DEVELOPING CONTROL TECHNIQUES FOR TWO-COORDINATE PLANAR POSITIONING SYSTEMS BY MEANS OF COUPLED ADVANCED SIMULATION TOOLS

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Abstract: The modular doubly salient permanent magnet variable reluctance planar motor can be successfully used for precise positioning tasks in flexible manufacturing systems. To optimize its control system three simulation platforms were coupled: ANSYS®, CASPOC® and SIMULINK®. Using the coupled simulation an efficient control system was tested. It achieves high dynamic performance and low torque ripple due to the optimal switching of the power electronics devices. All the obtained results fit perfectly to a manufacturing system's requirements.

Keywords: doubly salient permanent magnet variable reluctance motors, planar motors, co-simulation, control strategy.

1. INTRODUCTION

Modern computer-driven, automated flexible manufacturing systems (FMS) must handle a wide array of manufacturing tasks with few configuration changes and little downtime [1]. Such ideal system uses reprogrammable processing, material-handling machinery, and computer coordination of cycles to enable the simultaneous production of different part types with zero on-line setup time and costs. No system has thus far lived up to this ideal completely. Still, new developments in hardware and software are bringing state-of-the-art systems closer. Hence any improvements done in these fields could be of real interest for the specialists involved in FMS.

The handling of the parts to be processed in advanced FMS can be improved by using two-coordinate planar positioning systems instead of frequently used conveyors [2]. These consist of a set of platens, which serve as factory floor. Above couriers (the moving armatures of the planar motor) float on air bearings, and move the subassemblies fixed on them very precisely to various types of manipulators and parts feeders, which can insert parts and perform all the processing operations (see Fig. 1) [3].

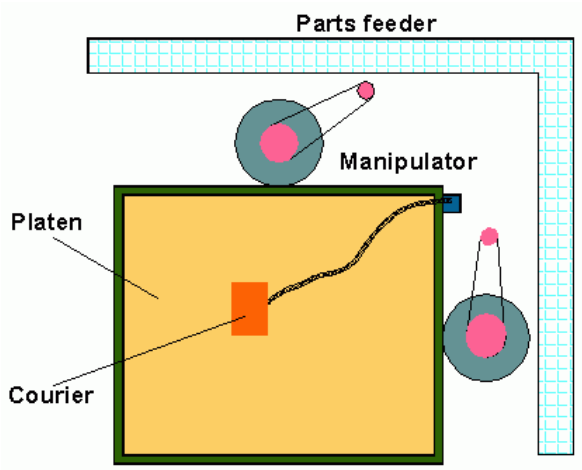


Figure 1. Advanced flexible manufacturing cell with a planar motor having a single courier

Each courier can be controlled separately by a real time operating system.

2. THE MODULAR DOUBLY SALIENT PERMANENT MAGNET VARIABLE RELUCTANCE PLANAR MOTOR

Several planar motors were cited in the literature in the last 40 years from the classical Sawyer surface motor [4, 5, 6] to the more advanced multi-coordinate planar motors [7, 8].

The modular planar motor developed at the Technical University of Cluj (Romania) was previously demonstrated to be a serious competitor in the field [9].

The planar motor consists of two main parts: the platen and the mover, as shown in Fig. 2. The load (for example the part to be processed in a FMS) can be fixed directly on the mover.

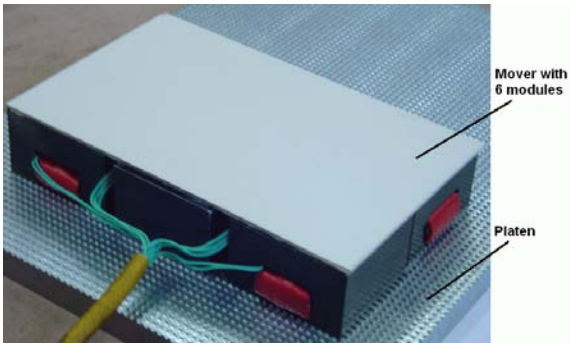


Figure 2. The modular planar motor in study

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 6 high force modules. 3-3 modules assure the displacement on *x*-, respectively *y*-axis, as shown in Fig. 2, Practically the motor is a combination of two independent modular double salient permanent magnet linear motors presented in detail in [10].

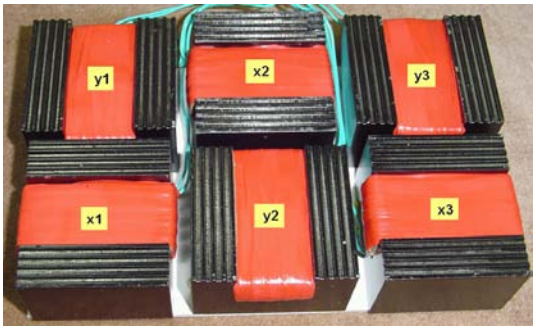


Figure 3. The placement of the modules in the mover

Each module shown in Fig. 4 has inset in the middle of the mover's core a rare earth permanent magnet magnetised on the direction of movement, two salient teethed poles and a command coil.

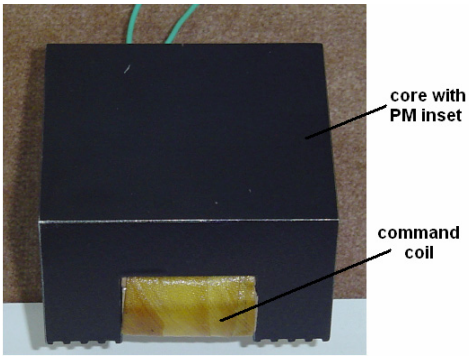
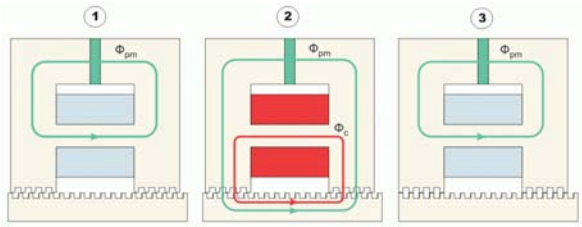


Figure 4. A module of the mover armature

The toothed structure is the same on the mover's poles and on the platen surface.

The working principle of the motor is quite simple. If the command coil of the mover 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 magnetic resistance. In this case there is no 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.



a) b) c)

Figure 5. The working principle of the modular motor

Feeding successively the command coils of the mover continuous step-type linear movement can be achieved. 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.

Hence most of the main drawbacks of the classical hybrid linear stepper motors and linear switched reluctance machines were solved: the high attracting forces between the armatures were diminished and the braking forces were totally eliminated, see [11].

3. THE CONTROL OF THE MODULAR PLANAR MOTOR

The control of the above presented motor is very simple. It is very similar to that of the hybrid stepper motor or of the switched reluctance machine [8, [11], [12]. The command coils of the motor have to be fed in the prescribed sequence by current pulses function of the mover's position and the direction of the displacement.

In was pointed out in [13] that in order to achieve maximum average tangential force and to reduce as much as possible the tangential force ripple the control system has to assure the commutation of the command coils at a specific

displacement, the optimal commutation point (x_{op}), before reaching the next intermediate equilibrium position of the motor. This optimum distance in the case of a three-phase modular motor is:

$$x_{op} = \frac{\tau}{4} \tag{1}$$

where τ is the tooth pitch.

Hence in order to enhance the overall performances of the modular planar motor (such as operation at great speed with high accuracy), as well as to improve 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 system, the supplementary cost of the closed-loop control system do not influence significantly the overall control costs.

A host computer co-ordinates the entire movement of the planar motor. Each motor part ssuring the movement in one of the two orthogonal directions has to be controlled apart.

The host computer calculates the point-to-point type imposed movement for the mover. Based on this the trajectory generator computes the two orthogonal imposed displacements (see the block diagram of the control system in Fig. 6).

Two control loops are in the control scheme for each motor part: an outer displacement control loop and an internal one controlling the speed of the modular planar motor.

The most sensitive part of the controller is the imposed current sequence generator. This generates the imposed current waveforms for a set of modules of the motor. The input signals in this unit are the magnitude of the command current (i^*) and the actual displacement of the motor (x) [13].

Two hysteresis current controller driven power converters are feeding the command coils of the motor.

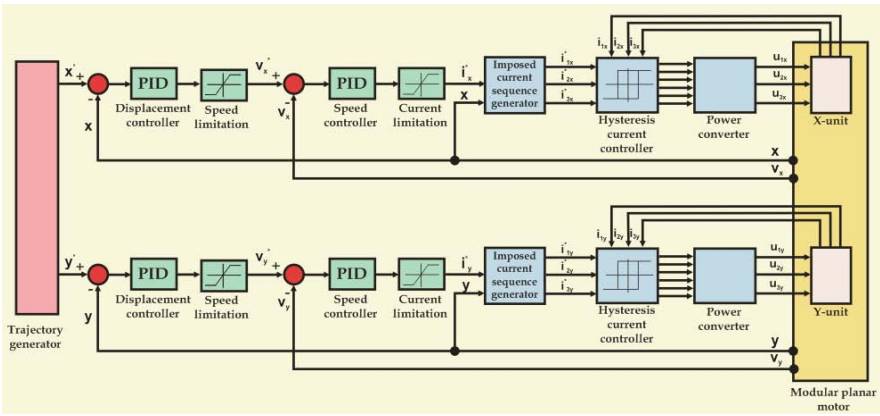


Figure 6. The block scheme of the control unit

4. MODELLING THE MODULAR PLANAR MOTOR

System modelling and simulation are very useful tools in testing the control techniques to be used in an advanced drive system. As the two-coordinate planar positioning systems are very complex and heterogeneous, the simulation of their dynamic behaviour using only a single simulation program should require considerable modelling effort and time [14].

The commercial available simulation platforms are focused mostly on a single engineering discipline (field computation, control, mechanical engineering, power electronics, etc.). Therefore, to provide the multidisciplinary simulation of such a positioning system unified approaches to system simulation must be developed. Hence three simulation platforms (all leaders in their own field) were used together in order to perform the system simulation.

ANSYS 10.0® was used for the numerical computation of the magnetic field within the planar motor and CASPOC 2005® for the simulation of the power electronics. The entire simulation was supervised by SIMULINK®.

In this stage of the research, when several control schemes were tested, the numeric field computation program was not coupled directly to the other two simulation platforms in order to reduce simulation times. Very numerous time steps had to be considered, hence the hysteresis controller working at 40 kHz required time steps of 10 μs and the simulated periods were of seconds.

Hence only the static characteristics of the modular planar motor (the values of the tangential and normal forces for certain currents and displacements) were previously computed using ANSYS 10.0®. These characteristics were integrated in the simulation program as look-up tables. The static characteristics were computed using the 3D model of a single mover shown in Fig. 7.

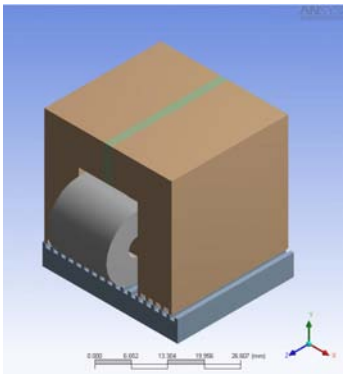


Figure 7. The ANSYS® model of a mover

The obtained static characteristics of the tangential force (the force vs. the displacement, the command current being the parameter) are given in Fig. 8.

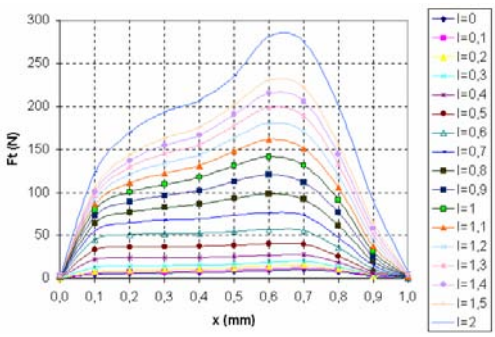


Figure 8. The static characteristic of the tangential force

The power electronics part of the control system was modelled in CASPOC 2005®, a comprehensive simulation and animation program for power electronics and electrical drives [15]. CASPOC 2005® is universal in modelling and viewing simulation results, hence it is very powerful for going in depth in modelling and simulation [16].

In the CASPOC project shown in Fig. 9 the two hysteresis current controllers and the two inverters can be clearly distinguished. Six inputs and six outputs are included in the scheme for the communication with the SIMULINK® program during the co-simulation [17].

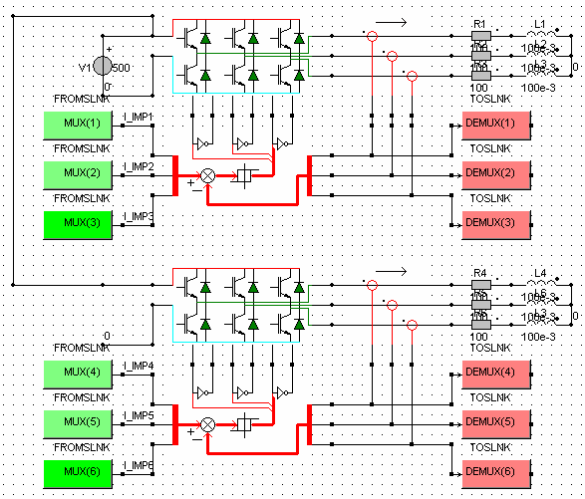


Figure 9. The CASPOC model of the power converter

The main simulation program is built up in SIMULINK®, a well-known and intensely used platform for simulating different dynamic systems. The entire simulation task is driven from this program.

The entire program has two identical parts, like that shown in Fig. 10, each simulating independently the two branches of the control unit given in Fig. 6.

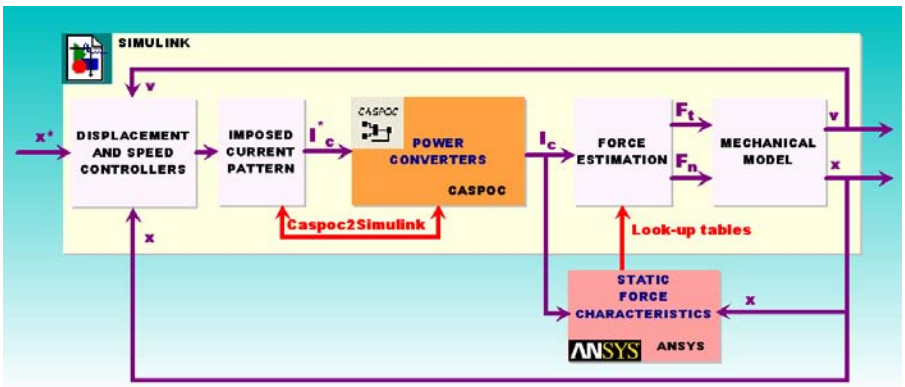


Figure 10. The block diagram of the coupled simulation program

As it can be seen the control part of the drive system is modelled completely in SIMULINK®. Thru the **Caspoc2Simulink link** the programme communicates with the attached CASPOC program in which the actual currents of the six command coils of the planar motor are computed. The velocity and displacement of the motor are computed using the forces taken from the above mentioned look-up tables.

The plotting of the results is commanded also from the SIMULINK® platform, because this way the powerful graphical visualisations (plots, diagrams, etc.) of MATLAB® can be totally exploited.

Using the coupled simulation programs several control systems and strategies were simulated for the planar motor in discussion. Next only results of a single simulated task will be presented.

5. THE SIMULATION OF A PRECISE POSITIONING TASK

A work-cell of a flexible manufacturing system in which the modular planar motor in discussion could be integrated is shown in Fig. 11. The platen, on which the mover of the surface motor is carrying the part in work, is surrounded by four universal manipulators, which processes the part [18].

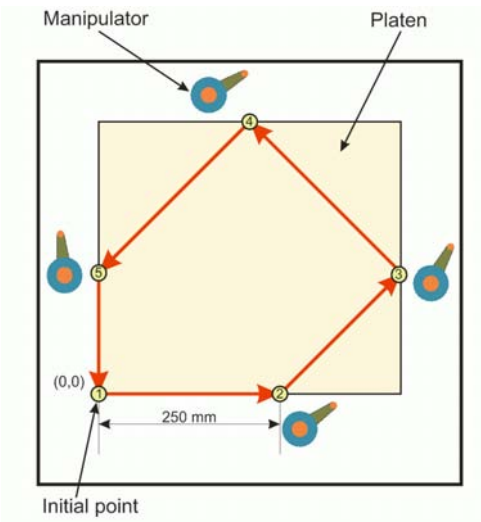


Figure 11. A work-cell in which the surface motor in study is applied

The mover has to start from the initial point *1*, and to reach sequentially the points *2*, *3*, *4* and *5*, and to arrive back to *1*. At each point the mover has to wait still the processing of the carried part is finished.

The main window of the SIMULINK program is given in Fig 12.

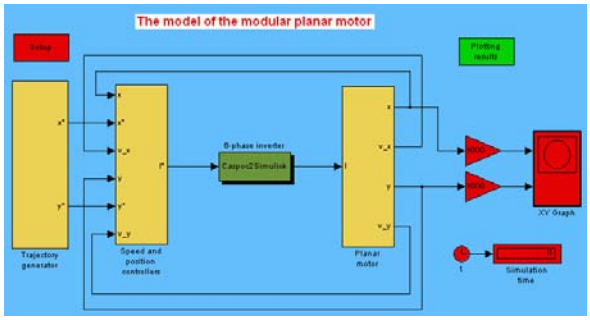


Figure 12. The main window of the simulation program

The sub-system of a mover module having the two look-up tables is shown in Fig. 13.

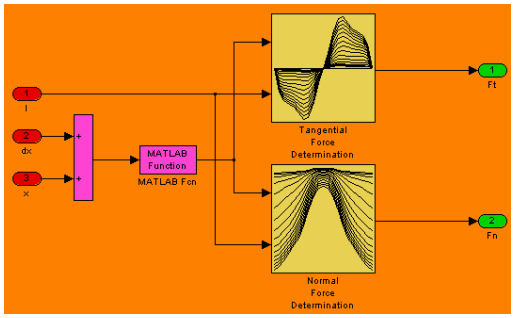


Figure 13. The model of a mover module

Next the results of simulation are shown. First the plot of the obtained planar movement is given in Fig. 14. As it can be seen the motor strictly followed the imposed trajectory.

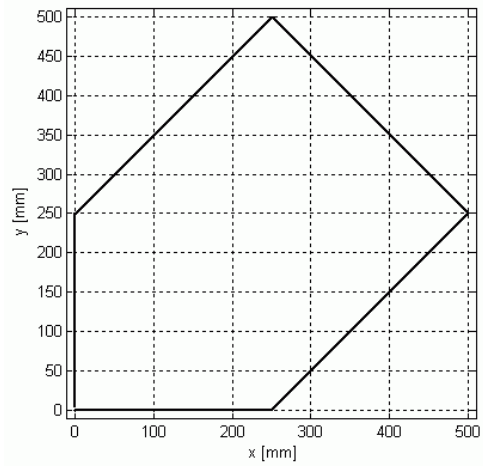


Figure 14. The simulated planar movement

The corresponding displacements on the two orthogonal axes are shown in Fig. 15. Again it is emphasised the precise movement of the modular planar motor in discussion.

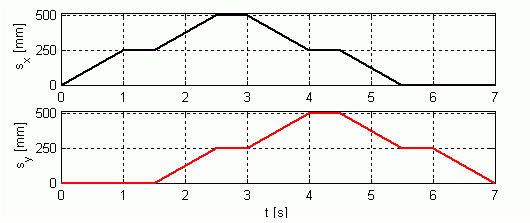


Figure 15. The displacements upon the two axis

In Fig. 16 the speeds of the two moving motor parts are given. It can be observed how the speed controllers impose the maximum speed of 0.25 m/s.

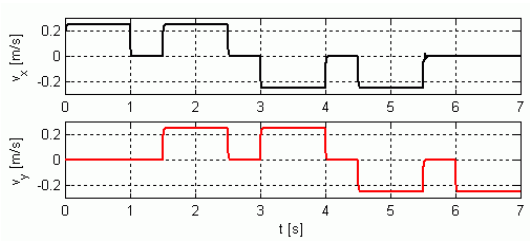
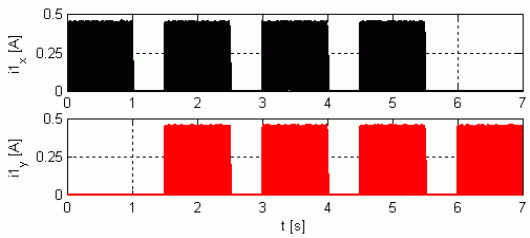
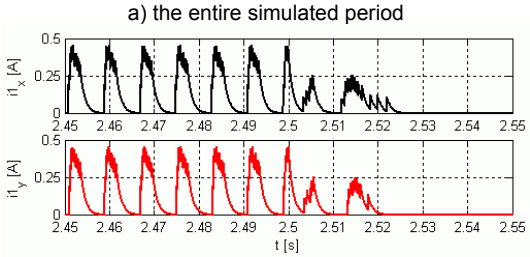


Figure 16. The speeds of the two motor parts

The current waveforms during the movement of the motor are given in Fig. 17.



a) the entire simulated period



b) detailed zoom for a period of 10 ms

Figure 17. The command current's plots

In the zoomed view of the current waveforms it can be observed how accurate the power converter was simulated using CASPOC.

6. CONCLUSIONS

All the obtained results are in good accordance with the theoretical expectations and also with the results of analytical computations. It emphasizes the advantages of the proposed coupled simulation platform, which may save a lot of prototyping time and money.

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