Experimental Verification of Drive with Segment Slotless Synchronous Motor with Permanent Magnet

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Abstract- **A series of measurements like measurement of moment characteristics, moment of inertia and loading characteristics and also measurements of servo drive performances are presented in this paper. The first part of measurement should to confirm agreement with calculated electrical parameters. Second part of measurements should to confirm drive performance (quality) such as accuracy, repeatability, stabilization test and etc. A comparison between measurement results and final specified parameters are given in the last.**

I. INTRODUCTION

Initially, linear motors have been particularly dedicated to transportation systems. Nowadays, linear motors are meant to replace a system using a rotating motor and a transmission to realize a linear movement. With linear motors the performances increase considerably since the mechanical limitations are removed. This leads to a better precision, a higher acceleration and a higher speed of the moving part. There are three main types of linear motors: the induction linear motor, the synchronous linear motor with permanent magnets (PM) and linear brushless DC motors. All these motors can be designed with a longitudinal or a transverse flux linkage. Motors with PM can be also designed with single side or double side magnetic way and with iron core or ironless. Ironless coil design eliminates cogging and makes them the optimal choice for extremely consistent velocity control in scanning-type applications and allows them to achieve the highest levels of positioning accuracy, repeatability and resolution.

In many servo drives there are used classical permanent magnets synchronous motors (PMSM), which have a nominal mechanical torque from 1 to 5 Nm. In application when higher torque is necessary with same PMSM motor, there are used a coupled gearbox with this one. Ratios of these gearboxes are usually from 75 to 125. The elements, transforming the rotary motion to the linear, normally introduce additional energy losses, elasticity and backlash in the drive. All this reasons are increasing usage of (rotation) linear motors instead of rotary motors in drives performing linear (rotation) motion. There are possibilities to use a Direct Drive motors and Slotless brushless ring motors with high torque output and zero cogging or ironless rotation–linear synchronous motor with permanents magnets as substitutions for classical PMSM with coupled gearbox. Direct drives with linear motors are increasingly used in industrial applications such as high precision industrial servo drives although these solutions need often more investment costs.

A series of segment slotless PMSM were developed by EVPU Company as substitutions for PMSM with gearbox solution. There were realized a series of measurements on these developed PMSM. Results from these measurements should to confirm matches with calculated electrical parameters of developed permanent magnet linear synchronous motor with ironless moving part at rotation construction labeled as segment slotless PMSM in the beginning.

Results from these measurements also should to confirm a quality of developed drive with segment slotless PMSM (such as accuracy, repeatability, stabilization test, unstableness running – in this type of measurement was servo drive in speed mode). Measurements were realized on two types of developed segment slotless PMSM which are implemented in biaxial manipulator. There was implemented field oriented control (cascade vector control with feed forward compensation of position) on this drive for these measurements (experimental verification).

II. ELECTRICAL PERFORMANCES OF PERMANENT MAGNET LINEAR SYNCHRONOUS MOTOR

A. *Design structure of segment slotless PMSM*

Segment slotless PMSM was designed as cylindrical shape with two main parts, it means, that winding with supporter (primary part) of machine is without iron and it can be seen on the Fig.1. The secondary part consists of double sided back iron yoke and permanent magnets.

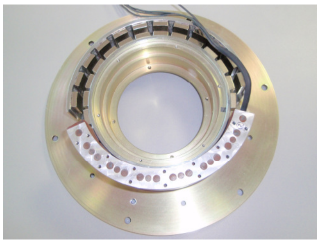

Fig. 1: Cylindrical shape design

B. *Electrical Parameters of Equivalent Circuit PMSM*

It was designed [1,3] two type of segment slotless PMSM. The motors are designed for biaxial manipulator RR (rotation, rotation) in application for high precision positioning system.

The final version of segment slotless PMSM is presented on figure 2. 3D model of biaxial manipulator are shown on figure 3. Motors are implemented as drive for two axis position motion (type MSLr 288.1 – 34 is implemented in axis R1 of manipulator, type MSLr 198.0 – 13 is implemented in axis R2 of manipulator).

Fig. 2. Permanent magnet linear synchronous motor for precision position's manipulator

Electrical parameters of equivalent circuit PMSM and other important parameters of drive for application with positioning system are presented in table 1. Motor inductance was investigated by measurement method of self and mutual inductance curve.

TABLE I
SEGMENT SLOTLESS PMSM SERIES ELECTRICAL PARAMETERS

Segment Slotless PMSM with inner rotor		
Type	**MSLr 288.1-34**	**MSLr 198.0-13**
Rating	34 Nm 15.5 A	13 Nm 8 A
Number of pole pair	18	12
Resistance of armature winding (Ω)	0.216	0.408
Inductance (μH) L L_σ	120 28	249 56
Linkage magnetic flux of PM (Wb)	$73 \cdot 10^{-3}$	$80.6 \cdot 10^{-3}$
Moment of inertia ($g.m^2$)	112.3	47.8
Motor main Dimension(mm)	133(h) x ϕ416	141(h) x ϕ 330
Frequency (Hz)	0 ÷ 22,5	0 ÷ 20
Rotary position sensor	RESM 206+SR015	RESM 103+SR015
Type of inverter	SN100 – 1.05	
Maximum rating of inverter	2 kVA	
Switching frequency	15 kHz	
Control	FOC – cascade position system	

Investigation for moment of inertia was measured by after running curve.

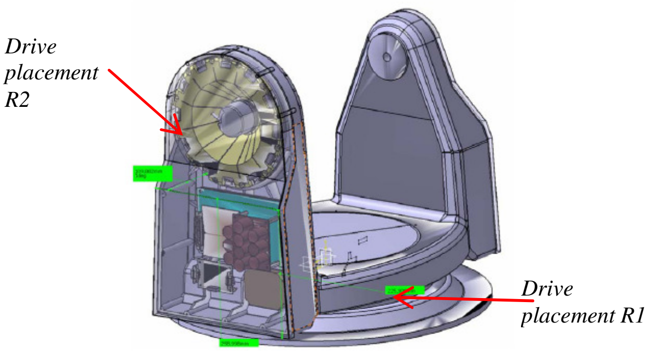

Fig. 3. 3D model of biaxial manipulator where are implemented a developed segment slotless PMSM to axis R1 and axis R2

C. *Motor loading characteristics*

Designed motor was measured on the stand where PMSM was loading by ASM and motor input was measured by power precision analyzer YOKOGAWA type WT3000. Electrical torque was computed from difference between motor input and motor losses divided by mechanical angular speed and also it were deducted mechanical losses investigate from no-load test. Motor losses are making only copper losses on the armature winding and are depended on winding temperature. Others losses as iron losses in stator and rotor are not critical (it is ironless motor with large air gap, 2 times $\delta = 0{,}6$ mm and winding width 7 mm). Measurements for loading characteristics of motors are shown on figure 4 and 5 and moment characteristics are on figure 6.

The measurements confirm the suitability of designed motor for application on manipulator. Investigated performances are in accordance with analytical design that was described in [4,5].

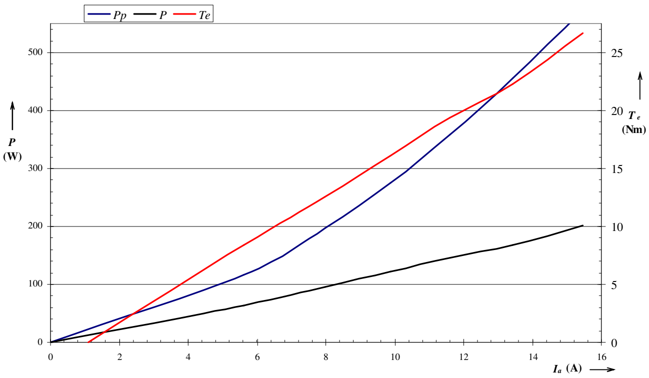

Fig. 4 Loading characteristics at rotation speed n_s=72 rev/min of motor for drive in axis R2, motor with nominal torque 13 Nm

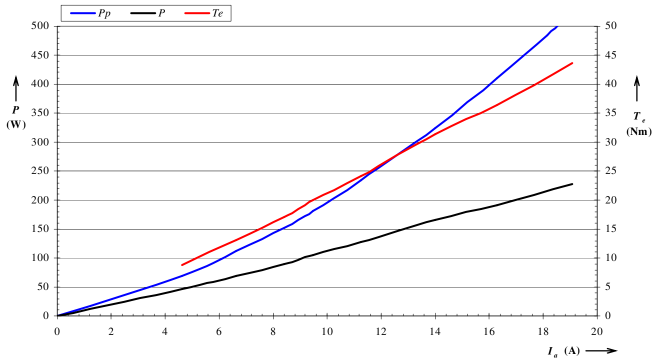

Fig. 5 Loading characteristics at rotation speed n_s=50 rev/min of motor for drive in axis R1, motor with nominal torque 34 Nm

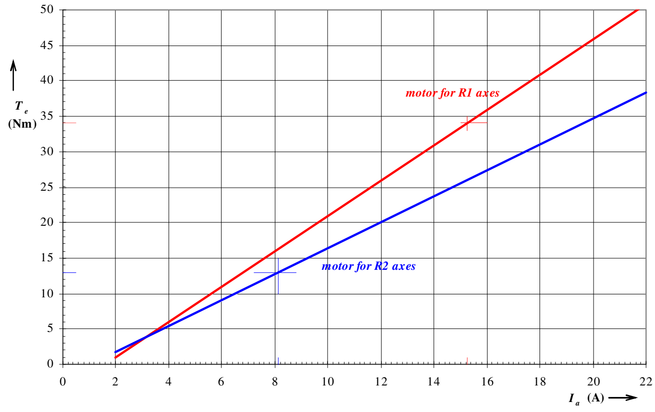

Fig. 6 Moment characteristics of segment slotless PMSM

III. CONTROL STRUCTURE FOR SEGMENT SLOTLESS PMSM

In generally, the most know position system is a cascade structure including several superimposed control loops for force, speed and position. An acceleration control loop is occasionally added to eliminate the effects of load force. It is no substitute for force control, however, because it cannot prevent static overload, for instance when the drive is mechanically jammed.

Main advantages of cascade structure and its nested control loops are:

- transparent structure,
- step-by-step design, beginning with the innermost loop thereby solving the stability problem,
- commissioning is greatly simplified by closing one control loop after other, from inside out,
- opening of outer loops permits simple procedure for diagnostics and field test.

Theoretically there is only one serious drawback of the cascade control structure as seen in figure 7 that is caused by the fact that the response to the reference input becomes progressively slower as more outer loops added. Practically, another terrific drawback occurs. Classical cascade structure it not able to eliminate steady state and dynamic error due to discreteness or resolution of variables (demand value for inner loop) for digital control. This problem solves adding a feed forward compensation to cascade structure.

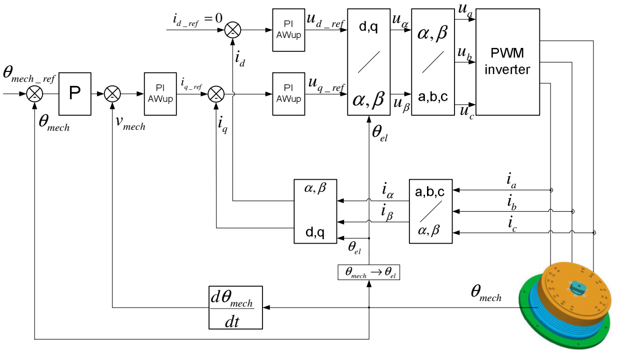

Fig. 7. Implemented cascade vector control of segment slotless PMSM on DSP TMS320F2812

Experimental verification has been done with drive employs a 1.05 kVA inverter (type SN100 – 1.05) develop by EVPU Company with digital signal processor from TI TMS320F2818. As position sensor was used RESM angle encoder, SR optical readhead sensor and SIGNUM system from RENISHAW Company with 0.1 µm resolution. Sampling frequency of current loop was set on 15 kHz. Speed measurement has been done in 3 kHz loop to obtain suitable accuracy (pulse counting method has been used).

IV. SERVO DRIVE PERFORMANCES

To evaluate the characteristics and quality of servo drive for different applications are used specified criteria. Within the frame of prototype tests for both servo drives type 1 (MSLr 288.1) and type 2 (MSLr 198.0) have been realized the following measuring: accuracy, repeatability, unstableness running and stabilization test.

A. *Accuracy*

Positioning accuracy is defined as the difference between the demanded position s_r and the measured (real) position s_m. It's especially dependent on resolution of position sensor. The sensor resolutions of type 1 were 6 480 000 counts/rev and type 2: 3 240 000 counts/rev. The results are shown in Table II and Table III (where Δ is position error).

TABLE II
SERVO DRIVE TYPE 1

s_r (µm)	1000	100	10	-10	-100	-1000
s_m (µm)	999.9	99.9	9.9	-10.1	-100.1	-1000.1
$s_r - s_m$ (µm)	0.1	0.1	0.1	0.1	0.1	0.1
Δ (%)	0.01	0.1	1	1	0.1	0.01

TABLE III
SERVO DRIVE TYPE 2

s_r (µm)	1000	100	10	-10	-100	-1000
s_m (µm)	999.9	99.9	9.9	-10.10	-100.1	-1000.1
$s_r - s_m$ (µm)	0.1	0.1	0.1	0.1	0.1	0.1
Δ (%)	0.01	0.1	1	1	0.1	0.01

B. *Repeatability*

Reaching the prescribed repeated accuracy of the positioning is one of the main parameter that is required for position servo drive. The measurement of the servo drive type 1 has been realized with 10 times (n) repeating n x 360°. The repeated accuracy of positioning was achieved: 0.97 μrad (0.1 μm).

C. *Unstableness running*

Unstableness running for segment slotless PMSM is calculated from maximum n_{max} and minimum speed n_{min} and can be defined by term [7]:

$$\delta = 2\frac{n_{\max} - n_{\min}}{n_{\max} + n_{\min}} . \qquad (1)$$

The measurement has been realized with nominal DC bus voltage: $U_{DC} = 150$ V, maximum rotation speed: $n_m = 65$ rev/min and ambient temperature: 20 °C ± 5 °C. The results are shown in Table IV and Table V.

TABLE IV
SERVO DRIVE TYPE 1

Rotation speed	Actual rotation speed n_s (rev/min)		δ
	n_{max}	n_{min}	
100% n_m	65.06	64.86	0.0031
10% n_m	6.48	6.45	0.0046
1 rev/min	0.99	0.94	0.0518
1% n_m	0.65	0.60	0.0723
0.1% n_m	0.053	0.027	0.6501

TABLE V
SERVO DRIVE TYPE 2

Rotation speed	Actual rotation speed n_s (rev/min)		δ
	n_{max}	n_{min}	
100% n_m	65.11	64.85	0.0039
10% n_m	6.50	6.37	0.0198
1 rev/min	1.02	0.96	0.0645
1% n_m	0.64	0.57	0.1053
0.1% n_m	0.064	0	-

Notation: We have received resolution limit of position sensor in case of smallest rotation speed (0.1% n_m) of servo drive type 2 (see Table V).

D. *Stabilization test*

Stabilization test has been done on two axis manipulator with implemented segment slotless PMSM with inner rotor type MSLr 288.1-34 (see figure 8) in azimuth axis.

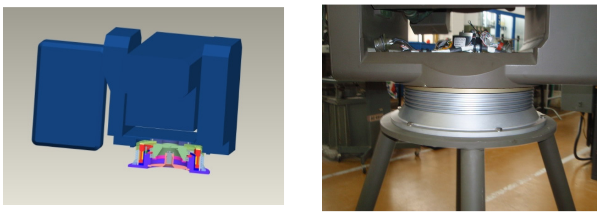

Fig. 8 3D model and real implementation with segment slotless PMSM on two axis manipulator used for stabilization test

This measurement consisted of two parts. The first part of measurement was generated demanded sinus position (as error in stabilization mode – this sinus position was calculated in DSP) with a frequency of 1Hz and amplitude of 1 mechanical degree (see figure 9). The main objectives of this measurement were minimized position error and prepare control structure for stabilization mode. On the figure 9 and 10 are shown final results (demanded a real position and position error) from this measurement.

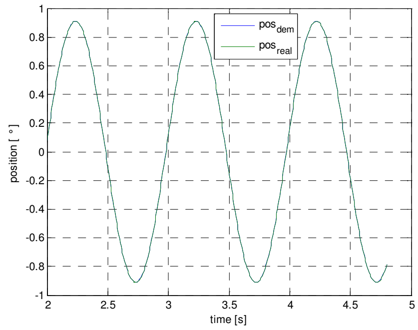

Fig. 9 Generated sinus demanded position and real position from first part of measurement

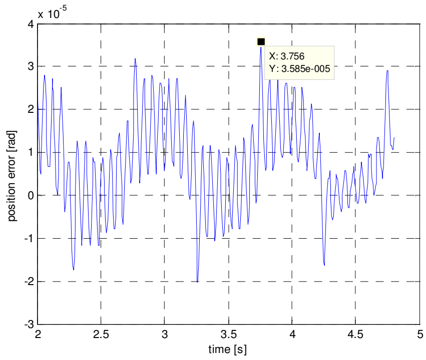

Fig. 10 Position error from first part of measurement

We can see that position error was minimized to 35 μrad on figure 10, in this part of measurement.

In the second part of measurement was manipulator in stabilization mode. Simulator generated again sinus move of stand with frequency of 1Hz and amplitude of 1 mechanical degree. There was placed gyro (ADIS 16120) on stand which sent the demanded speed to control system of manipulator by CAN bus with sample time 2ms. The main objective of this measurement was minimized position error, this parameter is most important in stabilization mode. Result from measurement you can see on figure 11 and figure 12. On the figure 11 is shown demanded position (position was calculated from stand gyro speed) and real mechanical position from PMSM. As you can see from figure 11 calculated demanded position has offset. It caused by offset in gyro speed which is not compensated, because most important parameter for us was position error not final position in this case.

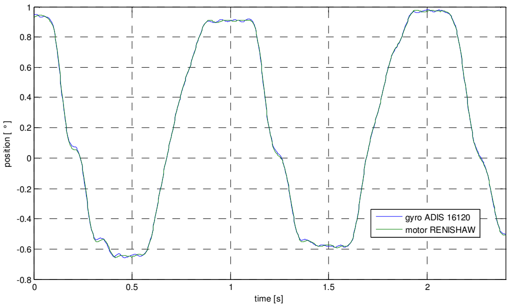

Fig. 11 Sinus position from gyro and real position from motor in stabilization mode with offset

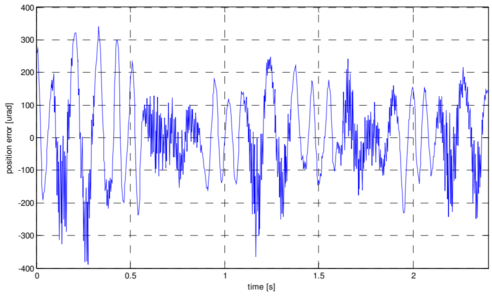

Fig. 12 Position error in stabilization mode

We can see that position error was minimized to 150 - 200 µrad on figure 12, in second parts of measurements.

We can see the differences between position errors from result of both measurements. It caused by noise in gyro position that was ± 0.05 mechanical degrees and also content of higher harmonics in gyro speed.

V. CONCLUSION

This paper deals with experimental verification of two drives for biaxial manipulator in application with high precision positioning system. Drives are based on segment slotless permanent magnet synchronous motor. Results from experimental measurements confirm the suitability of designed motors for this application. The quality and efficiency of servo drive have been evaluated by three criterions: accuracy, repeatability, unstableness running and stabilization test. The main objective of research project was achieving accuracy from 5 to 10 µm and repeatability up to 2 µm. The presented results confirm that specified parameters of servo drive have been achieved.

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