Structure and Characteristics of Closed-loop Two-dimensional Surface Motors

—a Literature Survey

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*Abstract--***At present, Sawyer planar motor is the only form of two-dimensional motor available to industry. Often operating in an open-loop stepping manner, it has the disadvantages such as susceptibility of loss of steps and external disturbances. This paper investigates a new generation of closed loop 2D surface motors, including permanent magnetic planar motor, planar induction motor and planar variable reluctance motor. Also the corresponding performance, structure, and characteristics are summarized and compared.**

Keywords—**2D planar motor, Surface motor, 2D direct drive**

I. Introduction

Sawyer planar motor was first used by combination of two identical linear ones with their axes perpendicular to each other to perform two-axis motion. Often operating in an open-loop stepping manner, it has the characteristics of providing uniform performance over the entire workspace and offering fairly high speeds, accelerations and precision. But it has the drawbacks of i) susceptible to loss of steps, ii) unable to reject external disturbances, iii) unable to provide high stiffness. Though several attempts have been made to implement sensors upon the motor to provide closed-loop control ([1-5], the results are not satisfactory as complexity and cost are concerned.

A new generation of two-dimensional motors, controlled in a closed loop manner by the use of electronic control systems with accurate position detection and rapid response are discussed below. This paper investigates several kinds of planar motors and examines their characteristics and drawbacks. These include the permanent magnet planar motor, planar induction motor and planar variable reluctance motor.

II. PERMANENT MAGNETIC PLANAR MOTOR

The two-axis linear motion in Sawyer planar motors is achieved by the combination of two linear ones in orthogonal directions. However, in the permanent magnetic (PM) motor proposed in [6], there is only one mover and can be directly driven and controlled in both X and Y axis.

Fig.1 (a) shows the basic structure of the motor. The mover is composed of eight core coils and the stator is a checkerboard arrangement of N- and S- pole magnets, laid atop a back iron plate.

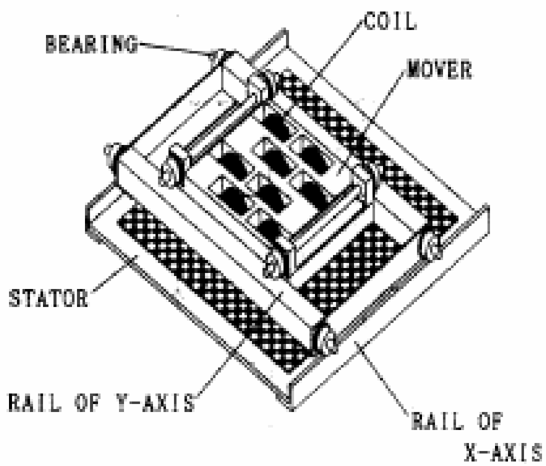

Fig. 1 (a) Overall structure of the PM planar motor with moving coil

The operating principle of PM surface motor originates from the interaction between the permanent magnets and the induction coils. The layout of mover poles is shown in Fig.1 (b). Phase A is completely opposite to the N pole, while phase B is pitched $\tau/4$ out of phase along X axis; phase C, $\tau/4$ along Y axis, phase D, $\tau/4$ along both X and Y axis. These coils are positioned in such a way that by selecting among different combinations of excitation phases, the mover can move in both X and Y directions. For example, if phase A is changed to phase B excitation, because phase B is positioned half the magnetic width along X axis, it will generate the magnetic force so that the mover will move half the magnetic width along X axis only.

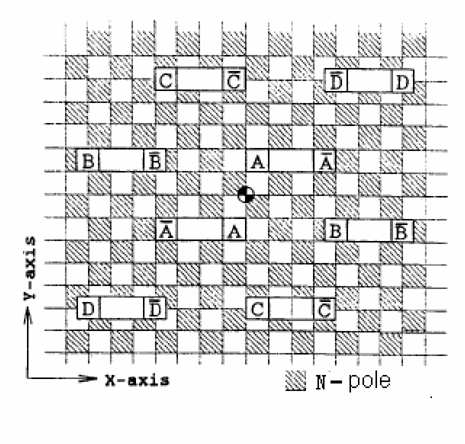

Fig.1 (b) Stator layout

At present, the stator structure of PM planar motor is as follows (Fig.2) [7-10]. The magnetic packing density of type (a) and (b) is much less compared with that of the one-axis driving linear motor. The disadvantages of the PM planar motor which employs the stator arrays of type (c) and type (d), compared with the rate of one-axis driving linear PM motor, is the lower rate of using magnet.

By finite element method (FEM), flux density along the air-gap between magnet and mover surface is calculated respectively. The amount of type (d) is 21% larger than type (b) and 45% larger than that of type (a). Therefore the efficiency of the planar motor that employs the type (d) magnet array is higher than that of others [10].

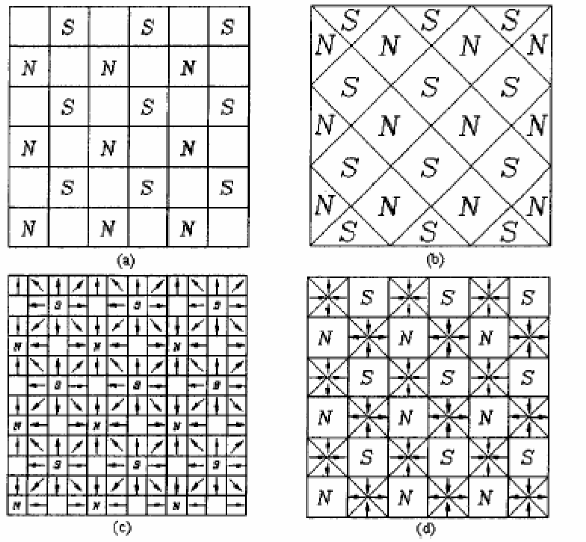

Fig. 2 Magnetic arrays for planar motor

Fig.3 shows the drive circuit. PWM drivers are used to control the excitation current for relevant phases. In this manner, the motor can be driven using various excitation sequences [11]. A displacement measurement device to conduct drive tests is also provided. Laser sensors are mounted to avoid creating a load on the motor. The signals are recorded on an X-Y plotter (Fig.4).

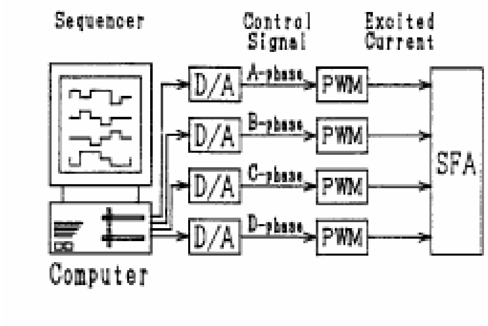

Fig.3 Drive system

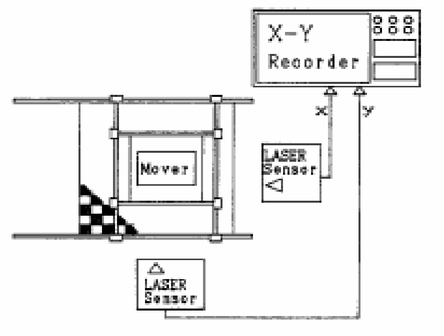

Fig.4 Drive test device

The above planar motor uses permanent magnets as the stator and the electromagnets as the mover. However, [12] proposed a totally inversed structure. The structure of the stator is a stationary slotless armature with orthogonal windings. The mover is composed of two high-efficient permanent magnets (Fig.5). The orthogonal windings have no electric connections and they are produced in such a way that on top of one layer of the X-coil there will be a layer of the Y-coil and so on. Each winding is divided into twelve independent phases and has the same width as the permanent magnets. For driving the motor, only necessary coil sections will be excited just for a short time. The disadvantages of this structure are significant presence of end effects and the normal force that reduced the actuator performance.

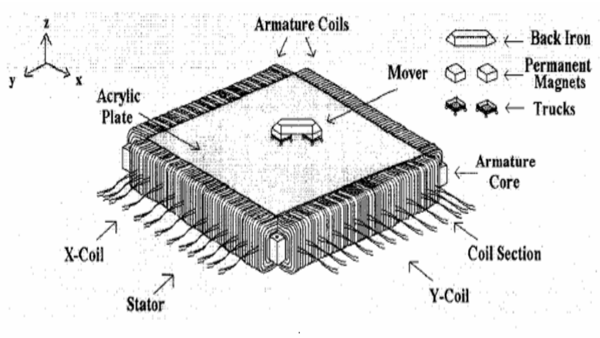

Fig.5 Perspective view of the planar actuator

Another PM planar motor is proposed in [13]. The mover is free from wire connections and it can rotate itself in addition to performing motions in two directions on the X-Y plane.

Fig.6 shows the structure of this motor. The stator is composed of multiple electromagnets and a yoke. The mover consists of several permanent magnets, a back iron with four bearings. A glass board is inserted in between to support the mover and adjust the air gap.

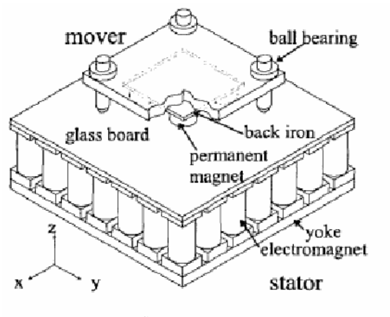

Fig.6 Structure of the planar motor

According to the structure of planar motors, three-dimensional field calculation is required for optimal analysis. The numerical methods, such as finite element analysis (FEA), provide a means of determining the flux density distribution [14-16]. And the force calculation is obtained by means of the Maxwell's Stress Tensor equation applied to FEA. Because of the interaction between magnetic poles and excitation coils in two directions, it is often difficult to get an accurate measurement. Another approach is volume integral equation method (VIEM). It is more suitable for the detent force calculation and back-EMF analysis. In Article [12], detent force due to end effect of a mover is analyzed and optimal shape of mover is determined for minimizing the detent force, and coil shape is also optimized for making back-EMF to be constant.

Compared with PM linear motors, it is difficult to provide thrust output in compact configuration without the ripple of thrust effect in the movement. Reduction of such disturbance can be alleviated by optimization of stator or mover structure. A method of chamfering the mover side is provided by [17].

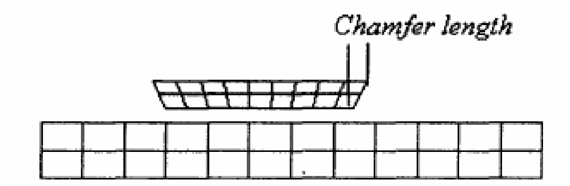

Fig. 7 Mover chamfering

The PM planar motors rely on permanent magnets to produce magnetic force, which require many armature windings or big magnet poles to be installed. So the working area of the secondary surface should be larger than the primary one, inevitably, the utility factor of the secondary is much smaller compared with of linear PM motors.

III. PLANAR INDUCTION MOTOR

The prototype of planar induction motor is the X-Y linear induction type, which does not have the drawbacks of many armature windings or magnetic field poles for the structure of planar PM motors. It has the same composition as a single-sided linear induction motor (LIM). However, the two windings for X and Y direction have to be perpendicularly intersected to each other. Due to the complicate configuration of core, it is difficult to form a good magnetic circuit [18].

An induction type of circular shaped planar motor is proposed [19], which has a toroidal core as a primary core (Fig.8). The secondary surface is composed of a flat conducting plate and back iron plate. The mover can perform rotation in addition to linear motion on the surface and it can obtain the thrust for any direction.

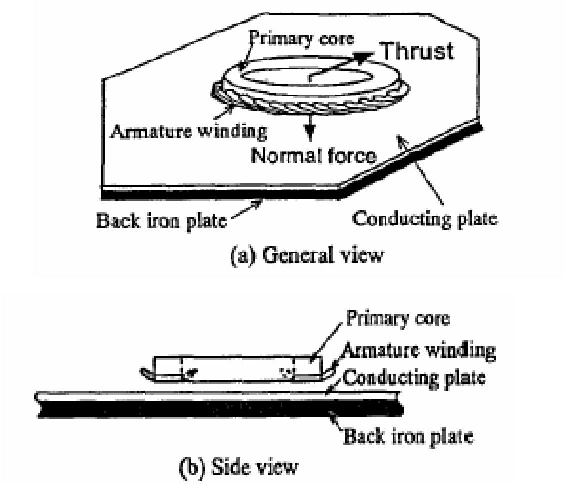

Fig.8 Surface induction motor

For the rotating drive, all the coils are used to generate the ordinary rotating magnetic field in the same as an axial gap type rotating motor, as shown in Fig.9 (a). For linear drive, the winding is separated into two groups every half of toroidal core for a desired direction of motion, then the partial rotating magnetic field is generated every winding group, as shown in Fig.9 (b) [20, 21].

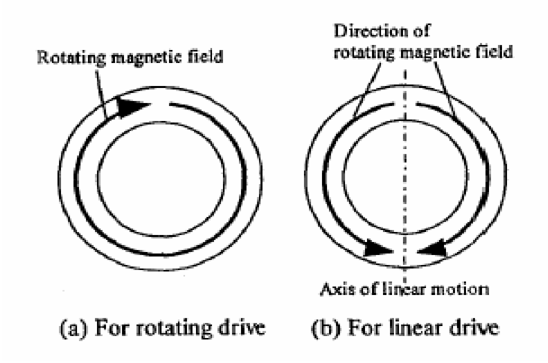

Fig.9 Principle of operation

Planar induction motors have smooth force output but generally they are difficult to develop high air gap flux density. But their simple conducing plate ensures wide area of movement.

IV. PLANAR VARIABLE RELUCTANCE MOTOR

The most outstanding feature for variable reluctance type motor is its simple and robust structure. Manufacturing of the actuator is simple, the base can be made from a single piece of ferrite metal, and the moving part is made from simple coil windings and ferrite metal pieces. But it has never been a popular choice for high-precision and high-speed motion applications due to its difficult control and high torque ripples of output, this is because the actuator's characteristics is highly dependent on its complex magnetic circuit, which is difficult to mode, simulate, and control. Until recent years, with the advancement of power electronics and digital signal processing, great steps have been made to improve output speed and torque of VR motor, which make it possible for the application of linear motion systems [22]. A VR motor with simple and robust structure is proposed

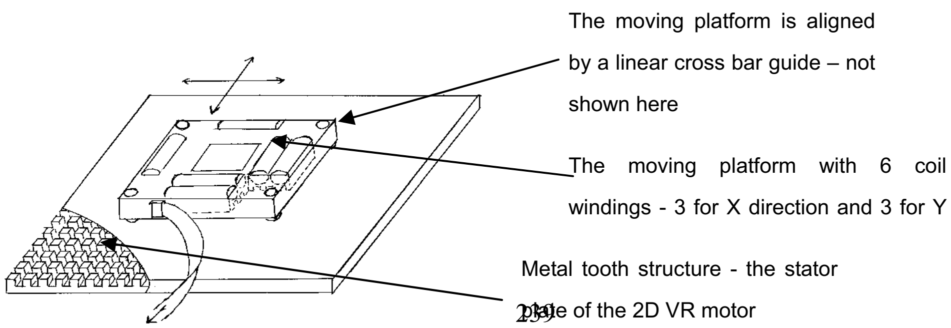

Fig.10 Overall structure of the 2D VR planar actuator

[23]. The 2D VR planar actuator is based on the "straightened-out" version of a 6/4 pole rotary switched reluctance motor, along the X and Y directions (Fig.10). Two sets of 3-phase coil windings with wide magnetic teeth ware are employed on the moving platform. The wide magnetic teeth ensure that there is little force coupling between the two motion axes.

The design of the "toothed structure" 2D planar motor is shown in Fig.12. The base was manufactured from layers of laminated steel plates aligned in the X and Y directions. Two linear position encoders with resolutions of 1 μm are mounted onto the two ends of a moveable mechanical cross bar.

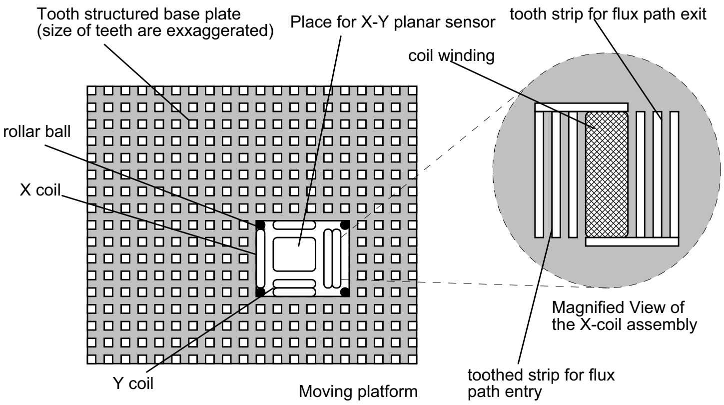

Fig.12 Layout of the toothed structure and coil arrangement

V. CONCLUSION

Several planar motors of different structures have been developed recently. Unfortunately, only Sawyer stepper motor has a steady output performance. It is the only type of planar motor that can be commercialized. There is still a long way to go for other types of close-loop motors. Due to the complex distribution of magnetic field, finite element analysis is not mature enough to fully solve three-dimensional problems; more advanced software package is needed.

At present, the main control methodologies for close-loop planar motors are mainly focused on digital control; non-linear control method is almost blank. One of the efficient means of improving motors' performance is to concentrate on the study toward robust control and analysis for control with good realization. In addition, X-Y plotter can be integrated with the mover for measurement for the whole system, however, this weaken the advantage of the mover and increase the complexity of the system at the same time.

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