Improvements in the Mechanical Structure of the Linear Switched Reluctance Motor

*Antares San-Chin Kwok, *Wai-Chuen Gan and **Norbert C. Cheung
*Motion Group, ASM Assembly Automation Hong Kong Ltd., Kwai Chung, NT,
Hong Kong SAR, China. Email: sckwok@asmpt.com
**Department of Electrical Engineering, The Hong Kong Polytechnic University, Hung Hom,
Kowloon, Hong Kong SAR, China. Email: eencheun@polyu.edu.hk

***Abstract* - In semiconductor manufacturing, wire bonding of chips and surface mount technology process require precise robotic linear motion. Traditionally, X-Y sliding tables driven by permanent magnet rotary motors, ball-screw and belt are used. However, they have position accuracy problem due to ball-screw backlash. Since motors and high precision grade ball-screws are expensive, high manufacturing cost is another disadvantage. Low reliability results from complex mechanical alignment and low ball-screw lifetime.**

This paper presents the basic structure of Linear Switched Reluctance Motor for high performance motions in manufacturing automation. No magnet is used and the traveling distance has no limitation. Consequently, this motor is extensively robust and applicable in hostile environment. A two-dimensional motor is introduced to replace the conventional X-Y table. Based on switched reluctance driving method, the proposed actuator has a very simple and robust structure with very few mechanical parts for easier manufacturing. 3 designs are compared on their mechanical structure and efficiency. Detailed motor framework description and corresponding mathematical model are shown. Applied control theory would be mentioned.

I. INTRODUCTION

In the manufacturing of advanced electronic products and components, a precise two-dimensional (2D) planar motion is essential for surface positioning, parts assembly and component insertion. To achieve precise 2D planar motion, most machines use cascaded X-Y tables with rotary motors and rotary-to-linear mechanical couplings. However, it has disadvantages of complex mechanical structure, frequent mechanical adjustments, high manufacturing/maintenance cost, and low reliability. Usually, ball-screw is applied to convert rotational motion from motor to linear motion. The backlash of ball-screw would degrade the accuracy and the rigidity of the system. The motor could not perform very accurate and high speed motion as expected.

Linear Switched Reluctance Motor (LSRM) presented in this paper contains only linear motion guide, silicon-steel plate and coil. The motion is directly driven by the magnetic field alignment among laminated steel plate. No magnet, ball-screw and coupling are required. Therefore, the manufacturing cost is greatly reduced due to absence of magnet, ball-screw and motor. The rigidity is also improved since no coupling is used and the system could withstand higher acceleration

In this paper, the author would make a comparison on three different 2D planar motors using LSRM technologies. Rigidity, moving mass and manufacturing cost would be considered. For the finalized design, the detailed mechanical structure is presented to highlight the improvement in 2D motor structure. Some features are newly applied for easier manufacturing operation.

Compared with those static permanent magnet and moving coil motor, LSRM is much more robust and simple in mechanical structure. System traveling range has no limitation and is more economic in production cost. However, LSRM motion control system is more complex than permanent magnet design because of its nonlinear magnetic and electrical behaviors. Mathematical model would show the nonlinear characteristics of LSRM. Among various intelligent control techniques, a particular control strategy will be developed to tackle the nonlinear properties challenge with proper simulation together.

II. MOTOR DESIGN COMPARSIONS

In the paper, three types of 2D planar are proposed. Different characteristics are highlighted and compared. Before considering control strategy, simple mechanical structure and high rigidity system are highly recommended for future high precise and high speed motion tests.

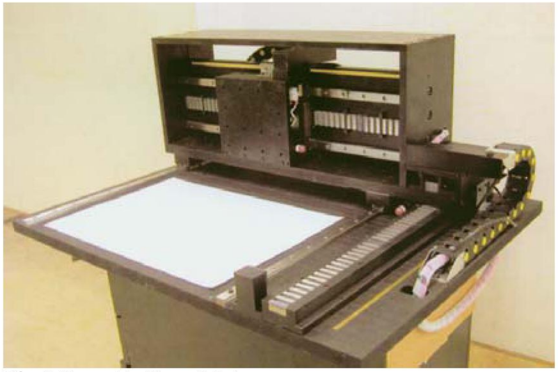

Fig.1 Cassette Type Motor

For cassette type motor, the total moving mass is about 10kg. At least 10A current is required for the motor to move slowly. The power efficiency is the lowest among three designs. The profile time is too long to meet typical robot pick arm for semiconductor assembly procedure target. To reduce travelling period, current becomes too high and results safety issue problem. Coil wire should be altered to thicker one at the same time. High moving mass and manufacturing cost become its disadvantages.

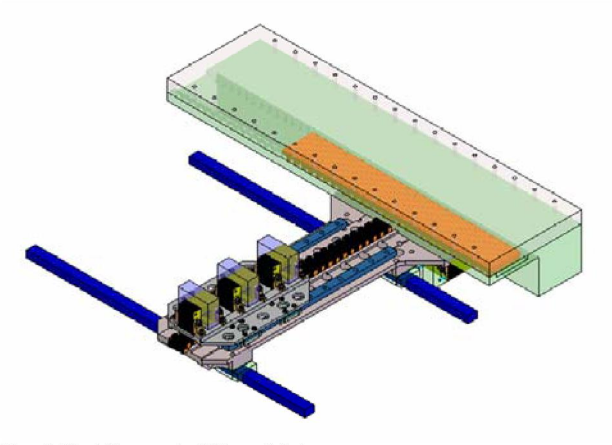

Fig. 2 End Supported Type Motor

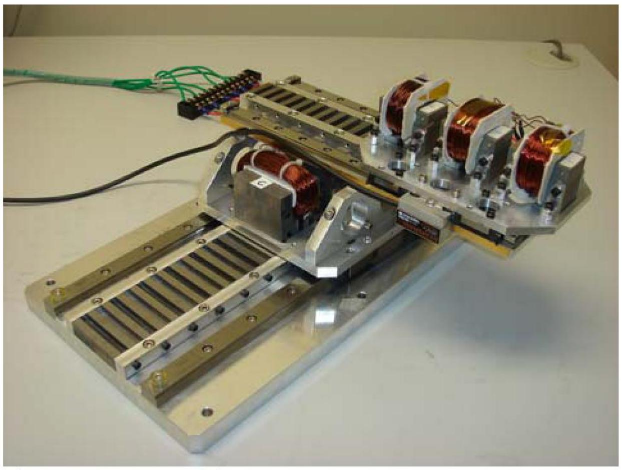

Fig. 3 Centre Mounted Type Motor

The second design is named as end supported type motor. Its moving mass is much lower than the cassette type one. Since the static laminated metal plate track is mounted above the moving platform, the attractive force between static and dynamic metal plate can reduce the moving platform weight. Unfortunately, only a single track applies force on the whole moving platform and creates a non-symmetric force system. This probably produces a resultant torque and extra friction on the moving mass during operation. The mechanical structure is also complex and requires specified alignment.

The last motor has the smallest moving mass which is only about 5kg and is able to achieve higher acceleration/deceleration. X-axis motor is shortened to reduce moving mass while y-axis laminated steel plate is doubled to increase magnetic field strength. Y-axis driving force is much higher than x-axis so as to counterbalance the different moving mass for x-axis and y-axis motor. From the view of manufacturing, silicon-steel laminated plates are mounted together individually for more convenient installation and maintenance.

Table 1 summarizes the advantages and disadvantages among these three motors.

III. DETAILED DESCRIPTION OF LSRM

The proposed motor is a combination of 2 axis of LSRM. For x-axis, the motor consists of a moving platform, 2 Linear Motion (LM) Guides, laminated plates at a base and a moving platform. The moving platform plate and the stands are made of aluminum to minimize the moving mass. The laminated plate is made of 0.5mm thick silicon-steel plate and every 50 pieces are grouped together. The total moving mass is about 4kg. Three groups of silicon-steel plate are fixed by stands on a plate and circulated by a number of wire coils. The coils are driven by 3 different currents with 120 · phase difference to provide phase A, B & C accordingly. With this Y configuration, the mutual inductance could be minimized.

	Advantages	**Disadvantages**
Cassette Type	✓ Simple mechanical structure	✧ Too heavy ✧ Poor response time ✧ High peak current required
End Supported Type	✓ Magnetic attraction counterbalances the moving mass ✓ Smaller moving mass compared to Cassette type	✧ Unbalanced model structure ✧ Complicated mechanical framework
Centre Mounted Type	✓ The smallest moving mass ✓ The shortest response time ✓ Symmetric structure ✓ High position accuracy achieved ✓ Y-axis magnetic field strengthened	✧ Difficult to access the Y-axis coils

Table 1 LSRM Comparsions

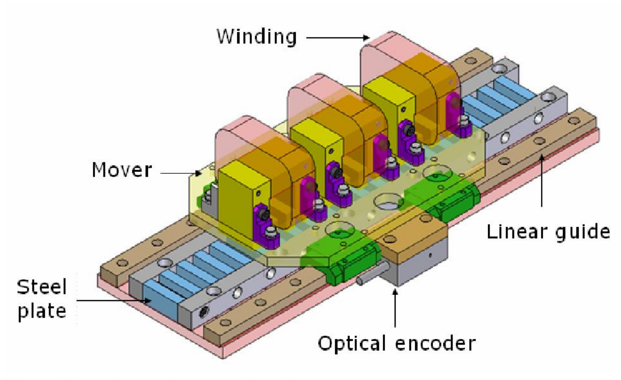

Fig. 4 X-axis motor construction

Despite flux phase difference, they are separated with 1+2/3 pitch distance (i.e.10mm) as shown in the figure. The pitch distance is preferred to be 12mm so as to avoid any rounding error from the 5/3 pitch distance.

The air gap between the upper moving plates and the lower fixed plates is kept as 0.2mm to prevent scratching event during movement. Since the attraction force between 2 parties of laminated plate is very strong, locking pins are inserted into the upper one while clamping bars are mounted to press the lower plates.

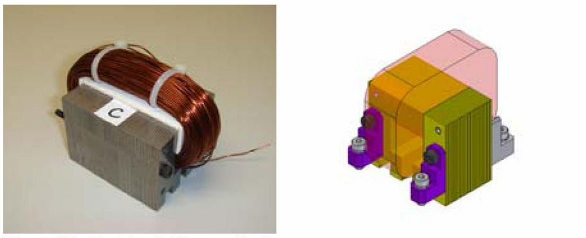

Fig. 5 Individual Phase Coil

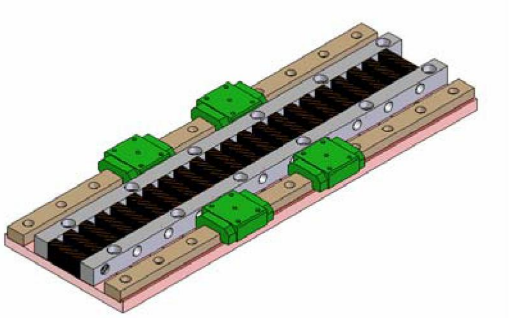

Fig. 6 Static Laminated Plates with Linear Motion Guide

IV. DESIGN SCHEMATIC OF LSRM SYTEM

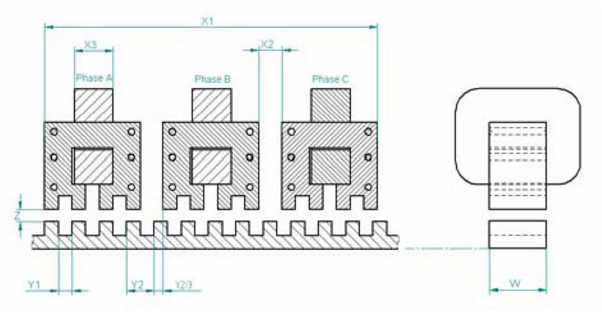

Fig 7. LSRM Design Schematic

Fig. 7 shows a three-phase coil arrangement with flux de-coupled path and 120 electrical degree separations. The design of three phase flux de-coupled motor windings with longitudinal configuration is chosen because:

i. The de-coupled flux windings lead to a simpler motor model due to zero mutual inductance.
ii. The individual phase windings reduce the manufacturing cost and complexity.
iii. Long travel distance can be accomplished easily by combining longitudinal track guides.

Power Output (P)	100 W
Traveling Distance (x)	300 mm
Maximum Load (L)	4 kg
Position Accuracy	±25 um
Feedback Device	Optical Encoder with 0.5 um accuracy
Pole Width (y_1)	6 mm
Pole Pitch (y_2)	12 mm
Coil Separation (x_2)	10 mm
Winding Width (x_3)	30 mm
Air Gap (z)	0.4 mm
Number of turns per phase (N)	200

Table 2 LSRM Characteristics

The switched reluctance linear drive system has a highly non-linear characteristic due to its non-linear flux behavior. Following is the mathematical model of the LSRM:

$$v_j = R_j i_j + \frac{\partial \lambda_j(x,i_j)}{\partial x}\frac{dx}{dt} + \frac{\partial \lambda_j(x,i_j)}{\partial i_j}\frac{di_j}{dt} \qquad (1)$$

$$f_e = \sum_{j=1}^{3} \frac{\partial \int_0^{i_j} \lambda_j(x,i_j)di_j}{\partial x} \qquad (2)$$

$$f_e = M\frac{d^2x}{dt^2} + B\frac{dx}{dt} + f_l \qquad (3)$$

where
v_j is the phase voltage,
i_j is the phase current,
R_j is the phase resistance,
λ_j is the phase flux linkage,
x is the travel distance,
f_e is the generated electromechanical force,
f_l is the external load force,
M is the mass and
B is the friction constants

V. CONTROL STRATEGE

Since the current dynamics bandwidth is at least ten times faster than the mechanical one, a dual rate cascade control approach is proposed. The faster inner loop current controller regulates the current-voltage non-linearity of the actuator while the slower outer loop trajectory one controls the mechanical dynamics. On top of this, a non-linear function is included to compensate the non-linearity of force against current and position. Fig. 8 is the overall block diagram of the control system.

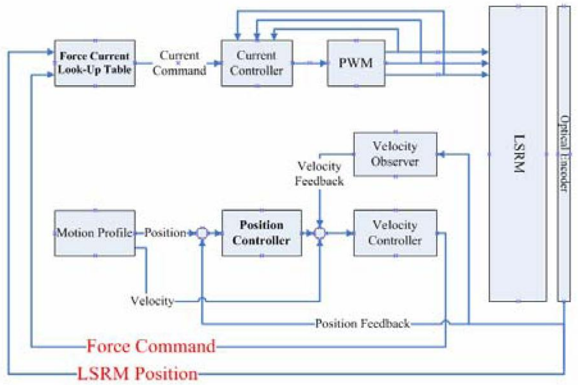

Fig. 8 Overall Controller Structure

A current controller is applied to linearize the current-voltage relationship of the actuator. A simple PI controller is proposed. Position can be assumed to be stationary during the control time frame of the current controller, since current dynamics are much faster than mechanical dynamics. The non-linear function bridges the link between the trajectory controller and the current controller. It receives force commands and position information, and outputs desired current set points to the current controller. The trajectory controller forms the essential part of the slow sub-system. It is a typical PID controller.

Since the relations of force, current, and position re non-linear in nature, a 3D lookup table is used to describe the force profile. A major factor influencing the operation of the variable reluctance linear actuator is the resolution of the look up table. A higher resolution generally leads to better accuracy.

In the implementation of the linear actuator control, it has been found that good continuity and smooth profile between points is more important than the accuracy of the look up table. To implement the force to current mapping by look-up table alone produces “chattering” in the travel of the linear motor, even when the size of the table is fairly large (100x100 elements).

In this project, a small look-up table (20x20 elements) is employed to store the force compensation values. Two-dimensional linear interpolation is used to find the intermediate values. This produces a 5% worse-case deviation from the original non-linear function and the output valve always follows a smooth profile. Such an arrangement provides adequate description of inverse force function for the variable reluctance linear motor.

The controller’s operation is based on the assumption that the current controller has prefect tracking capability, and the non-linear force to current look-up table generates the linearized current command to the current controller.

VI. CONCLUSIONS

In this paper, three kinds of 2D planar motor are compared. The finalized one is different from the existing planar motor based on permanent magnet synchronous drive, inductive drive, and open loop stepper drive. Based on dual rate cascade control approach and non-linear look-up table, the proposed actuator has a very simple and robust structure with very few mechanical parts for easier manufacturing. There is no need for magnets and no limitation on the travel distance. The actuator is extremely robust and can be used in hostile environment. Therefore, this 2D LSRM is a potential alterative to replace existing rotary motor, linear three-phase PM and induction motors in special areas which should be under high temperature and free of magnet.

VII. ACKNOWLEGMENT

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VIII. REFERENCE

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