On a High Force Modular Surface Motor

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Abstract – Surface motors are capable of fast and accurate two axes translation motion. It makes them useful for various industrial and laboratory applications. In this paper a new direct driven permanent magnet variable reluctance surface motor having high force mover modules is presented. The surface motor is capable of high position resolution, rapid acceleration and high speed on both directions with low mass payloads. The surface motor's structure and control possibilities are investigated and the dynamic behaviour of the motor is studied using MATLAB/SIMULINK.

1. Introduction

Surface motors assure two degrees of freedom movement in the plane. These are direct driven motors, the load can be put or fixed directly on the mover. Hence they have a lot of benefits, as simplicity, efficiency and positioning accuracy, due to the lack of rotary-to-linear conversion mechanisms, mechanically complex assemblies that require regular maintenance and develop inaccuracies over time [1]. In a typical application of the surface motors, the flexible manufacturing system, they carry the product subassemblies from one overhead manufacturing device to another and precisely position the subassembly so that the overhead devices can perform their required actions.

One of the first planar motors was invented by Bruce Sawyer in the late 1960's [2]. The so-called Sawyer motors have typically two linear stepping motors combined into a single housing. Such a planar motor has two main parts: a moving forcer and a stationary platen. Since then Sawyer motors have received a lot of attention from academic and industrial researchers. The original invention was documented in a series of patents by Bruce Sawyer covering the linear actuator operating principle and the grouping of actuators in a single housing to enable planar motion. Early applications of Sawyer motors were limited to xy-plotters and wafer positioning stages.

In the last over 30 years several surface motors based on Sawyer motors were investigated in the literature and were used commercially in various industrial and laboratory applications. Almost all of these motors are capable of high position resolution, rapid acceleration and high-speed with low mass payloads. Multiple motors can share a single platen and by this a more complex machining unit can be set up in a small place.

In this paper a new surface motor having high force mover modules is briefly presented. The main benefit of the modular construction is that motors of different force and positioning accuracy can be built up using the same modules. Its advantages in closed-loop control mode are discussed and an efficient closed-loop control system is also presented.

The surface motor's dynamic behaviour is studied by means of simulation, performed by a fast running program written in MATLAB/SIMULINK environment. The program is based on the coupled circuit-field mathematical model of the motor. All the results obtained by means of simulation prove the usefulness and advantages of the proposed surface motor.

2. The modular surface motor

The modular surface motor shown in Fig. 1 is relatively simple, like the classical Sawyer motor. It consists of two main parts: the platen and the mover (forcer). The load is fixed directly on the mover.

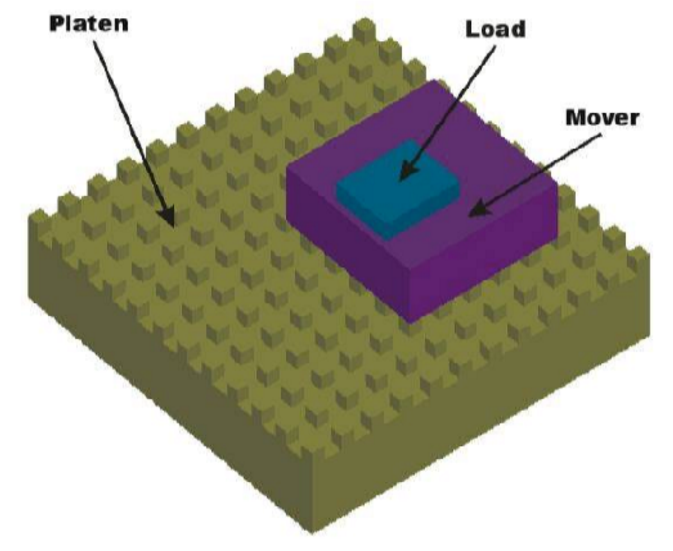


Fig. 1 The modular surface motor

The passive steel platen has a two-dimensional array of square teeth. Its surface is planarized using epoxy. It can have any sizes in order to ensure great travel area.

The mover, the active part of the motor, is built up of high force modules, Fig. 2, just like the modular double salient permanent magnet linear motors presented in detail in [3, 4].

Each module has a rare earth permanent magnet, two salient teethed poles and a command coil. The toothed structure is the same on the mover's poles and on the platen surface. If the command coil is not energised, Fig. 3a, the magnetic flux generated by the permanent magnet, Φ_{pm}, passes through the core branch parallel to the permanent magnet due to its smaller

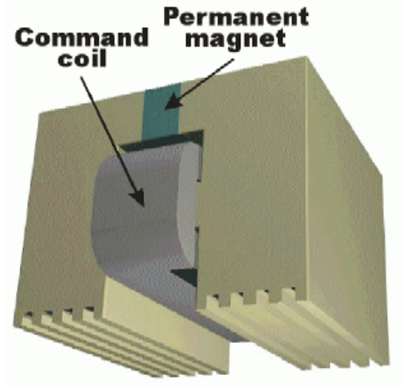


Fig. 2 The mover module

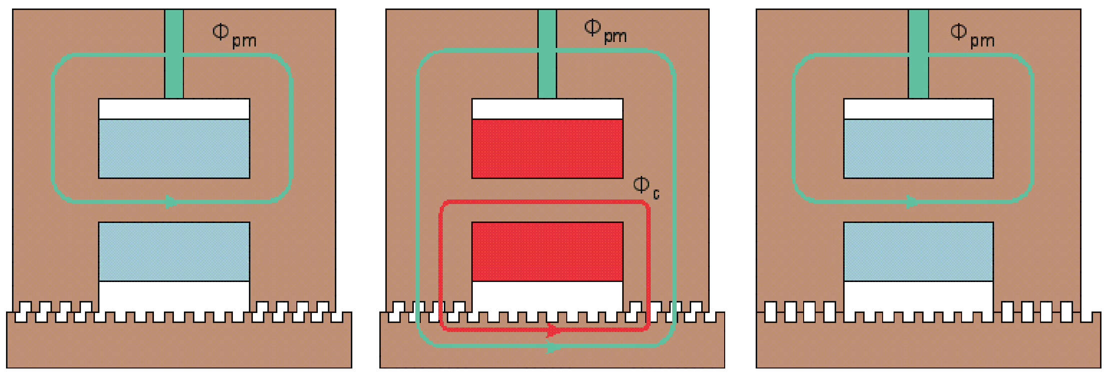
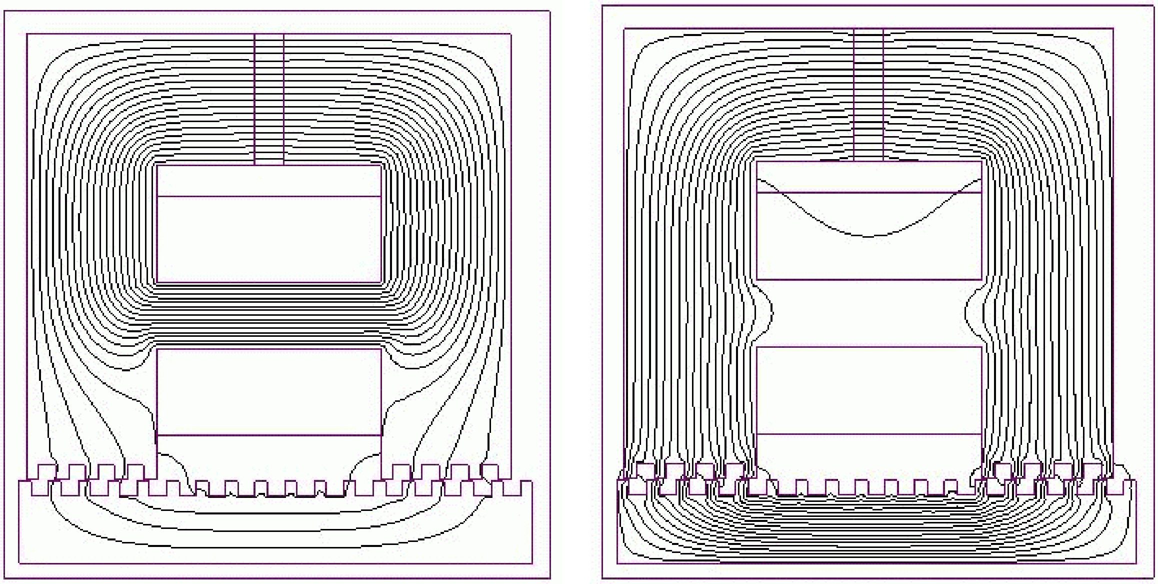


Fig. 3 The working principle of the motor

magnetic resistance. In this case there is neither braking, nor attractive force produced. If the coil is energised, Fig. 3b, the command flux produced by it, Φ_c, directs the flux of the permanent magnet to pass through the air-gap and to produce significant forces. Due to the tangential component of the generated force the mover moves one step to minimise the air-gap magnetic energy, Fig. 3c.

The tooth pitch and the number of phases (the number of modules) determine the motor's resolution. By advanced control strategies the resolution of positioning can be increased significantly.

The design of the modules and of the double salient permanent magnet linear motor built up using such of modules is discussed in [4]. The designed modules were checked by means of 2D numeric field analysis performed by MagNet 6.10 package [5]. In Fig. 4 the obtained flux plots are presented for an active, respectively passive module. As it can be seen, the obtained results are perfectly in accordance with the theoretical expectations. The surface motor's modules can be designed in a same manner.



a) passive module (unenergised command coil) b) active module (energised command coil)

Fig. 4 Flux plots of the designed module

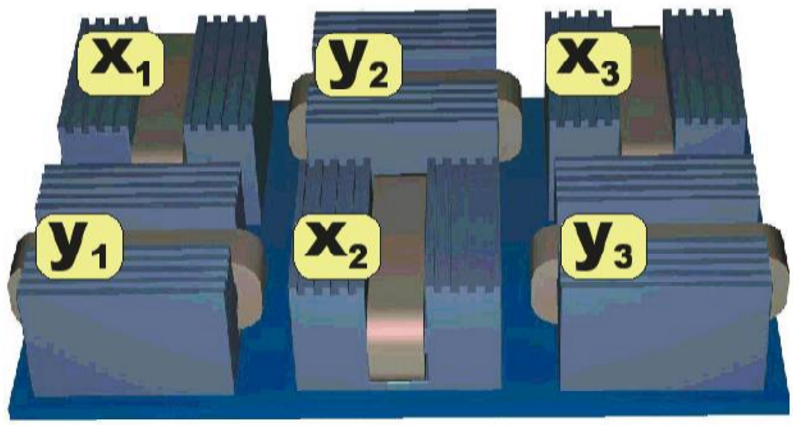


Fig. 5 The mover of the simplest three phase modular surface motor

Basically the mover of the proposed surface motor is composed of two double salient permanent magnet linear motors, each ensuring the movement in one of the two orthogonal directions (*x* and y). For easy control purposes a three-phase motor type was selected. This requires minimally six modules, three for each direction, Fig. 5. In this case the three modules that ensure the displacement in *x* direction (x_1, x_2 and x_3) are mounted ortogonally to those three for the y direction displacement. All the modules are fixed in a common housing. One set of three command coils drives the forcer in the x direction and the other in the y direction.

In order to reduce the skew of the mover due to undesired rotational moments a symmetrical structure must be selected. This has totally 36 modules placed perfectly symmetrical in the mover unit, Fig. 6. Each phase of the two motor parts (x_1, x_2 and x_3, respectively y_1, y_2 and y_3) is composed of six modules. The mover unit built up in this manner can develop high force (several hundreds of N) on both directions.

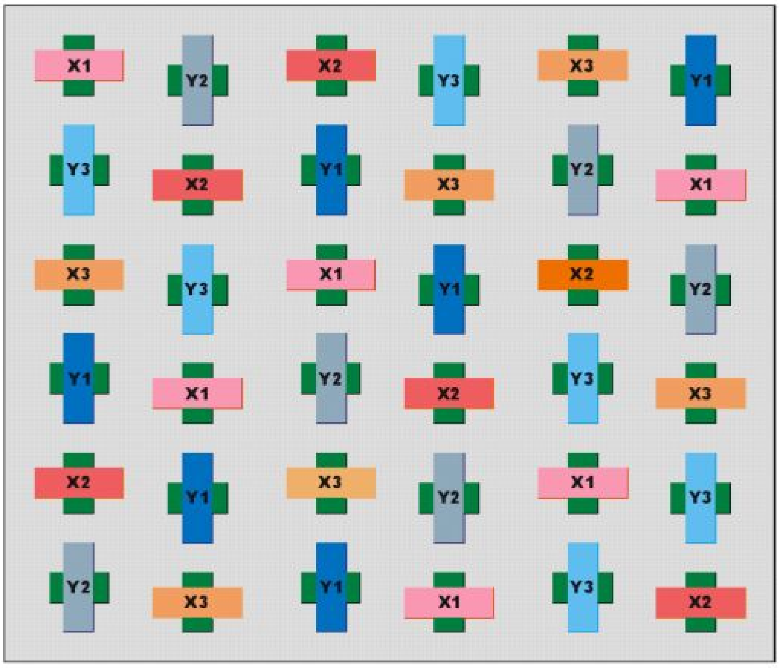


Fig. 6 The arrangement of the modules in the mover

Compressed air flows through the mover, creating a high stiffness air bearing. Thus a uniform, narrow air-gap can be maintained between the platen and the mover in the presence of great attraction forces. Due to the air bearing there is no friction between the armatures and no wear. The mover has a smooth travel and the motor's speed can be more precisely controlled. Great long-term system accuracy is assured and minimal maintenance is needed.

The modular surface motor has several advantages. By using the specified mover modules one of the main disadvantages of the classical hybrid linear motors (the presence of braking forces at each position) was eliminated [6]. The motor has the ability to perform simultaneous accurate orthogonal motion and to move anywhere on the platen surface. As the passive modules develop only small forces the total value of the undesirable normal force is significantly reduced.

Applying a sophisticated multi-level control system more than one mover can share simultaneously a common platen providing a compact multiaxis assembly with overlapping trajectories.

The modular surface motor, in a same manner as the other planar motors can be used in numerous industrial and laboratory applications. Its most typical utilisation is of pick and place type. For example the mover transports the sub-assembly from the feeder to a manipulator or overhead processor, it performs the assembly operations and the finished part is carried to a container. Such of systems are used for instance in electronic industry (for PCB throughhole and surface mount assembly, adhesive dispensing or probing for various types of testing requirements) or in pharmaceutical industry (for automated clinical lab sample handling or for multi-head pick and place workcells).

3. The modular surface motor control

Basically the modular surface motors are a sort of combination of two linear stepper motors. Hence these motors can be operated also in open-loop mode [7]. Nevertheless in this operating mode they can miss steps if large enough unanticipated external forces are acting. Controlled in this manner the motors have long settling times and low disturbance rejection. Also there is no possibility to provide controlled forces and high stiffness. They fall short of their potential capabilities due to possible loss of synchronism. All these limitations of open-loop operation restrict their usefulness in a wide range high precision application.

In order to enhance their overall performance (such as operation at great speed with high accuracy), as well as in improving the disturbance rejection properties of the motor it must be controlled in closed-loop mode. However its sophisticated, complex two axis movement requires a relatively complicated control systems, the supplementary cost of the closed-loop control system do not influence significantly the overall control costs.

Each motor part assuring the movement in one of the two transitional directions has to be controlled apart. A general planar motion system supervisor controller generates the imposed planar motion profile, that must be strictly executed. A *x* & *y* trajectory generator, shown in Fig. 7, serves the two displacement regulators with the imposed displacement signals.

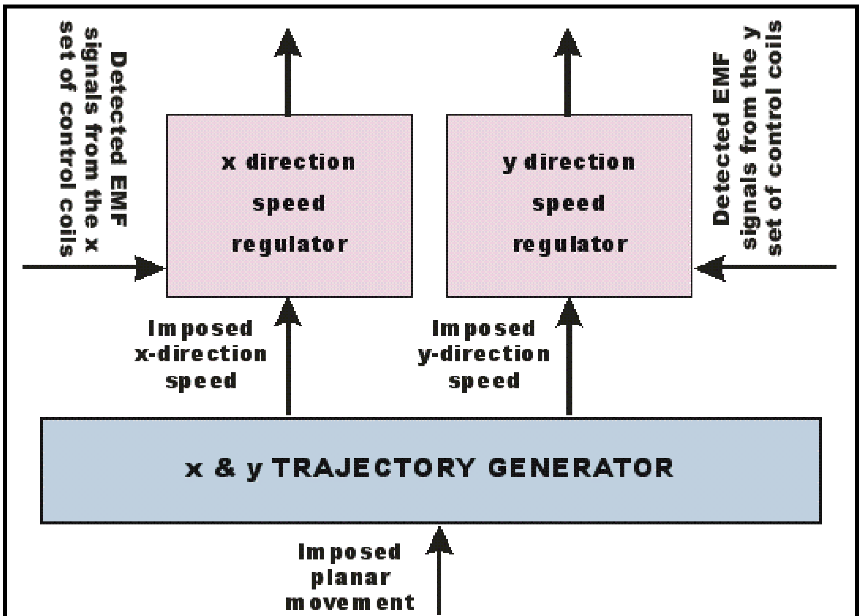


Fig. 7 The block scheme of the planar trajectory generator control unit

The two sets of control coils of the motor can be energised simply from two (one for each direction) low cost readily available modern standard three-phase compact converters. These are connected to the two microcontroller-based intelligent speed control units. For performing the so-called back EMF detection sensorless operation, the control system also has two special circuits to detect the back EMF generated in the un-energised command coils [8].

In order to achieve maximum average tangential force the command coils should always be energised at a precise moment, at the precisely computed optimal commutation angle, before an intermediate equilibrium position to be reached [8].

The control strategy has to be implemented using the adequate assembler language shared on the compact converter's built-in controller and on the speed/force controller unit.

4. The modular surface motor simulation

The proposed surface motor's dynamic behaviour is studied using a high performance simulation program written in MATLAB/SIMULINK [9]. This environment is one of the best suited for the dynamic simulation of electric machines.

The program is based on the simplified circuit-field mathematical model of the motor, presented in several previous papers [6, 10]. The magnetic field is computed analytically via the equivalent magnetic circuit of the motor. This method is not the most accurate one, but it requires very short computation time. This is a very important criterion for long time dynamic simulations where the field must be computed in many time steps.

The most significant characteristics of the simulated sample modular surface motor are given in Table I.

Table I. The sample motor's characteristics

Number of phases	3
Number of mover modules	36
Number of teeth per pole	5
Tooth width	0.84 mm
Slot width	1.16 mm
Tooth pitch	2 mm
Mover module width	83 mm
Step length	0.66 mm
Rated command current	0,75 A
Rated tangential force	300 N
Stator dimensions	5 × 5 m
Air-gap	0.1 mm
Permanent magnet type	VACOMAX148
Residual flux density	0.9 T
Coercive force	650 KA/m

The main window of the simulation program is given in Fig. 8. It is built up in a modular manner (using several sub-system type blocks). All the main components of the drive system can be clearly distinguished in the model. This way high transparency was assured for the users. Hence any changes

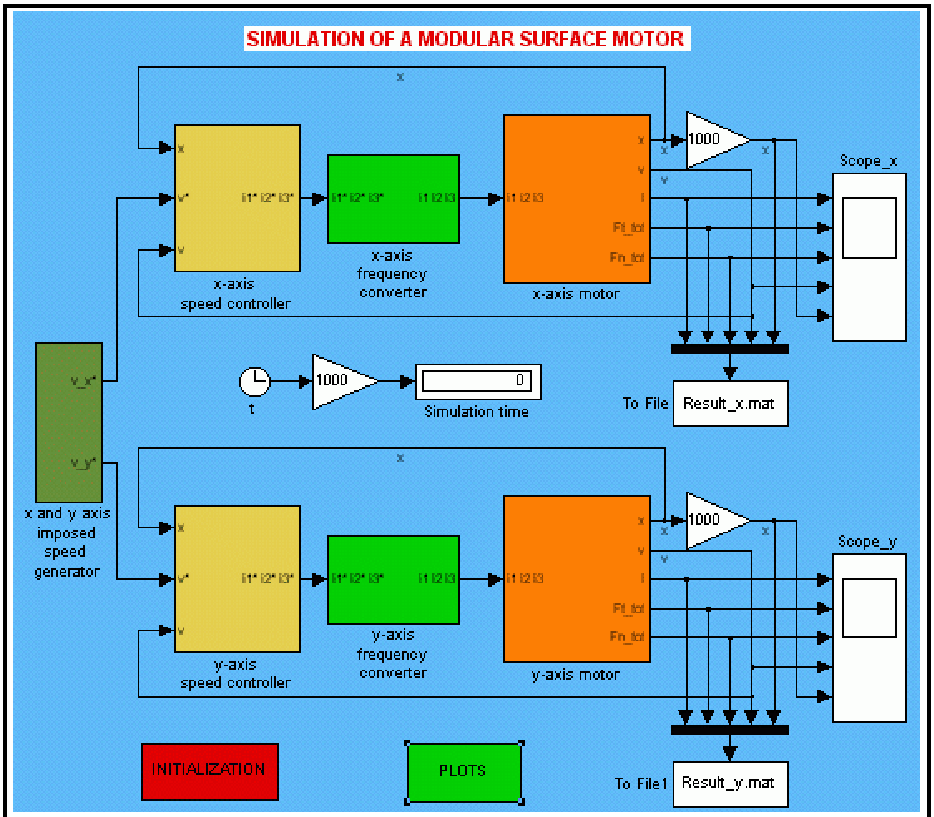


Fig. 8 The main window of the simulation program

in the program can be made quickly and easily. The program calls several MATLAB functions (e.g. for the field computation, for the command current sequence determination, etc.). All the benefits of MATLAB (easy to write program lines, advanced graphical visualisations) and of SIMULINK (simple modular model building, easy to use graphical interface, etc.) are fully exploited.

The simulated task was a typical pick and place one, Fig. 9. The mover starts without load from its initial position, *A*, and moves into position *B* where the load is put on the mover and it is displaced in *C*. Here the load is taken down and the motor returns to its initial position.

Three trapezoidal speed profiles must be generated for each sequence of the simulated task for both directions. The movements on the two directions must be perfectly co-ordinated. The motion time for both directions must be the same even if the two displacements are quite different.

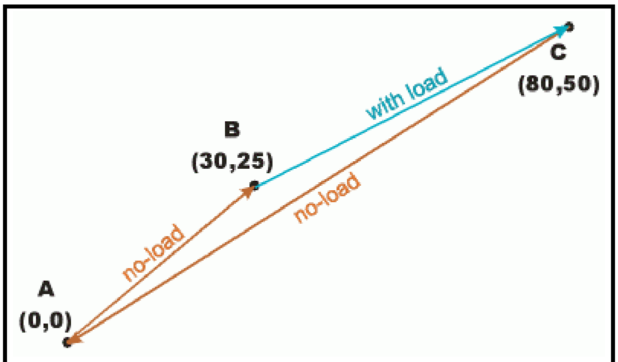


Fig. 9 The motion task to be simulated

The main results of the simulation for the part of the motor that ensures the displacement in *x* direction are given in Fig. 10. The command currents, the total tangential and normal forces, the speed and the displacement are plotted versus time.

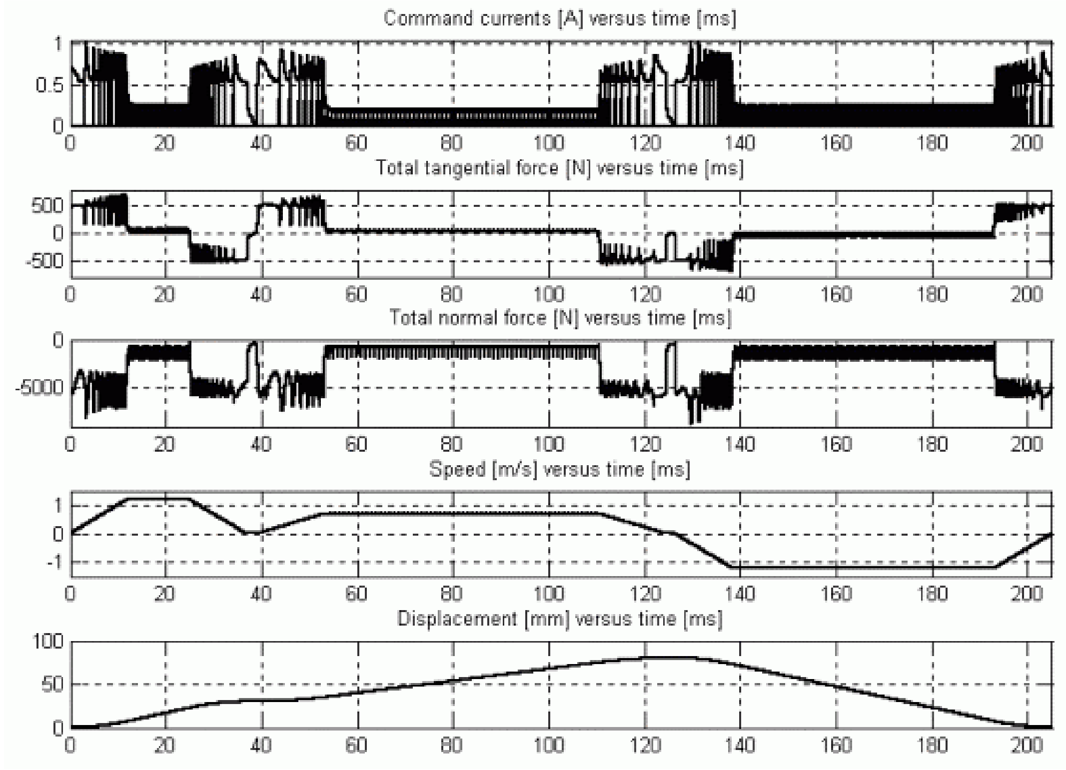


Fig. 10 The results of simulation for the x motor

As it can be clearly seen in the figure, the imposed motion task was precisely fulfilled. The speed followed up closely all the three imposed profiles. High tangential forces were needed for accelerating the mover. Due to the high force required for this stage of motion, the command currents also have significant values. After the mover was accelerated its imposed constant speed may be maintained by low tangential force. The results for the other part of the surface motor are similar to this one.

To emphasise the precision of the positioning capabilities of the surface motor in discussion the speed error (the difference between the imposed and actual speed) versus time is given in Fig. 11 for the motor that ensures the movement in *x* direction. As it can be seen, the error is greater during the hardest regimes of the movement, the acceleration and deceleration of the surface motor. The maximum value of the speed error is about 0,017 m/s, which means that actual motion is quite that designed to be followed up.

The movement of the motor in the plane is given in Fig. 12, where the *y* direction displacement is plotted versus that of *x* direction. As it can be seen the obtained movement is exactly that imposed given in Fig. 9. The displacement between two points follows up a quite straight line.

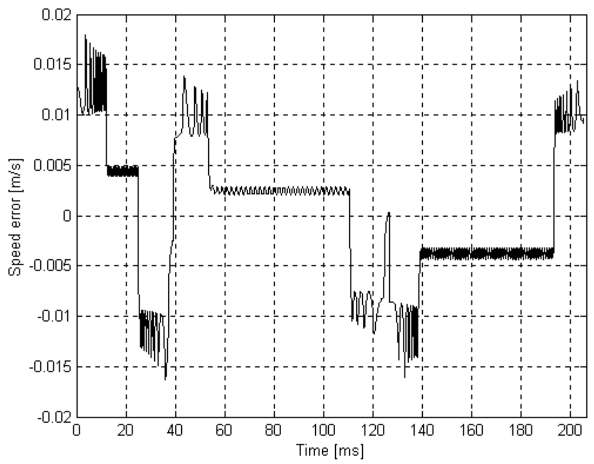


Fig. 11 The speed error of the *x* motor

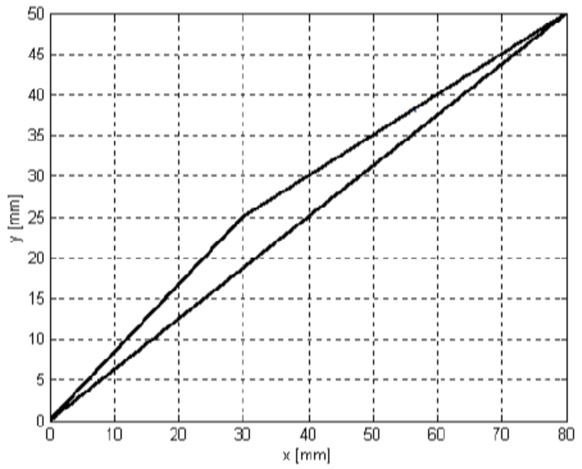


Fig. 12 The displacement in plane of the motor

5. Conclusions

A new direct driven permanent magnet variable reluctance surface motor was proposed. It is able of fast and accurate movement over a plane surface. Its mover is built up of high force modules. The surface motor can be assembled for different peak force and positioning accuracy in accordance with the user's needs. The tooth pitch and the number of phases determine the resolution of the motor.

The surface motor's sensorless closed-loop control system can guarantee the highest demands regarding the quality of the motion required in wide range of factory automation systems.

The dynamic behaviour of the motor was studied by means of simulation using MATLAB/SIMULINK. A coupled circuit-field mathematical model was applied. A simple pick & place type task was imposed for the sample surface motor. All the obtained results are in accordance with the theoretical expectations. The speed error is very low. It means that the motor follows very close the imposed speed profiles and so the obtained movement is also exactly that predicted.

Finally it can be stated out, that the proposed surface motor is a good choice for all the industrial applications were high forces and precise displacements in the plane are required.

6. Acknowledgements

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7. References

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