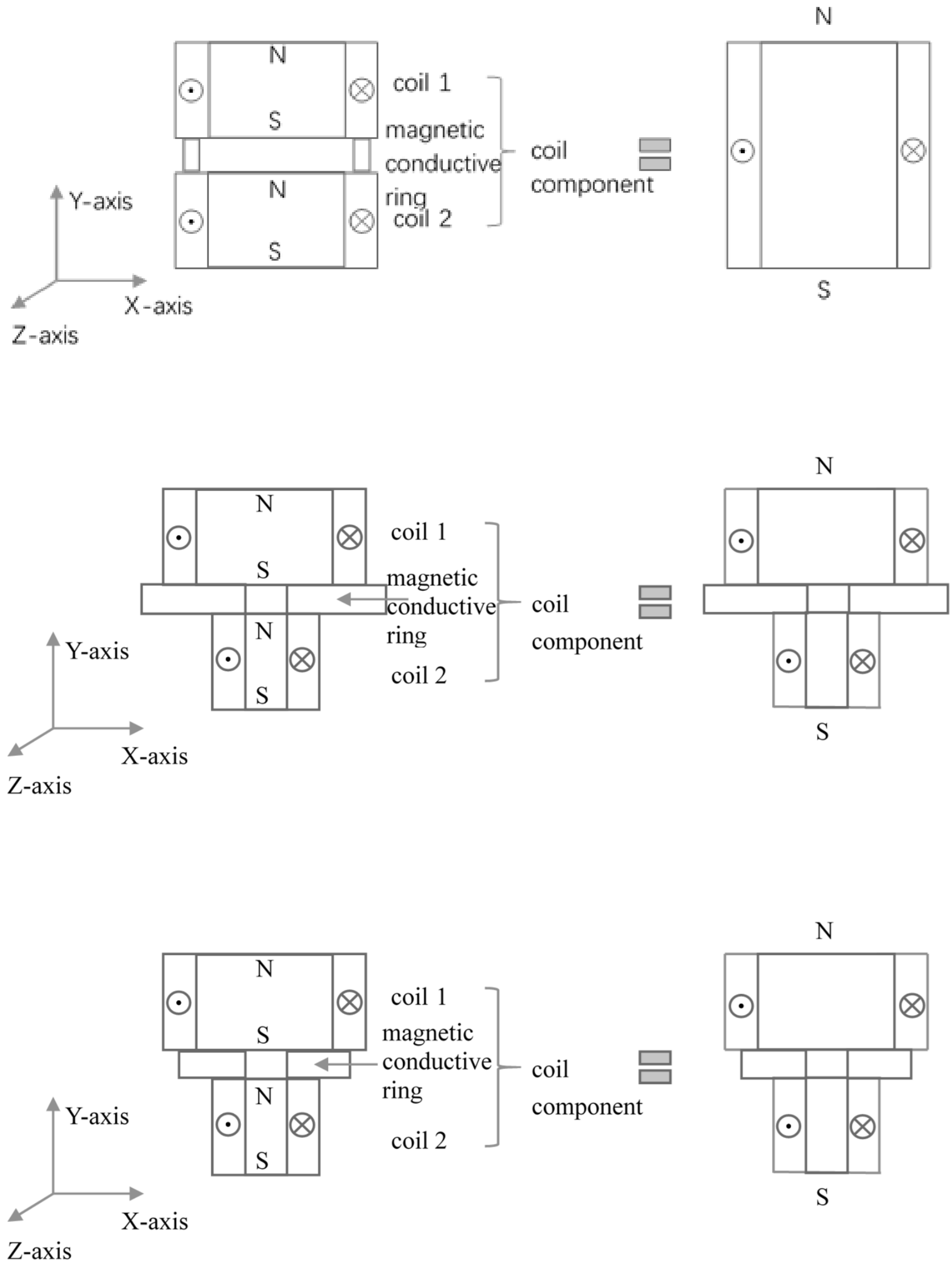

N
S
N
S
coil 1
magnetic
conductive
ring
coil 2
coil
component
N
S
Y-axis
X-axis
Z-axis
N
S
N
S
coil 1
magnetic
conductive
ring
coil 2
coil
component
N
S
Y-axis
X-axis
Z-axis
N
S
N
S
coil 1
magnetic
conductive
ring
coil 2
coil
component
N
S
Y-axis
X-axis
Z-axis

FIG. 46

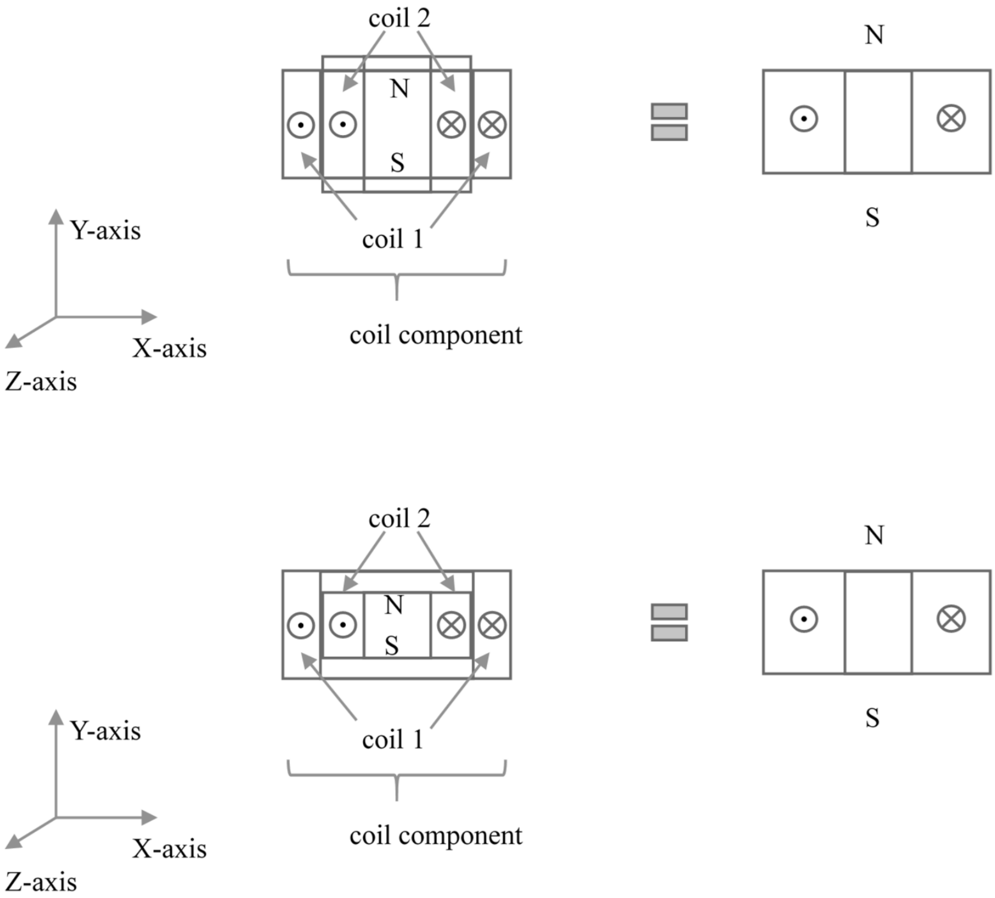

coil 2
N
S
coil 1
coil component
Y-axis
X-axis
Z-axis
N
S
coil 2
N
S
coil 1
coil component
Y-axis
X-axis
Z-axis
N
S

FIG. 47

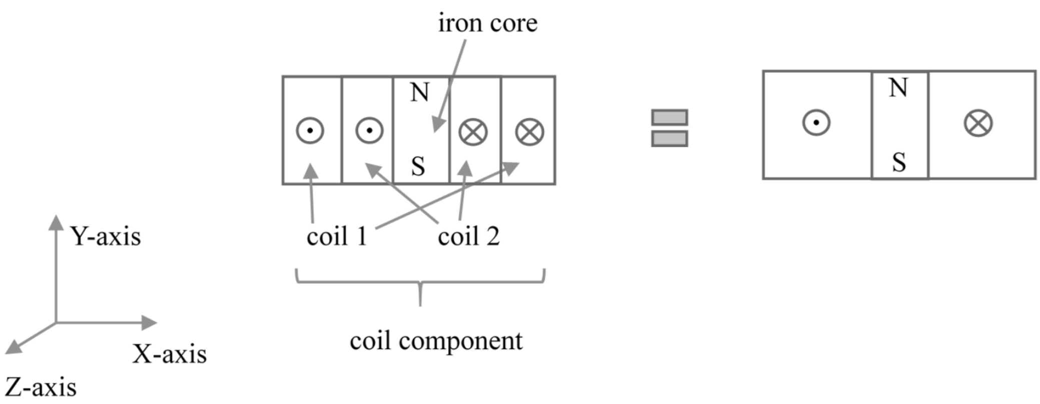

iron core
N
S
coil 1
coil 2
coil component
Y-axis
X-axis
Z-axis
N
S

FIG. 48

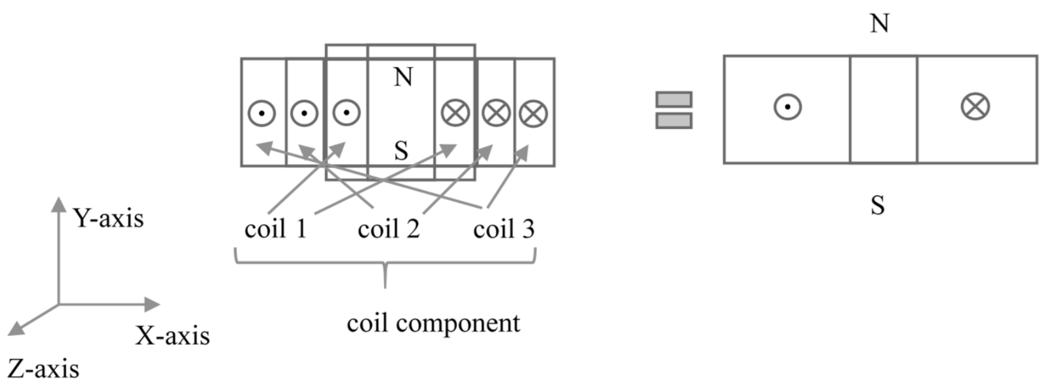

N
S
Y-axis
X-axis
Z-axis
coil 1
coil 2
coil 3
coil component
N
S

FIG. 49

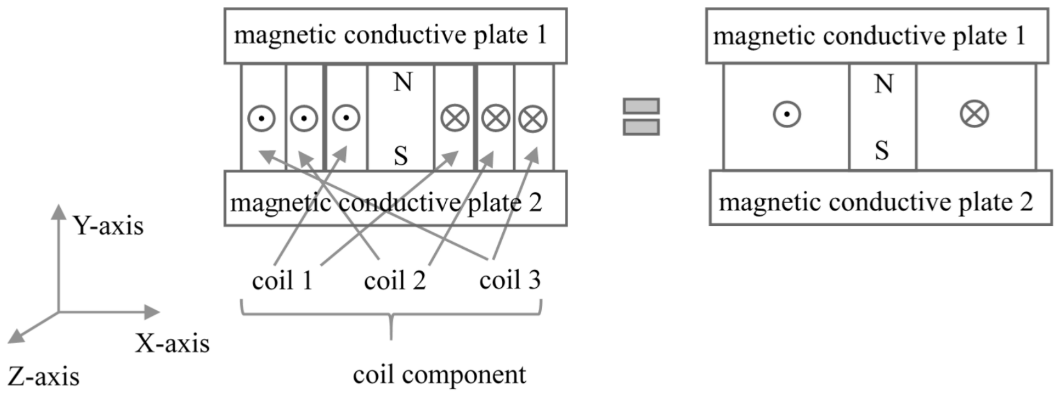

magnetic conductive plate 1
N
S
magnetic conductive plate 2
Y-axis
X-axis
Z-axis
coil 1
coil 2
coil 3
coil component
magnetic conductive plate 1
N
S
magnetic conductive plate 2

FIG. 50

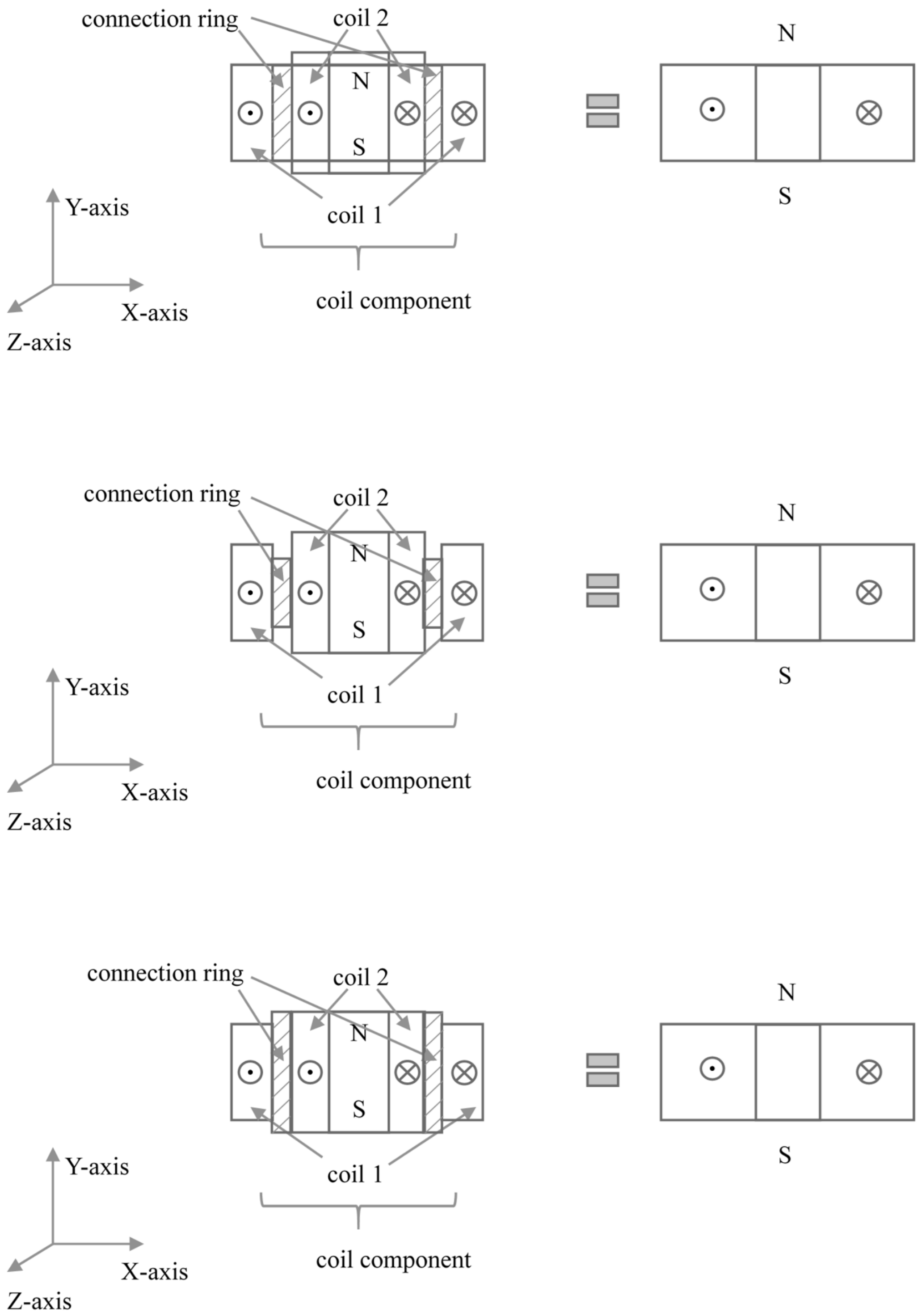

connection ring
coil 2
N
S
coil 1
coil component
Y-axis
X-axis
Z-axis
N
S
connection ring
coil 2
N
S
coil 1
coil component
Y-axis
X-axis
Z-axis
N
S
connection ring
coil 2
N
S
coil 1
coil component
Y-axis
X-axis
Z-axis
N
S

FIG. 51

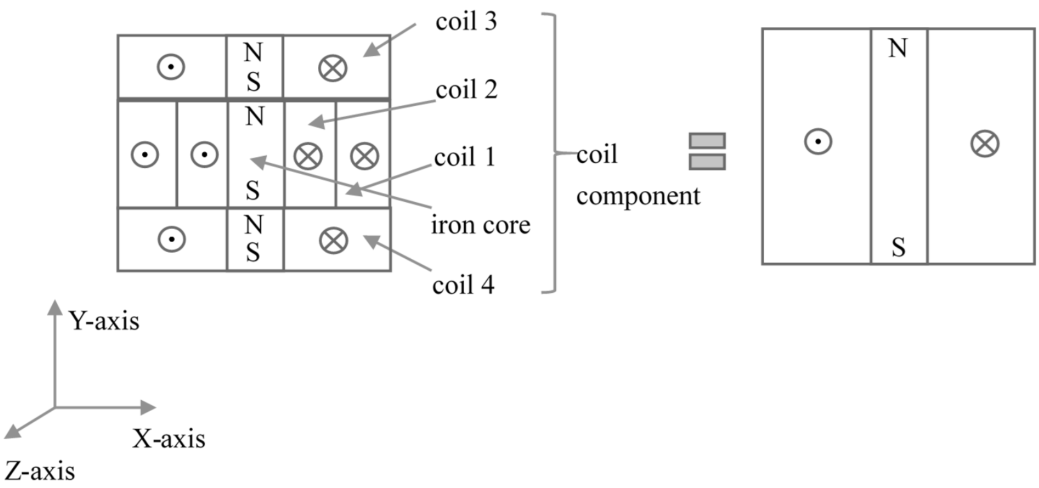


FIG. 52

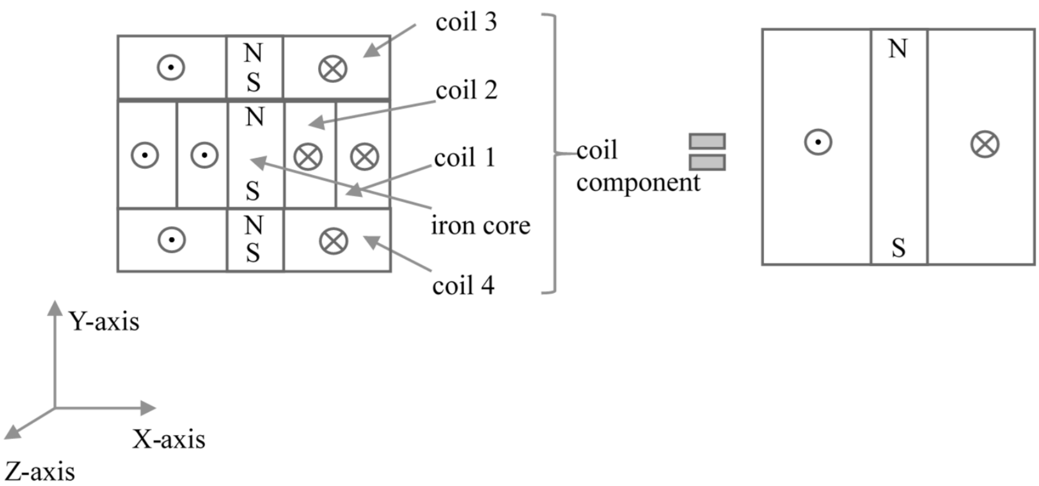


FIG. 53

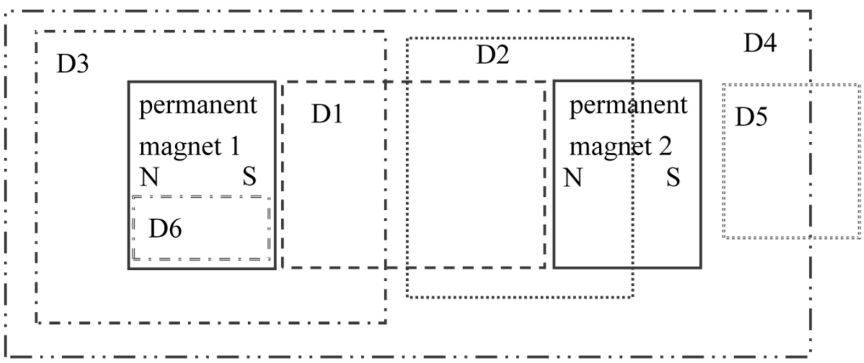


FIG. 54

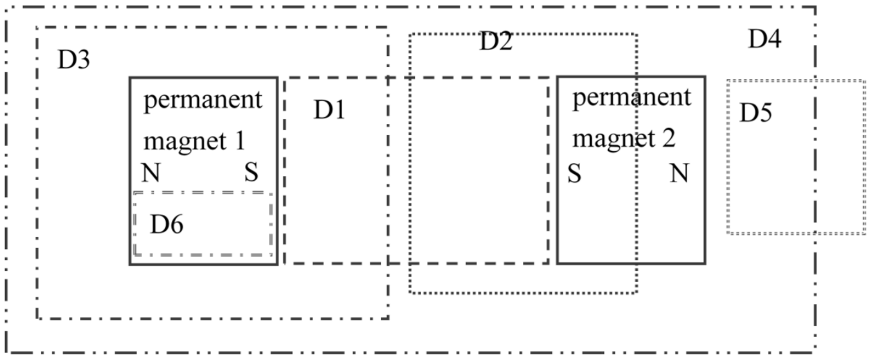


FIG. 55

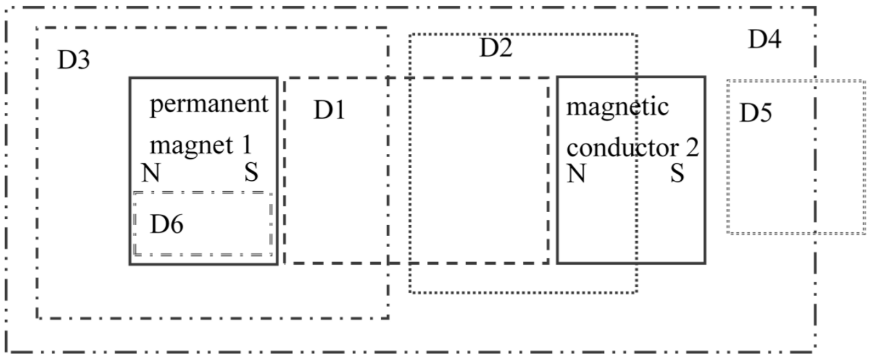


FIG. 56

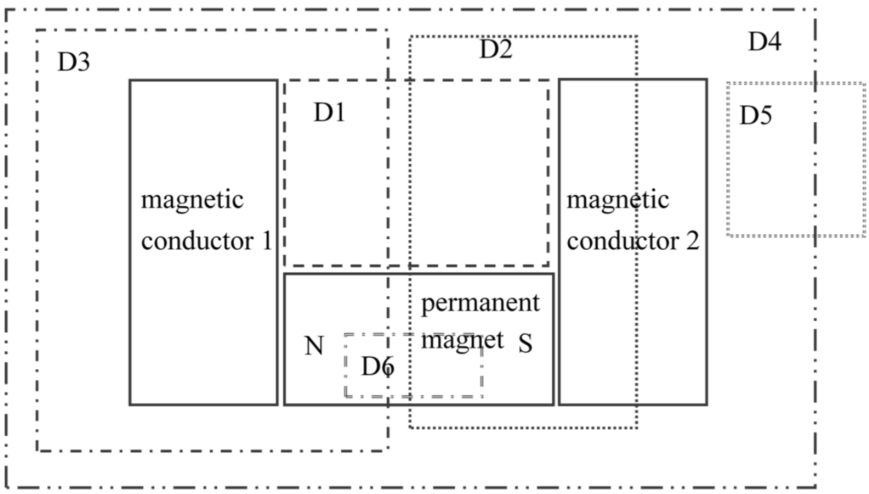


FIG. 57

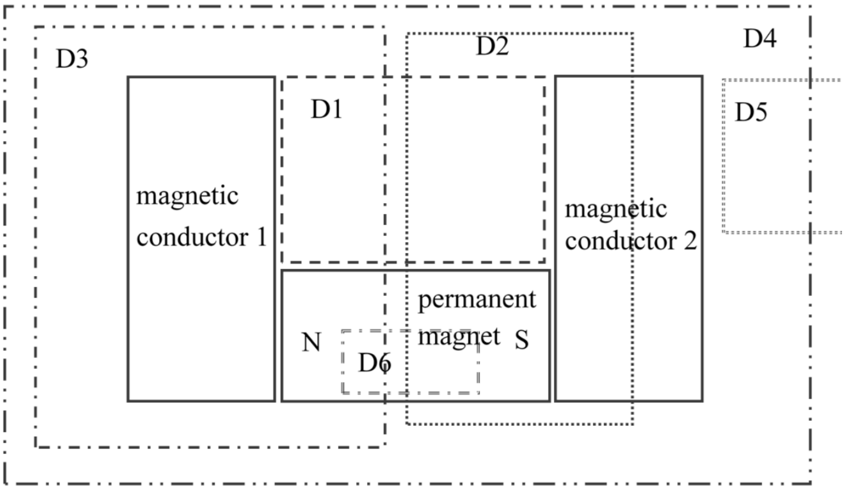

D3
D2
D4
D1
D5
magnetic
conductor 1
magnetic
conductor 2
permanent
magnet
N
S
D6

FIG. 58

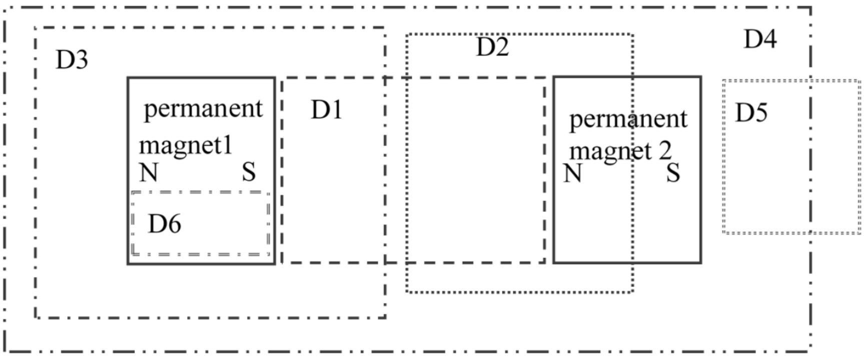

D3
D2
D4
permanent
magnet1
D1
permanent
magnet 2
D5
N
S
N
S
D6

FIG. 59

INTERNATIONAL SEARCH REPORT

International application No.
PCT/CN2024/082548

A. CLASSIFICATION OF SUBJECT MATTER

H04R 9/06(2006.01)i

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC: H04R

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

CNKI; WPABS; ENTXT; CNTXT; VCN; VEN: 抵消, 电流, 动圈, 非线性, 失真, 振子, 线圈, 磁铁, 导磁体, counteract+, current, moving coil, nonlinear, distortion, oscillator, coil, magnet+

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	CN 219248016 U (DONGGUAN WEIDONG INTELLIGENT TECHNOLOGY CO., LTD.) 23 June 2023 (2023-06-23) description, paragraphs [0030]-[0167]	1-20
X	CN 219204661 U (DONGGUAN WEIDONG INTELLIGENT TECHNOLOGY CO., LTD.) 16 June 2023 (2023-06-16) description, paragraphs [0040]-[0233]	1-20
X	CN 219227802 U (DONGGUAN WEIDONG INTELLIGENT TECHNOLOGY CO., LTD.) 20 June 2023 (2023-06-20) description, paragraphs [0030]-[0226]	1-20
X	CN 219247678 U (DONGGUAN WEIDONG INTELLIGENT TECHNOLOGY CO., LTD.) 23 June 2023 (2023-06-23) description, paragraphs [0035]-[0141]	1-20
A	US 2014354381 A1 (ACTIVE SIGNAL TECHNOLOGIES INC.) 04 December 2014 (2014-12-04) entire document	1-20

☐ Further documents are listed in the continuation of Box C. ☑ See patent family annex.

* Special categories of cited documents:
- "A" document defining the general state of the art which is not considered to be of particular relevance
- "D" document cited by the applicant in the international application
- "E" earlier application or patent but published on or after the international filing date
- "L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
- "O" document referring to an oral disclosure, use, exhibition or other means
- "P" document published prior to the international filing date but later than the priority date claimed
- "T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
- "X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
- "Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
- "&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
27 May 2024	**14 June 2024**

Name and mailing address of the ISA/CN	Authorized officer
China National Intellectual Property Administration (ISA/CN) **China No. 6, Xitucheng Road, Jimenqiao, Haidian District, Beijing 100088**	Telephone No.

Form PCT/ISA/210 (second sheet) (July 2022)

INTERNATIONAL SEARCH REPORT
Information on patent family members

International application No.
PCT/CN2024/082548

Patent document cited in search report			Publication date (day/month/year)	Patent family member(s)			Publication date (day/month/year)
CN	219248016	U	23 June 2023	None			
CN	219204661	U	16 June 2023	None			
CN	219227802	U	20 June 2023	None			
CN	219247678	U	23 June 2023	None			
US	2014354381	A1	04 December 2014	US	9390875	B2	12 July 2016
				US	2016293310	A1	06 October 2016
				US	9947448	B2	17 April 2018
				WO	2014194140	A2	04 December 2014
				WO	2014194140	A3	05 March 2015

Form PCT/ISA/210 (patent family annex) (July 2022)

REFERENCES CITED IN THE DESCRIPTION

Patent documents cited in the description

- CN 2024082548 W **[0001]**
- CN 202310832430 **[0001]**