On the Usefulness of Simulation in Designing a Permanent Magnet Modular Surface Motor for Advanced Mechatronic Systems

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Abstract **– The design of advanced mechatronic systems involves the integrated design of the mechanical system, of the actuator assuring the precise movements inside the system and of its control unit. In order to make proper choices early in the design stage, innovative tools are required to model and simulate both the entire physical system and each subsystem which are composing the mechatronic device. The usefulness of simulation techniques will be demonstrated through the design and building-up of a permanent magnet modular surface motor, which can assure very precise planar movement in the framework of any mechatronic system.**

I INTRODUCTION

Mechatronics is a rapidly evolving field of engineering that can roughly be defined as the design of complex products that are a synergistic integration of mechanical, electrical and electronic components. The design of the motor/actuator which assures the required precise movements, and of its control systems has a very big influence on the design of the entire advanced mechatronic system. During the design of a mechatronic system it is important that changes in the mechanical construction, or in the actuator and its controller to be evaluated simultaneously.

Although an actuator with a proper controller can enable building a cheaper mechanical construction, a badly designed mechanical system will never be able to give a good performance by adding a sophisticated controller. Therefore, it is important that during an early stage of the design a proper choice could be made with respect to the mechanical properties needed in order to achieve a good performance of the controlled system.

In order to make these carefully selections already in the design stage innovative tools are required, that support modelling and simulation both of the entire physical system and of each subsystem which are composing the mechatronic device [1].

A part of these software tools are already relatively long time ago widely spread (for example MATLAB/Simulink, Spice, etc.). Others, as the three-dimensional (3D) finite elements method (FEM) based magnetic field computation programs, become to be widely used by the designers only in the last years, due to the achievements made in computer techniques (speed of the computers, high capacity storage devices, etc).

In this paper the 3D FEM based simulation of a novel permanent magnet modular surface motor will be presented. The obtained result will be compared with those obtained via laboratory measurements.

II THE SURFACE MOTORS

Surface motors, also named planar motors, x-y motors or two-dimensional linear motors, can be used in numerous mechatronic systems that require movement on a plane in two directions (*x-y* axes), e.g. semiconductor waffles, printed circuits movers, pieces machined by numerically controlled (NC) machines, flexible manufacturing systems, etc. The use of adequate electronic control systems allows motion of surface motors with accurate position detection and rapid response without position deviation [2].

In the early stage of designing surface motors almost all the research centres were involved in the development of planar motors usually based on the now classical Sawyer motor topology [3].

The novel surface motors and actuators as compared with the conventional two-dimensional (2D) positioning devices with cumbersome stacked arrangements possess the advantages such as direct driving, low friction, no backlash, high accuracy, etc.

Until now, many types of surface motors have been cited in the literature. The industry's interest for these special electrical machines is continuously increasing. Hence it has been attracting more and more attention both in the academic field and of the engineers.

However, according to their principles, most of the surface motors can be classified into three types:

- variable reluctance planar motor [4]
- induction planar motor [5]
- synchronous permanent magnet planar motor [6].

The proposed permanent magnet modular surface motor combines the advantages of variable reluctance planar motors with those of the synchronous permanent magnet surface motors (simple construction, high power conversion ratio, high accuracy, etc.) [7].

III THE MODULAR SURFACE MOTOR

The basic structure of the permanent magnet modular surface motor was designed on the basis of the three-phase modular double salient linear motor [8].

The permanent magnet modular surface motor, shown in Fig. 1, is simple. It consists of two main parts: the platen and the mover (forcer). The load is fixed directly on 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. Hence the mover has a smooth travel and the motor's speed can be more precisely controlled.

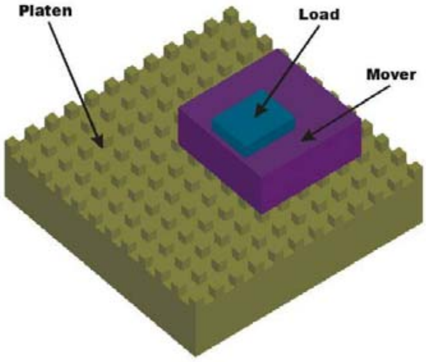


Figure 1
The permanent magnet modular surface motor

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 as great travel area as it is required by the mechatronic system in which it is used.

The mover, the active part of the motor, is built up of high force modules, as one shown in Fig. 2, just like the modular double salient permanent magnet linear motors presented in detail in [9].

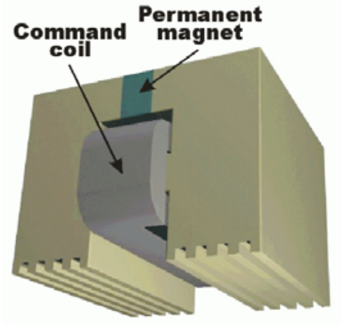


Figure 2
The mover module

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 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 generated tangential force the mover shifts a step to minimise the air-gap magnetic energy, Fig. 3c [10].

Basically the mover of the permanent magnet modular 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 variant of the motor was selected. This requires minimally six modules, three for each direction, Fig. 4.

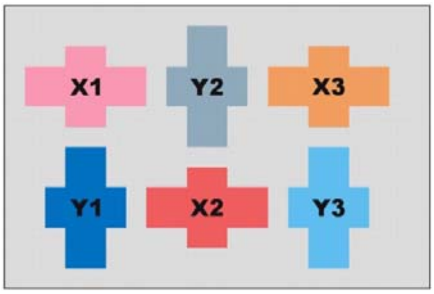


Figure 4
The arrangement of the modules within the mover

In this case the three modules that ensure the displacement in x direction (x_1, x_2 and x_3) are mounted orthogonally to those three for the y direction displacement. All the modules are fixed in a common housing (see Fig 5).

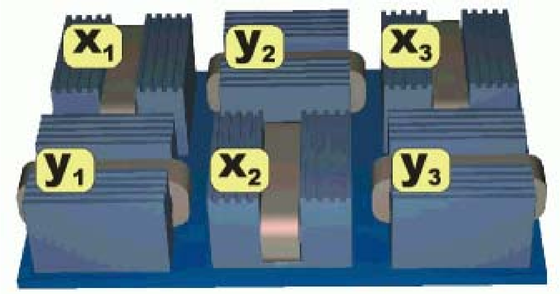
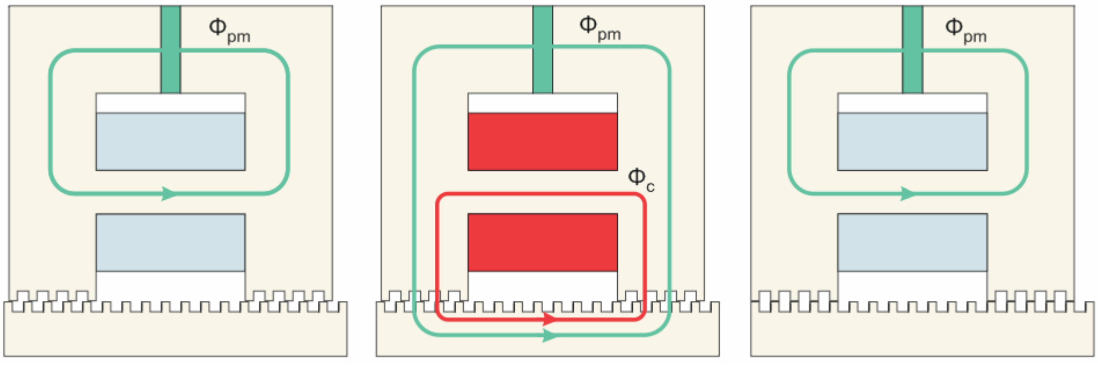


Figure 5
The mover of the modular planar motor

The surface motor can be assembled for different peak forces and positioning accuracy in accordance with the



a) b) c)

Figure 3
The working principle of the permanent magnet modular surface motor

user's needs. The tooth pitch and the number of phases determine the resolution of the motor. By advanced control strategies the accuracy of positioning can be increased significantly.

The modular surface motor has several advantages. By using the above presented modules one of the main disadvantages of the classical hybrid linear motors (the presence of braking forces at each position) was eliminated.

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 [11].

Applying an adequate multi-level control system more than one mover can share simultaneously a common platen providing a compact multi-axis mechatronic system with overlapping trajectories.

IV 3D FEM COMPUTATIONS

The designed structure of the proposed permanent magnet modular surface motor was analyzed by means of three-dimensional (3D) finite elements method based numerical magnetic field computation.

As in any time moment for a single axis movement only one module is active in the machine it was enough to analyze only a single module (one assuring the x-axis movement) and the portion of the stator under it, as shown in Fig. 6.

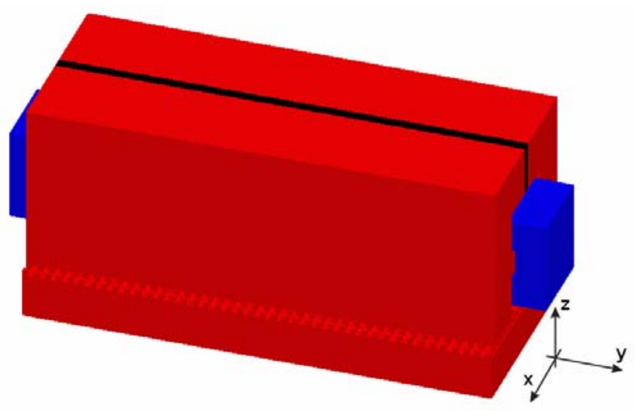


Figure 6
The analyzed motor structure

The frontal and lateral views of the analyzed structure are given in Fig. 7 for better understanding of the problem to be solved.

Figure 7
Two views of the analyzed surface motor structure

The three-dimensional mesh generated over the analyzed structure is given in Fig. 8.

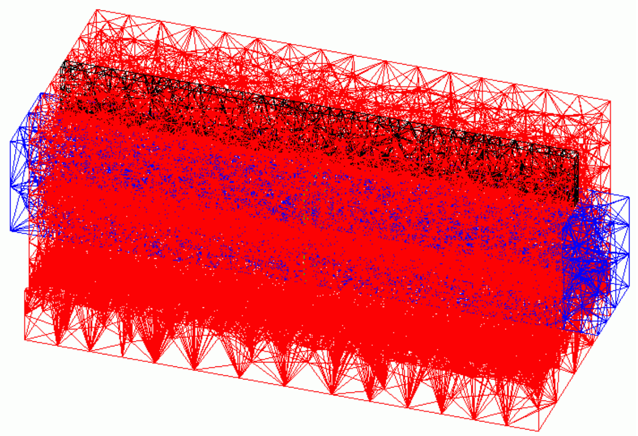
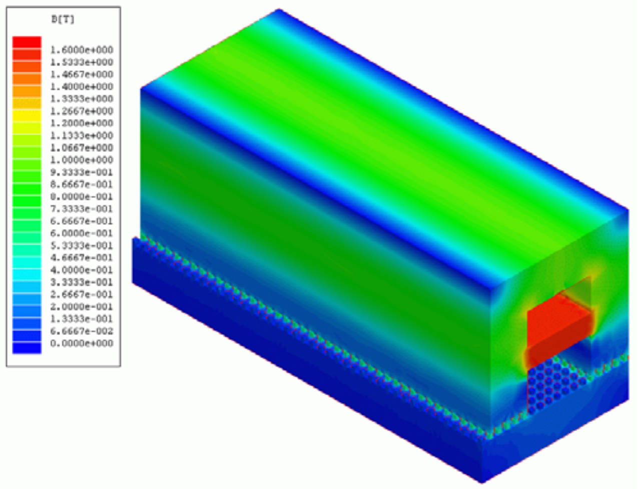
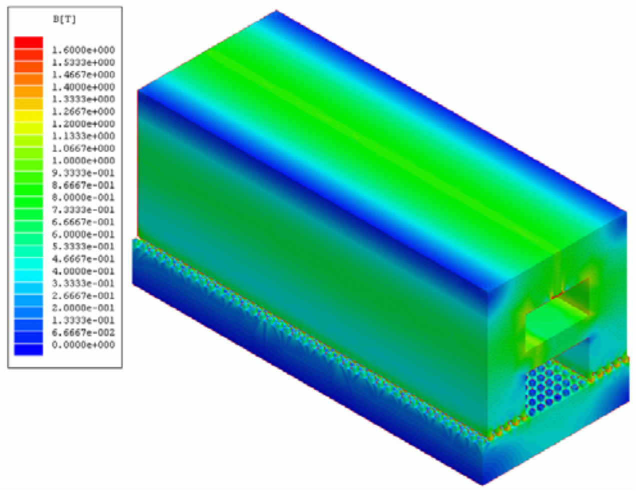


Figure 8
The 3D mesh generated

Next results of the 3D field computation performed for the presented motor structure are given. First see the field density distribution in the two basic cases in study: when the teeth on the stator and on the mover are aligned on the x-direction (relative positions of the mover are $x = y = 0$), and the command coil is not fed (Fig. 9a), respectively when the mover is at a third of the teeth pitch relatively to the stator ($x = 0.66$ mm, $y = 0$) and its command coil is energized by $I_c = 0.7$ A (Fig. 9b).



a) passive module (command coil un-energized)



b) active module (command coil energized)

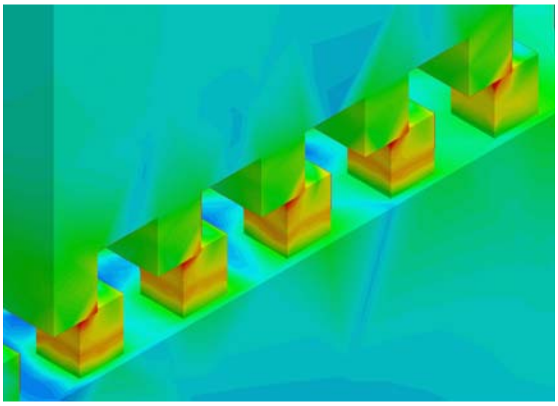
Figure 9
The flux density distribution obtained via 3D FEM analysis

As it can be seen the working principle of the modular surface motor was proven by means of simulation: when the command coil is not energized almost no magnetic flux is passing through the air-gap. Hence only very small forces are generated: $F_t = 0.018$ N and $F_n = 12.24$ N, where F_t, respectively F_n are the tangential (x-axis) and normal components of the produced force.

In the other case, when the command coil is energized, the magnetic flux is of the permanent magnet is forced to pass through the air-gap, therefore high forces are generated ($F_t = 76.59$ N, $F_n = 371.86$ N). Unfortunately not only the useful tangential force is greater in this case, but also the normal one which is attracting the two armatures.

Next for a better view a zoom on the air-gap area of the flux density distribution maps shown in Fig. 9 are given (see Fig. 10).

a) passive module



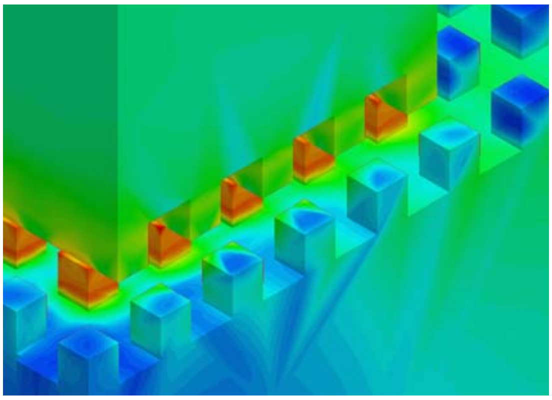
b) active module

Figure 10
Zoomed view on the flux density shaded plots given in Fig. 9

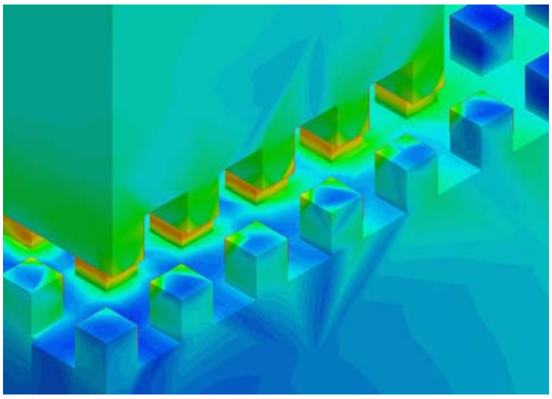
In this figures it can be observed more clearly that the flux densities in the teeth are very small in the case of an inactive module, and have much more greater values when the module's coil is energized.

It should be of real interest what should happen if the module in study, which assures the displacement in the x-direction, is moved by other modules in the y-direction. Hence the module was shifted by 0.66 mm on the y-axis and the simulations were repeated.

The active module was placed in two relative positions: at $x = 0$ mm and $y = 0.66$ mm, respectively at $x = 0.66$ mm and $y = 0.66$ mm. Zoomed views on the flux density distributions in these two cases are given in Fig. 11.



a) the active module placed at $x = 0$ mm and $y = 0.66$ mm



b) the active module placed at $x = 0.66$ mm and $y = 0.66$ mm

Figure 11
Zoomed view on the flux density distribution

As it can be seen from the figures the magnetic flux generated by the permanent magnet placed in the mover passes through the air-gap mainly on the x-direction. This phenomenon is also emphasised by the values of the computed force components: $F_t = 0.041$ N, $F_n = 12.64$ N, respectively $F_t = 77.02$ N, $F_n = 373.17$ N. In both cases the developed force has only minor components on the y-axis.

All these means that the force development capability of the mover acting on the x-axis is not influenced by its position on the y-axis. This is very important from the point of view of the control strategy.

Performing several field computations varying the position of the module, respectively its command current the static characteristics of the total tangential force could be plotted, as it is shown in Fig. 12.

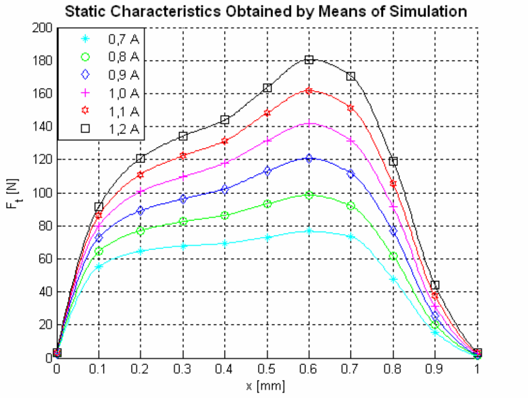


Figure 12
The static characteristics obtained via simulations

V THE BUILT UP SURFACE MOTOR

A laboratory model of the designed permanent magnet modular surface motor was built up at the Electrical Machines Lab of the Technical University of Cluj.

Here only some pictures of this laboratory model will be presented.

The mover module is given in Fig. 13.

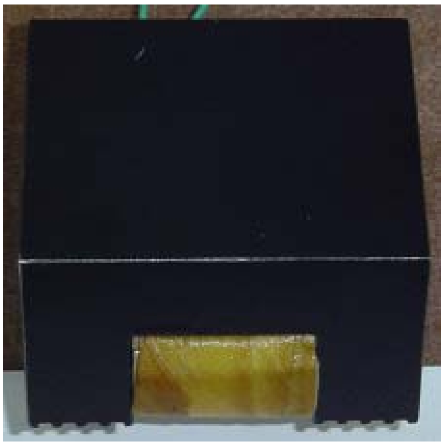


Figure 13
The built-up mover module

The assembled mover's photo is presented in Fig. 14.

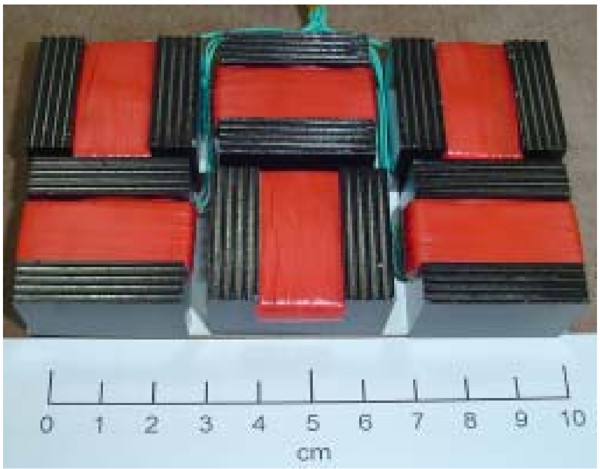


Figure 14
The mover of the surface motor

The mover of the permanent magnet modular surface motor placed over the stator is shown in Fig. 15.

Figure 15
The laboratory model of the modular surface motor

VI LABORATORY TESTS

In order to validate the results obtained via simulations a laboratory test rig was built up. Its block scheme is given in Fig. 16.

The surface motor to be tested was fixed on a linear bearing system, which allows only movements in a single direction. In order to determine the motor's characteristics upon different movement directions several sets of measurements were performed by changing the placement of the stator relatively to the mover fixed on the guiding system.

In all the cases the position of the mover was adjusted by a precise positioning device and the tangential force developed by the machine was measured using a load cell. The measurements were performed at different control currents. Hence the static characteristics of the total tangential force could be plotted (find in Fig. 17 the characteristics obtained for an *x*-axis movement).

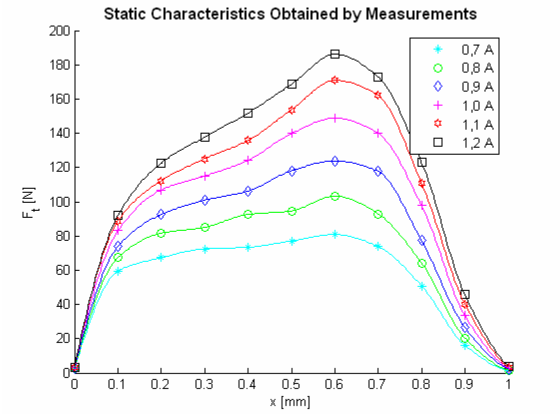


Figure 17
The static characteristics obtained via measurements

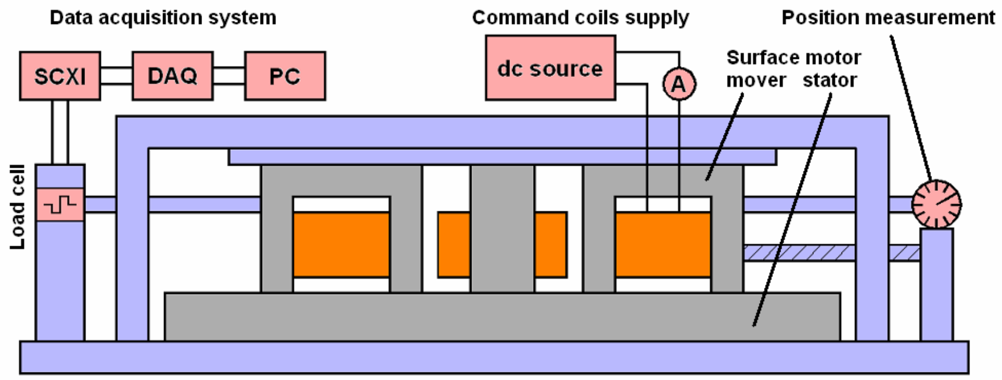


Figure 16
The laboratory setup

VII CONCLUSIONS

A direct driven permanent magnet variable reluctance modular surface motor was proposed. It is able of fast and accurate movements over a plane surface. An adequate control system can guarantee the highest demands regarding the quality of the motion required in advanced mechatronic systems.

At the end of the design stage and before building up the motor its performances were evaluated by means of simulation.

The now most precise finite elements method based numerical field computation was applied. As the surface motor in study has a real three-dimensional structure the 3D FEM method had to be used, although it requires much more computation times as its two-dimensional variant. By this way the flux densities were studied in the different regions of the motor and its forces were computed.

As it could be seen all the obtained results were in accordance with the theoretical expectations and with the designed values. This way the design procedure was proved to be correct. The results of the 3D FEM analysis were also used to create a model of the motor in SIMULINK. This was used in studying the dynamic behaviour of the designed modular surface motor [12].

In the next step a laboratory model of the designed surface motor was built up and tested. During the measurements the same static characteristics were plotted as in the case of the simulations.

The static characteristics obtained by means of 3D FEM numeric field computations, respectively by laboratory tests were put side by side. Comparing the static characteristics given in Figs. 12 and 17 it can be stated out, that the plots obtained by the two methods are very close. This is also emphasized in Fig. 18, where the static characteristics of the total tangential forces obtained upon the two ways are plotted. The tangential forces obtained via simulations are a little bit smaller, because the accuracy of the computations was limited by the maximum number of finite elements permitted by the applied FEM program.

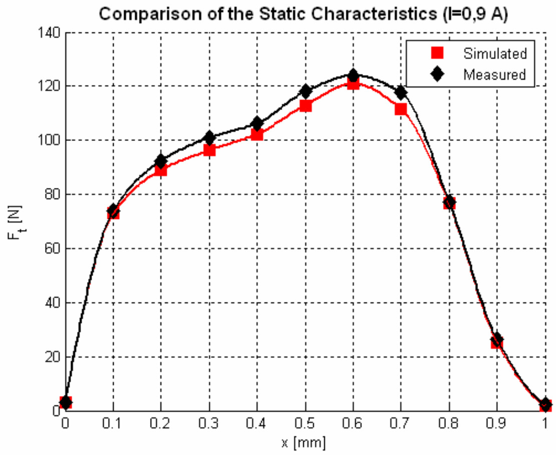


Figure 18
The comparison of the static characteristics obtained via simulation and measurement

Hence the designed surface motor fits perfectly into the requirements given at the beginning of the design procedure.

The simulation method applied proved to be very useful in the development stage, because several variants of the surface motor could be checked without building up its prototypes.

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

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