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ON THE PERFORMANCE OF LINEAR AND ROTARY SERVO MOTORS IN SUB MICROMETRIC ACCURACY POSITIONING SYSTEMS

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Abstract. *The growing needs for very high quality surface finishing and sub-micrometric dimensional uncertainty have challenged researches in the area of precision tool machines. Precision tool machines require positioning systems with electro-mechanics structures capable of providing sub-micrometric positioning and tracking errors. Reducing positioning errors in this range require sophisticate mechanisms and advanced control devices. This paper presents the experimental results of a two positioning system that employ different electro-mechanical structures. Each system has its position controlled by a closed loop control system that employ the PID+FF control technique. This setup can be used in a precision tool machines which will be able to produce parts with sub-micrometric precision.*

Keywords: *Sub micrometric positioning, positioning system, linear motor.*

1. INTRODUCTION

The design of accurate positioning systems involves a proper selection of devices such as servomotors, servo-amplifiers, position measurement systems and data acquisition-control board and an optimal choice of the system mechanical structure. Additionally, the control algorithm must be designed to achieve repeatability with precision in the sub-micrometric range and to keep a stable this behavior under load changes (feed rate, friction, loads, etc.). An efficient control algorithm leads to fast and precise positioning system behavior.

This paper considers two different types of positioning systems. Each of them has a particular electromechanical structure. The main difference comes from the type of motor employed, the first system utilizes a linear motor, and the second one uses a rotary conventional motor. The final objective is to obtain a smooth movement and reach sub-micrometric positioning errors with a velocity range from 1 mm / min to 50 mm / min.

In Section 2 the linear positioning system is considered, in Section 3 the rotary positioning system is analyzed. Finally, in Section 4 final comments and conclusions about the relevant features and performance of the two assemblies are presented.

2. THE ELETROMECHANICAL STRUCTURE OF THE LINEAR SYSTEM

This positioning system consists of two parallel cylindrical aerostatic slides, each one using 2 cylindrical air bearings. The motion of the carriage (Fig. 1) is provided by a brushless DC linear motor. The direct assembly of the linear motor with aerostatic slide allows a frictionless and a stick-slip free motion. Since it does not require a rotational/translation gear, there is no mechanical coupling between the motor and carriage; eliminating in this form inertial torsion backlash and compliance elasticity. The reduction of backlash and elasticity results in a greater system rigidity, which, in turn, allows faster responses and improved precision.

The position feedback signal is provided by an opto-electronic scale, which has a basic resolution of 10 μm that is extended, by interpolation, to 50 nm. The opto-electronic scale is fixed directly in the base of the system without coupling. The scale feeds back the positioning measured value to the position controller. A CNC control module with semi-open architecture is used to control the carriage position. The positioning control strategy implemented in each CNC module is a Proportional-Integral-Derivative controller that includes a Feed Forward action of velocity and acceleration (PID+FF), (Rossi, 2005).

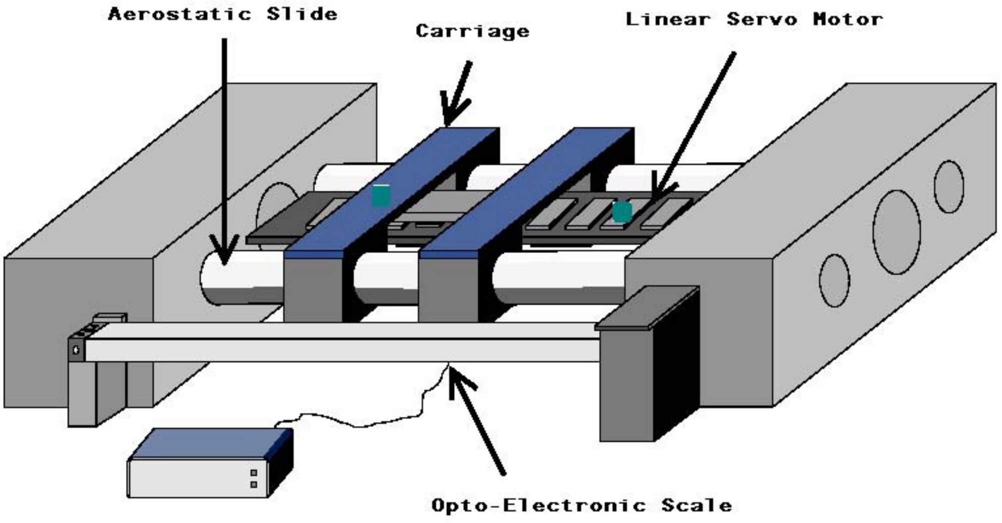

Figure 1. Schematic of the Linear System Assembly.

Figure 2 illustrates the operation of the linear motor and its assembly. The motor produces the force that makes the cursor to slide. In this case, the axis moves without contact among its moving parts and a no backlash system is obtained. A drawback of this structure is the effect caused by the open magnetic field. This field causes a large magnetic force that appears between the moving and stationary system parts requiring a more bulky mechanical design. Besides supporting the load provided by the axis, the bearings have to support the force of the magnetic attraction produced by the linear motor. In addition, the magnetic base of the motor (stator) can easily attract magnetic particles, being necessary the use of an appropriate isolation in this case. The problem of the attraction force could be avoided by employing linear servomotors that have null attraction force, however, they are usually expensive (Slocum, 1992).

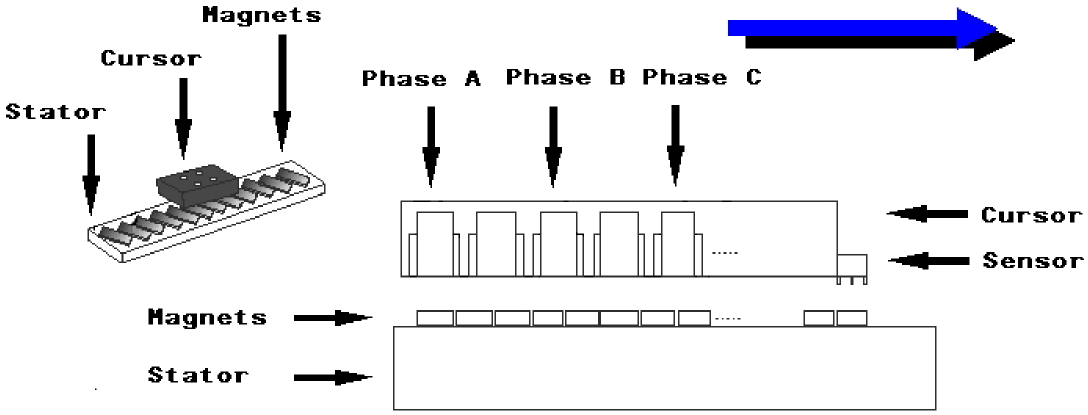

Figure 2. Linear Servo Motor.

In the linear motor case, the magnetic field in the stator is created by permanent magnets. When a current circulates in the coil located in the cursor, a magnetic field is created that interact with the permanent magnetic field of the base producing a resulting force (Lorentz force) that is proportional to the magnitude of the current and its direction depends on the direction of the current in the coil. The resulting force depends on the value of the excitation current and on the gap of the motor.

Figure 3 shows the results for the linear case. Notice that three curves are being displayed: the commanded displacement overlaid by the actual displacement response (the path curve) and the commanded displacement minus the actual displacement response (the error curve). One can observe that the error curve presents periodic peaks. These peaks are caused by the no ideal commutation of the motor phases. Due to the no ideal commutation of the motor phases (phases A, B and C), the produced force is not continuous causing the undesirable peaks on the resulting displacement.

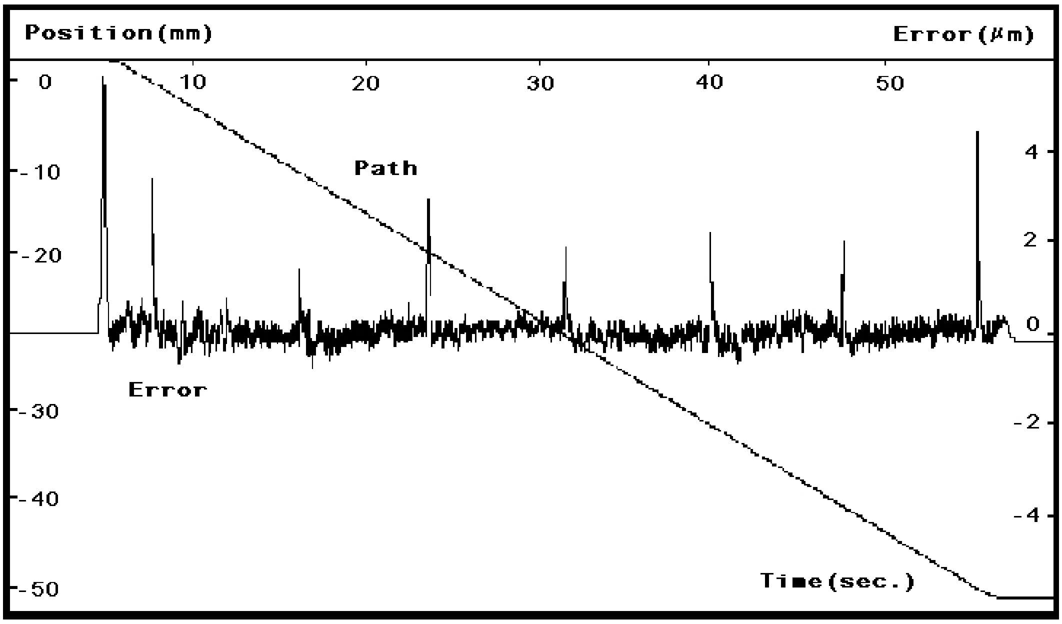

Figure 3. Positioning Tests - 60 mm/min.

In the case of ideal phase commutation, the resultant error curve will not present peaks of force every time that happens a phase change (commutation). However, due to small mechanical assembly problems of the group: stator, cursor and Hall sensor, peaks of force happen during commutation and that is reflected in the cursor-carriage displacement. The linear DC servomotor requires a driver to feed and to perform the phase commutation of the motor. The switching time of the phases are typically determined by the Hall-effect sensors connected to the cursor and used to capture the density of the magnetic field.. In this case, a driver that employs the trapezoidal technique was used so that the current supplied to the phases of the motor is constant. The Hall-effect sensors board was connected to the cursor as shown in Fig. 4 and was designed to send to the PWM trapezoidal driver the information about which phase of the motor should be on. Three Hall sensors are used to perform the change of the phases and they are fixed on a plate as shown in Fig. 4. When the cursor moves, the plate slides on the stator surface, which is composed by several small magnets (poles) with north or south polarity, arranged alternately.

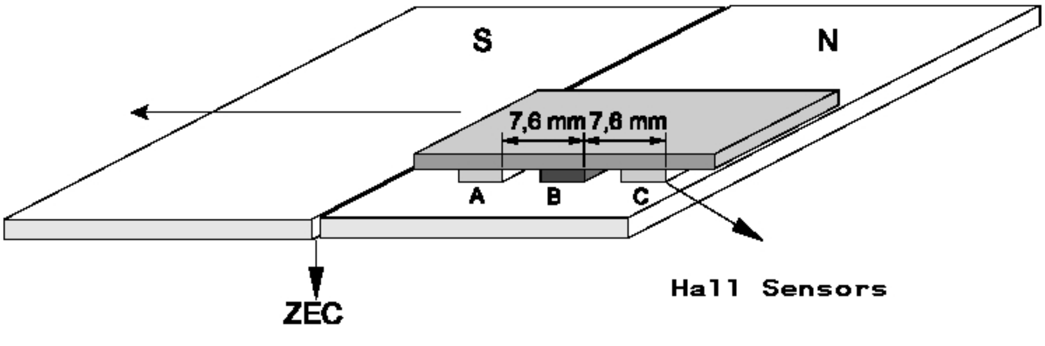

Figure 4. The Hall Sensor and the Poles of the Linear Motor.

In the ideal case, the area of low magnetic field (ZEC) located between the poles does not affect the performance of the Hall-effect sensors and the generated force. The signals emitted by the Hall-effect sensors during the cursor displacement are shown in Fig. 5. The PMW trapezoidal driver receives these signals and performs the phase commutation.

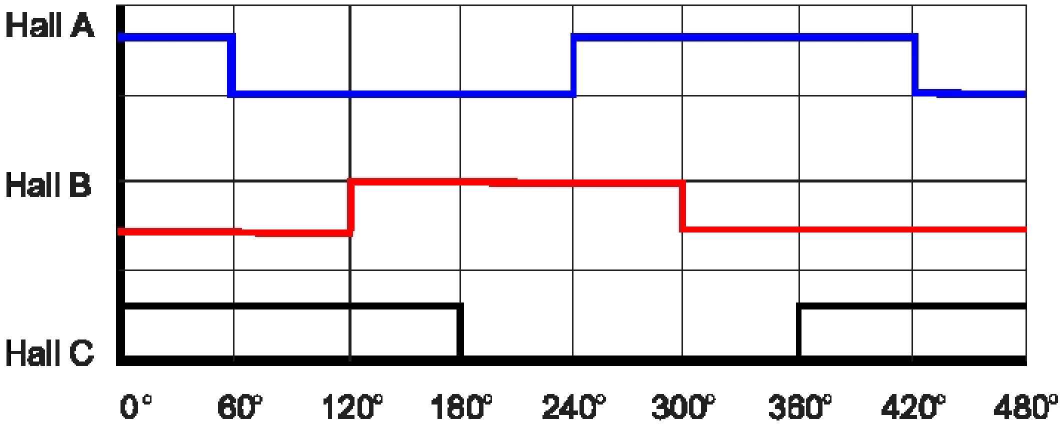

Figure 5. The Signals from the Hall-effect Sensor.

The switching time during commutation is influenced by the distance between the stator and Hall-effect sensors. Moreover, for an ideal commutation, it is necessary that the three Hall-effect sensors were equally spaced, also, the sensors do not have any protection against possible accidents that could shift them from the right position, all of that requires a very carefully assembly of the system..

The Hall-effect sensor output switches (changes from ON to OFF state or vice versa) when it detects the presence of a magnetic field, as shown in Fig. 6. The larger is the distance from the magnet the smaller the density of the magnetic field. This factor is of great relevance to switching, especially in the zone called ZEC, or between two adjacent poles, where the field is usually smaller and becomes even smaller with increasing distance.

Figure 6 shows the magnetic field density curve at a point near the pole (situation A) and at a point further away (situation B). In situation B, the width of the field weakening zone (ZEC) is larger than the one of situation A, and therefore, the switching of the stages that should occur at the exchange of poles (or as close as possible) will occur only some time later.

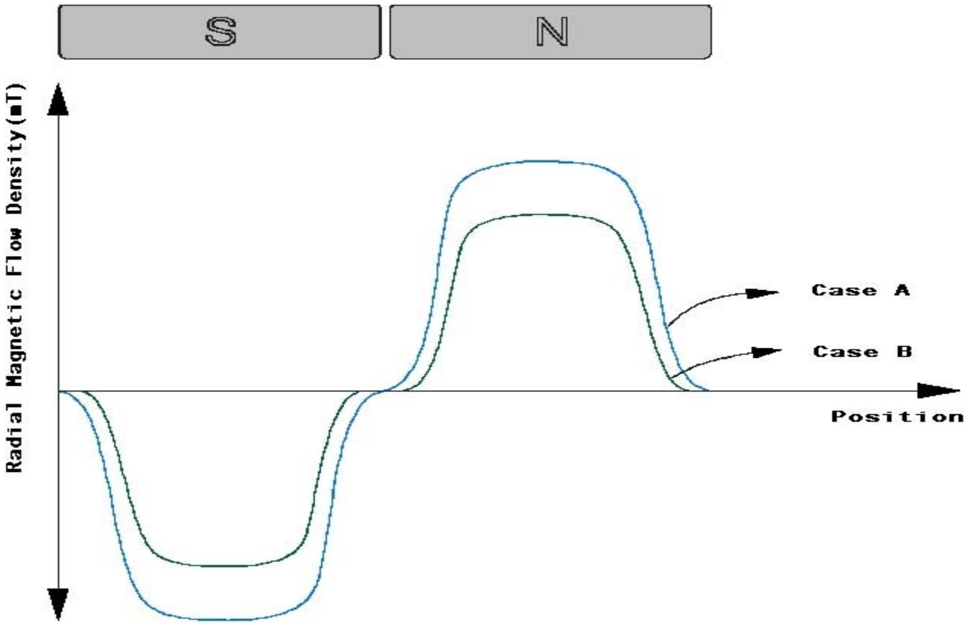

Figure 6. The Magnetic Field Density.

Figure 7 shows an example of how the ZEC influences the switching of the Hall-effect sensors. To facilitate the understanding of this effect it will be assumed that the ZEC causes a delay of 10° in the switching of the sensors.

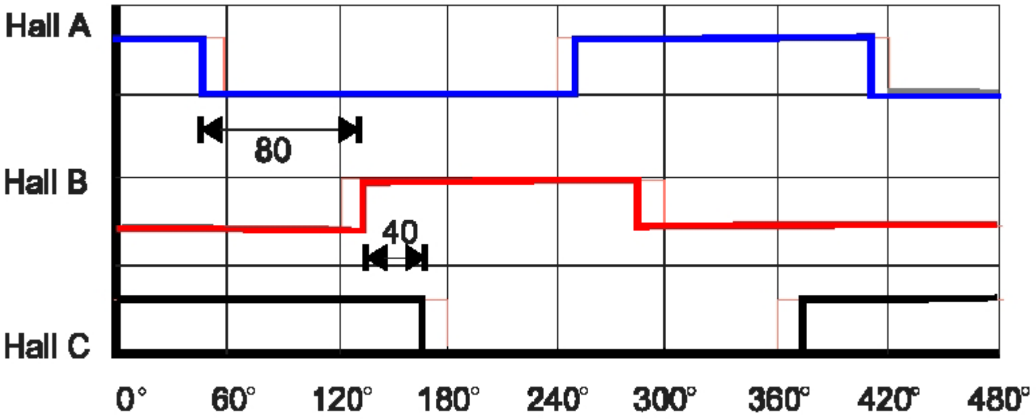

Figure 7. The Electrical Signals from the Hall Sensors.

Figure 7 shows clearly that each switching step does not have 60 degrees any more (as shown in Fig. 6). In this case, the steps have duration of 40 degrees during the feeding stage, and 80 degrees during the phase exchange stage. As the exchange of phases takes longer than ideally there is a reduction of the resultant force before the switching and discontinuity appears and is transmitted to the cursor - carriage displacement.

Based on the study of the linear motor and its commutation, the problem was solved through the readjustment of the Hall-effect sensor. Approaching the Hall effect sensor to the stator to a distance between 1 and 0,5 mm, it was obtained the results shown in Fig. 8. It can be noted that the error peaks (that previously reached 6 µm) have disappeared. During this test, the cursor traveled 70 mm with a speed of 100 mm/min (3 mm/s) meaning that the cursor went through 3 poles (each magnet measures 23,4 mm).

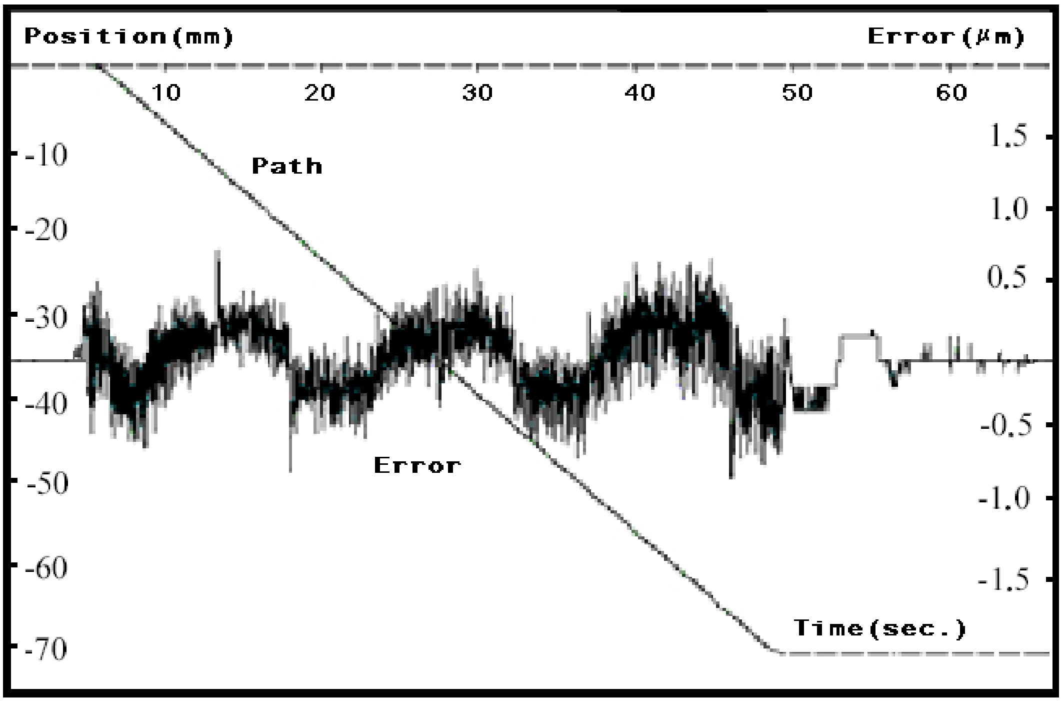

Figure 8. The Positioning Test Results.

In the linear motor case, there is only a discrete number of magnets in the stator, consequently, a ripple appears in the resulting force that affects the axis displacement as can be seen in Fig. 8.

In this positioning test, the motor crossed 3 magnets (each magnet measures 23,4 mm) consequently there are 3 ripple peaks. The ripple could be reduced by using a DC linear servomotor with a PWM sinusoidal drive, because this servomotor type is more appropriate when one wants to obtain a minimum oscillation (Lammers, 1994).

3. THE ELETROMECHANICAL STRUCTURE OF THE ROTARY SYSTEM

This Section considers a positioning system that consists of a pair of cylindrical aerostatic slides with 45 mm diameter. The motion is delivery by a frameless brushless torque motor assembled directly in a precision ball screw with 2 mm of pitch. The position measurement system of this axis is an opto-electronic encoder with 25920 lines, having a basic resolution of 77 nm that can be improved, by interpolation, to a resolution of 0.77 nm. Even though the encoder has high resolution, it is necessary to consider that the encoder is connected to a ball screw, so this is not a direct measurement such the one made by an opto-electronic scale. The problem that could arise because of that is considered next.

In this system, the torque servomotor was designed to produce smooth movements especially in low speed. However, the smooth movement can be deteriorated if the guides and the ball screw introduce friction in the system. The static friction and the elasticity of the transmission mechanical elements, such as the ball screw, joins, etc., can produce the stick-slip effect when the axis moves in very low speed. To reduce the chances of such effect to happen, the servomotor is placed directly in the ball screw, and thus, torsion backlash can be reduced.

Therefore, it is necessary to consider in the analysis the transmission errors caused by elastic and torsion deformations and ball screw uncertainties. Besides that, it is necessary that the joins used to fix the encoder have no clearances, be resistant to torsions and have reduced inertia. Positioning tests are accomplished in order to analyze the effect of the indirect measurement. Figure 9 shows the mains components of this axis.

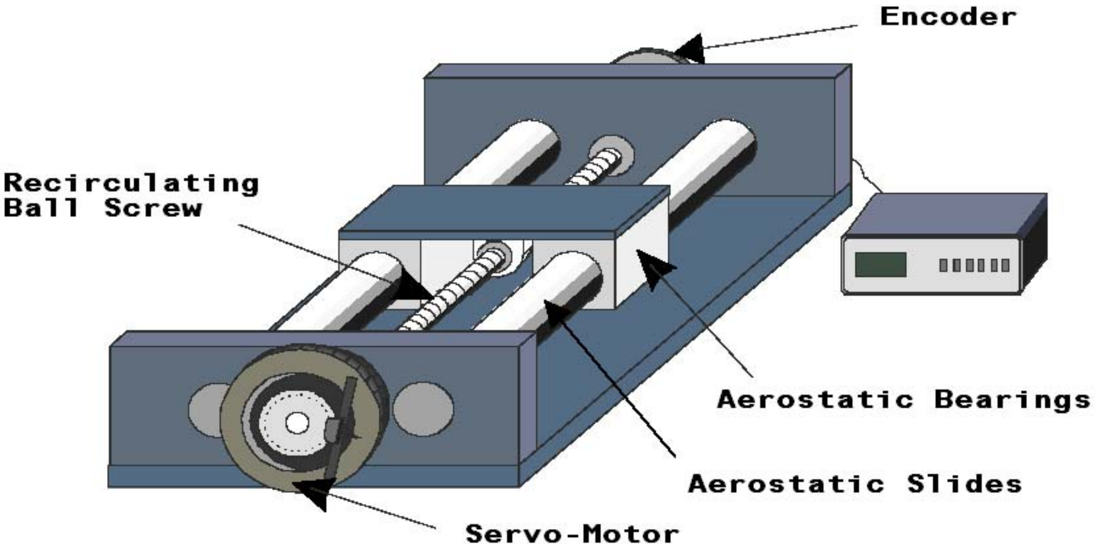

Figure 9. The Rotary System.

The Pros and Cons of Rotary Positioning Systems

The principle of operation of the rotary PWM drive is very similar to the linear PWM drive. The main difference is that the rotary PWM drive employs the sinusoidal technique, where each of the three phases of the motor is powered by a sinusoidal current. The sinusoidal commutation is used in order to obtain smooth motion with minimal ripple. In practice, the generated EMF and sinusoidal current are not completely pure, therefore, the torque produced is not constant. However, it can be considered that the torque ripple is minimum especially when compared with other techniques.

The phase commutation of this motor depends on information sent by the Hall-effect sensor and encoder (Fig. 10). Unlike the linear motor, the three Hall-effect sensors of the motor are rigidly fixed in its stator, not likely to move from its position and thereby causes switching errors due to unequal spacing between sensors. Moreover, the spacing between rotor and stator is determined by the cylindrical configuration of the motor. However, the mechanical assembly of the commutation encoder strongly influences the behavior of the motor. It requires a coupling without clearances and a perfect alignment between the encoder shaft and the rotor shaft, because the switching depends on the correct reading of the position of the rotor.

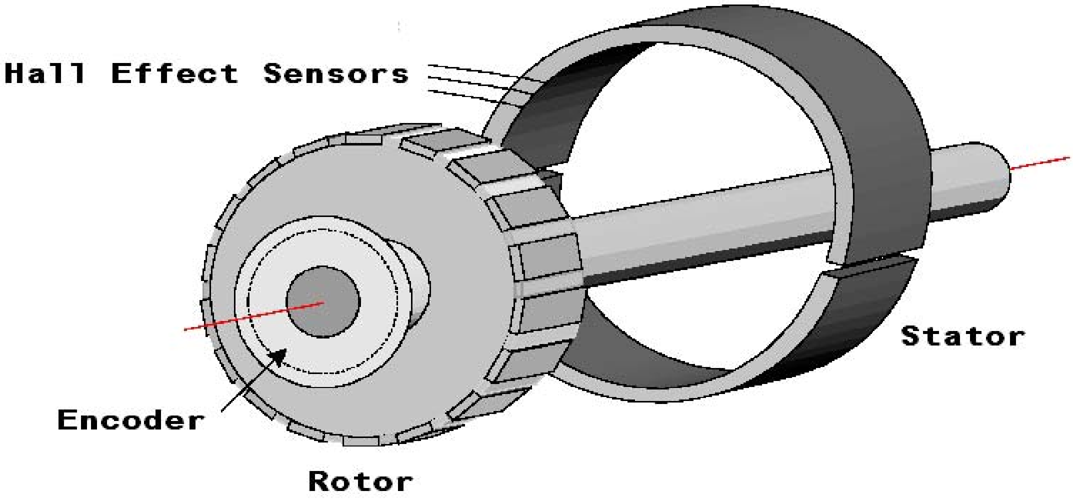

Figure 10. Torque Servo-Motor.

Figure 11 shows the displacement curve obtained when the encoder was mounted without a correct alignment with the axis of the rotor. The error peaks occur at each change of phases.

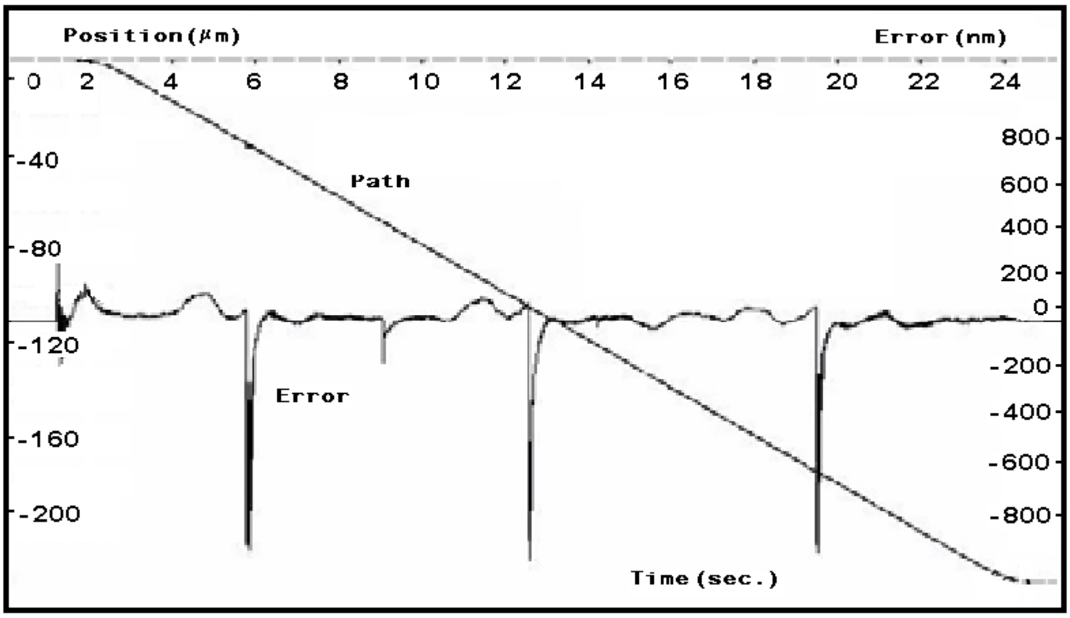

Figure 11. Non Ideal Commutation of the Phase's Motor.

This problem was eliminated after the correction of the encoder assembly. Figure 12 shows the result of a positioning test with a speed of 10 mm / min and a displacement of 2 mm, equivalent to one rotation of the spindle.

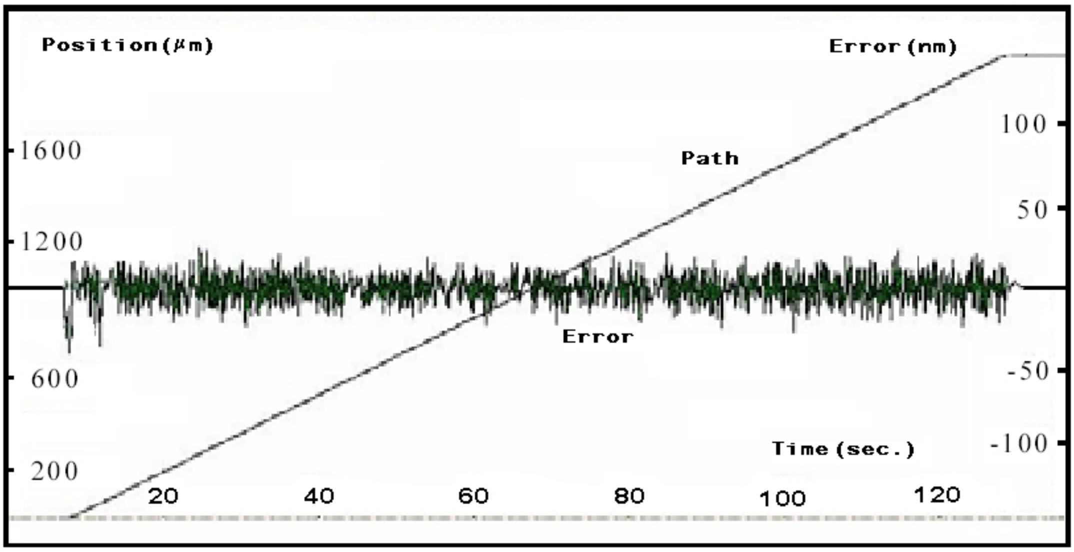

Figure 12, The Positioning Test Results - 10 mm/min.

The peak error is no longer perceived. The maximum error is about ±30nm Unlike the linear motor, the ripple due to the 12 poles of the rotor is not perceived because it is employed the sinusoidal PMW drive.

4. FINAL COMMENTS AND CONCLUSIONS

This paper presented important aspects concerning the performance of two high precision positioning systems. The electro-mechanical structures of each positioning system employ different technologies and therefore have different problems and behaviors, allowing the opportunity for analysis of two types of electro-mechanical structures. The resulting precision of the positioning system depends strongly on the precision of its components and on the perfect integration of the same ones.

The main difference between the two systems is that the linear system has direct driving and direct positioning control and the rotary system has indirect driving and indirect positioning control. The positioning precision of the rotary system depends on the clearances of the system mechanisms and on the ball screw uncertainties that in some case can deteriorate the positioning performance.

The use of a linear motor shown to be more suited for high precision positioning systems, The fact that this type of system does not have mechanical clearances makes the resolution and precision of the axis dependent only on the resolution of the measurement system.

5. REFERENCES

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