LINEAR AND PLANAR VARIABLE RELUCTANCE MOTORS FOR FLEXIBLE MANUFACTURING CELLS

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Summary Most advanced manufacturing processes require precise linear motion for several tasks as material transfer, packaging, assembly or electrical wiring. To achieve precise linear motion, most of the usual high-performance manufacturing machines use X-Y sliding tables with rotary motors and rotary-to-linear couplers. Though this method is the most widely used, it has disadvantages of low accuracy, complex mechanical adjustments, high cost, and low reliability. This paper describes a novel modular construction which can be used to build up linear and surface direct-driven motors for high performance motions in flexible manufacturing automation. The proposed motors have simple modular structure and they have no limitation on the travel distance. Simulated results of the linear and planar motion systems indicate that the motion system has good accuracy.

1. INTRODUCTION

Flexible manufacturing systems are the most advanced production units. They can assure high efficiency and adaptability for rapidly changing production requests. They are high-density mechatronic systems, consisting of modular elements, such as high-precision platens, efficient manipulators, couriers or conveyers and parts feeders [1].

The most typical task to apply in a flexible manufacturing cell are the pick and place applications and the manipulator/parts positioning tasks. Both of them require very precise point to point motion.

Ensuring reliability and reducing per unit cost are the two fundamental objectives of process automation in the flexible manufacturing cells. For pick and place applications accurate positioning is essential in assuring the product quality. Fast and stable operating speed enables high production rate to be achieved.

Accuracy and speed are often two conflicting requirements, which are not so easy to attain together. Sometimes a compromise between them is required. To build a high performance positioning system for modern manufacturing units having high precision and high speed positioning necessitates the use of intelligent variable speed drive is needed. This requires powerful electric motors and advanced control algorithms.

In this paper novel modularly built up linear and surface variable reluctance motors will be presented. Using these motors the tight requirements needed in modern flexible manufacturing systems can be achieved. Two motor variants will be presented, one for linear and another for surface precise motions.

The dynamic performances of the proposed modular variable reluctance motors were studied via simulation tools. The simulation program is based on a coupled multi-level mathematical model of the motor. The program models also the power converter feeding the motor. All the results of simulations confirm that both the modular variable reluctance linear and surface motors are well suited to be integrated in modern flexible manufacturing cells.

2. FLEXIBLE MANUFACTURING CELLS

The most widely used solution for manipulator positioning purpose is that shown in Fig. 1.

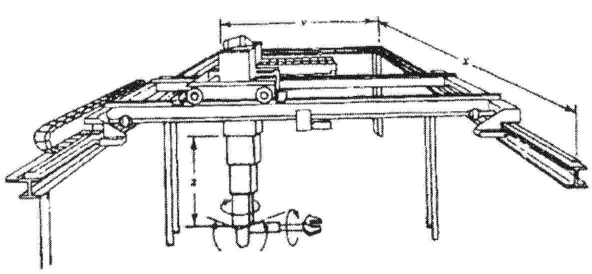


Fig. 1. Manipulator positioning system.

The manipulator is guided by rotary motors moving on rails above the part to process. The need of applying rotary-to-linear converting mechanisms decreases the efficiency and the precision of the entire drive system.

In a more advanced concept the main structure in a flexible manufacturing cell is a set of platens which serve as the factory floor. On the platens, couriers float on air bearings and move around in the factory with subassemblies on their backs (see Fig. 2).

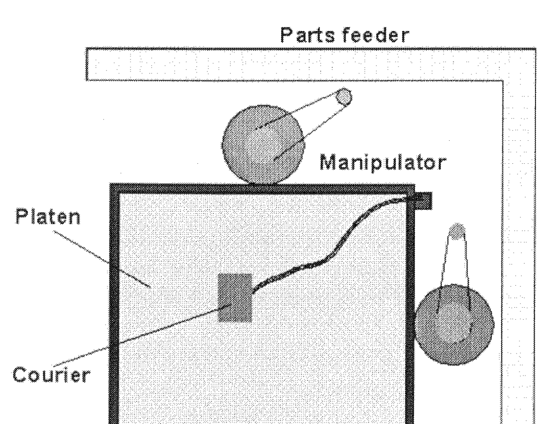


Fig. 2. Advanced flexible manufacturing cell

The couriers can navigate the platens to within high accuracy. Mounted round the platens are various types of manipulators and parts feeders, which can insert parts and perform other simple operations on the subassemblies, being carried about by the couriers. Each courier is controlled separately by real time operating system. The motor controllers are connected to each other in a sort of parallel or distributed architecture.

The couriers can replace the conveyer belts in a traditional factory, allowing for fewer restrictions on the paths of subassemblies between manipulators [2]. When only linear movements are required precise conveyors can be built up using direct-driven linear motors.

Both the conveyers and the couriers can provide linear, respectively two dimensional planar motion for the products, both for gross movement from point to point in the factory and for fine positioning when co-ordinating with other agents, such as manipulators. This means that they are one of the most critical parts of the manufacturing unit. The attached manipulators and part feeders can be of a great variety in complexity and in task to fulfil [3].

As all the other advanced manufacturing systems the above-presented flexible manufacturing cells require precise linear or surface motion for several purposes, as material transfer, packaging, assembly, electrical wiring, etc.

One of the most typical tasks for a flexible manufacturing cell is the pick and place operation, very precise point to point motion.

To achieve precise linear or surface motion, most of these high-performance manufacturing machines use moving tables with rotary motors and rotary-to-linear couplers. This solution has several disadvantages, as low accuracy, complex mechanical adjustments, high cost, and low reliability [4]. The proposed direct-driven motors can eliminate almost all of these disadvantages.

3. MODULAR VARIABLE RELUCTANCE LINEAR AND PLANAR MOTORS

The direct-driven motors eliminate all mechanical transmission parts between motor and load as gearboxes, ballscrews, belts, couplings, or other rotary-to-linear motion converters [5].

This way increased reliability, more force density and smaller size can be achieved. The direct-driven motors also offer superior speed, acceleration, load-positioning accuracy, and rapid stroke cycling [6].

The different variants of the modular variable reluctance linear motors in discussion eliminate several disadvantages of both the classical hybrid stepper motors and linear switched reluctance machines [7].

Due to their above mentioned benefits the modular variable reluctance motors are one of the best choices for modern manufacturing system applications where fast and accurate linear or planar motion under heavy loads are required.

The mover of the variable reluctance linear and surface motors to be presented is built up of modules, like the one presented in Fig. 4.

Each module has a rare earth permanent magnet, two salient teethed poles and a command coil. The

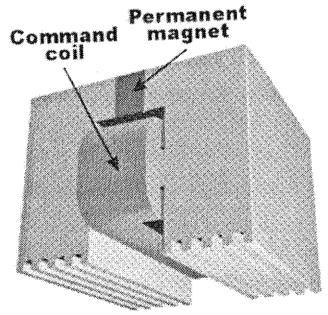


Fig. 4. The mover module.

working principle of the motor can be followed in Fig. 5.

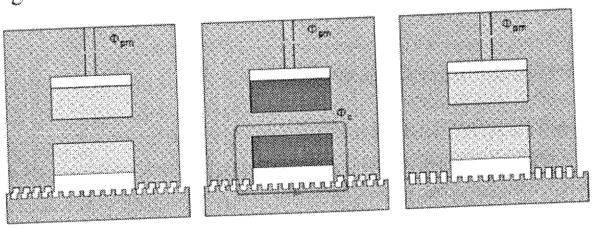


Fig. 5. The working principle of the modular motor.

If the command coil is not energised the magnetic flux generated by the permanent magnet (Φ_{pm}) passes through the core branch parallel to the permanent magnet due to its smaller magnetic resistance compared to the air-gap one. In this case practically there is neither tangential nor normal force produced.

If the coil is energised the command flux produced by it (Φ_c) directs the flux of the permanent magnet to pass through the air-gap and to generate significant force.

Due to the tangential component of the generated force the mover (forcer) moves one step to minimise the air-gap magnetic energy [8].

Several motor structures having linear or planar movement can be built up using the modules like that shown in Fig. 4.

From the various possible linear motor structures a three-phase variant is presented in Fig. 3. Its main advantage is that it can be controlled from a three-phase commercially available power converter. The three-phase construction still can assure the accuracy required in flexible manufacturing units.

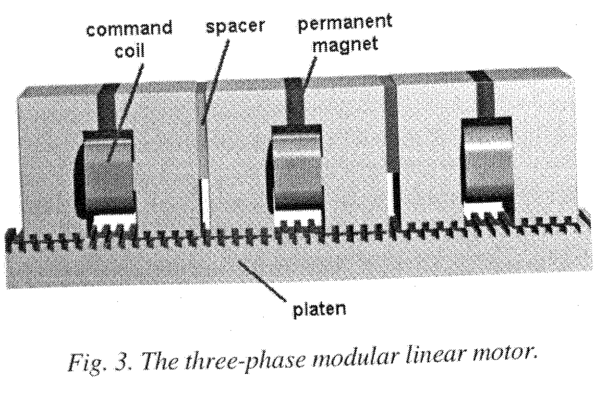
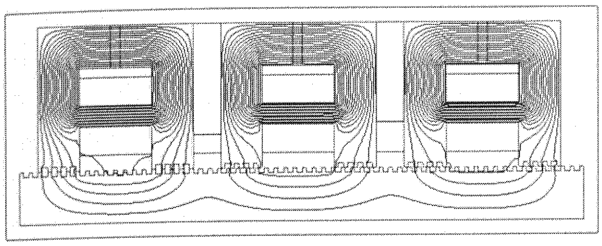


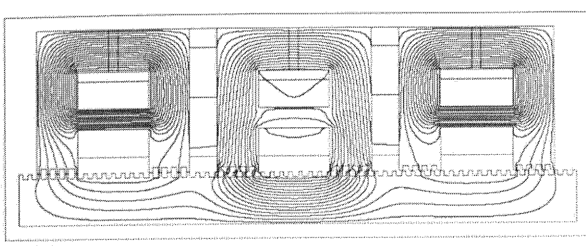
Fig. 3. The three-phase modular linear motor.

The above presented motor structure was analysed by means of numeric field computations performed using a finite elements method (FEM) based commercially available program package (MagNet 6.10).

Some results of this magnetic field analysis are given in Fig. 7. First the case when all the command coils are un-energised is presented. The flux plots for the case when a single, the middle command coil is energised are given in Fig. 7b [9].



a) all the command coils are un-energised



b) the command coil of the middle module is energised

Fig. 7. The field plots obtained by FEM analysis.

From the same modules also planar (surface) motors can be built up. The mover of the simplest (three-phase) modular planar variable reluctance motor is presented in Fig. 8.

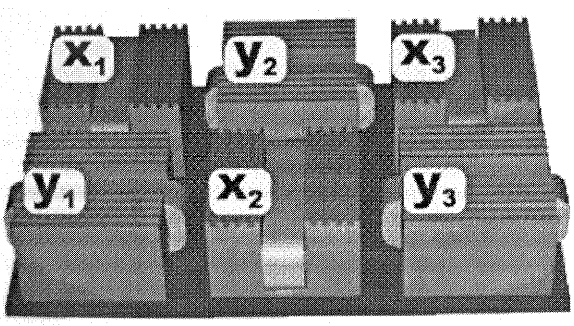


Fig. 8. The mover of the modular planar motor.

The mover of the surface motor has six modules, three for each direction. The three modules that ensure the displacement in x direction (x_1, x_2 and x_3) are mounted ortogonally to those three modules for the y direction displacement (y_1, y_2 and y_3).

All the modules are fixed in a common housing. The air-gap between this mover and the fixed platen is assured by air bearing. One set of three command coils drives the mover in the x direction, and the other in the y direction [10].

The entire modular surface motor can be seen in Fig. 6.

The usefulness of applying variable reluctance linear or planar motors in flexible manufacturing systems will be demonstrated by means of simulation.

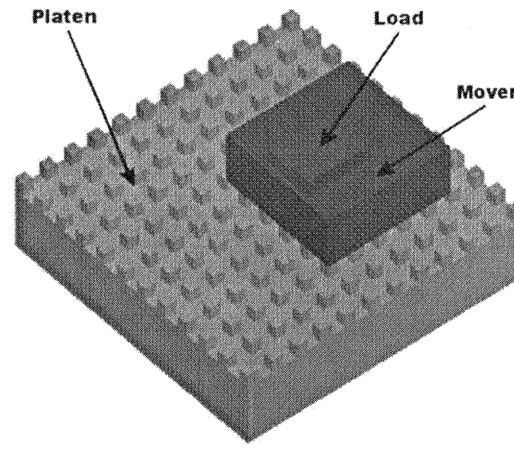


Fig. 6. The modular surface motor.

4. SIMULATION OF THE MODULAR VARIABLE RELUCTANCE MOTORS

The applied simulation program, presented in detail in a previous paper, is a compound of three coupled units [11]. Each simulation unit is implemented in different analysis and simulation platform. Hence for all the simulation tasks almost the best software environments were used. This way the accuracy of the entire simulation program was increased.

The main simulation program is built up in SIMULINK. The forces developed by the motor for given command current and relative displacement were previously computed very accurately using the 2D-FEM based analysis. The power converter was simulated in SIMPLORER and integrated in the SIMULINK program by an S-type function. The main window of the simulation program is given in Fig. 9.

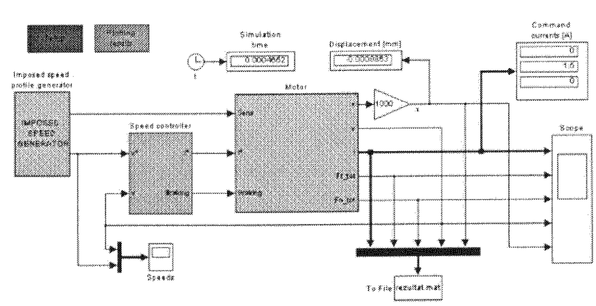


Fig. 9. The main window of the SIMULINK model.

The program was used to simulate the dynamic regimes of both the linear and planar modular motor. Here only the results of a single simulation of the three-phase modular linear variable reluctance motor will be presented.

A simple precise positioning task was simulated: a short (10 mm long) displacement of the motor at controlled speed. The most typical trapezoidal speed profile was imposed. The maximum speed of the motor was set at 0.25 m/s and the motor is running 0.02 s at this speed. The acceleration, respectively deceleration times were fixed to be 0.02 s.

The sample three-phase motor's rated command current, respectively tangential force is 1 A and 135 N. Its step size is 0.66 mm.

The main results of the simulation are given in Fig. 10. The command currents, the total tangential and normal forces, the speed and the displacement are plotted versus time.

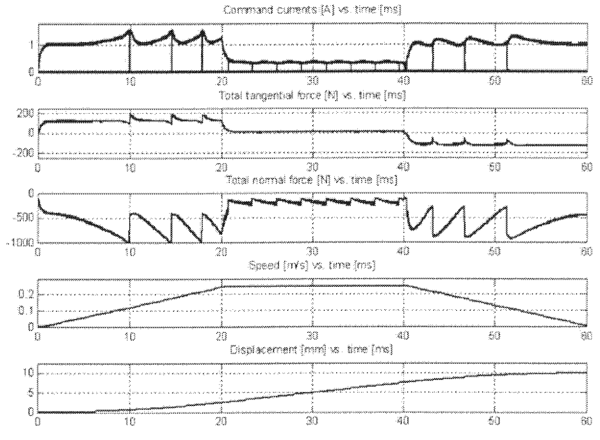


Fig. 10. The results of simulation.

The imposed speed profile was precisely followed. So the performed displacement was exactly that required. High tangential forces were needed for accelerating the mover. Due to the high force required in this stage of motion, the command currents also have significant values.

After the mover was accelerated, low tangential forces obtained by feeding the motor with reduced command currents may maintain its imposed constant speed.

5. CONCLUSIONS

Upon the simulated results it can be clearly stated out that both the modular variable reluctance linear and surface motors are well suited to be integrated in modern flexible manufacturing cells.

These systems have the following main advantages:

- Precision: assuring joint and link flexibility
- Throughput: conveyers and couriers can proceed to different manipulators while the current one is picking a part and preparing for the arrival of a different courier.
- Floor space: the combination of the variable linear motor driven conveyers or couriers and of the manipulator occupies much less space than a conventional assembly robot for the same size product.
- Flexibility: mechanical and electrical modularity allows easy integration of any overhead processing elements (e.g. screwdrivers, orbital head formers, glue dispensers, laser processors, etc.).

Acknowledgement

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