Position Based Static Friction Estimation for DC Motors Using Disturbance Observer

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***Abstract* – Estimation of friction is not considered necessary in motion control systems when the precision is not a major concern. Effects of the frictional components could be ignored for small friction: motor torque ratio DC motors. Friction estimation is required to increase the precision of the motion control system. Available research illustrates a way of average value estimation for static friction and viscous friction for a full rotation. As far as practical scenario is concerned, frictional components are having a rotor wide variation. Proposed method attempts to estimate the rotor wide static friction variation for a small DC motor. Disturbance Observer has been used for static frictional torque measurements. Rotor wide static friction variation is shown in the results and it illustrates mechanical health of the system.**

Key words: Static friction, Estimation, Disturbance Observer

I. INTRODUCTION

When developing sophisticated and high accuracy motion dependent machines for special applications in Robotic systems, friction could not be neglected. Friction is a natural resistance for the relative motion in-between two contacting bodies. Friction depends on the material surface, lubricant characteristics and the perpendicular contact force characteristics of a motion control system. Due to this developed control algorithms for standard PID, Disturbance Observer (DOB) and Artificial Intelligent based servo systems are not capable of delivering the desired precision under the influence of friction. Available knowledge show that, friction dynamics depends on the direction of the rotation as well as the velocity of the motor and obtaining an exact parametric model for the friction is a challenging task. Static friction, viscous friction, coulomb friction and stribeck effect are the available frictions in a motor [1][2]. Static friction is the main concern in this research since it is the most significant factor in all the cases.

Substantial no of researches have been conducted regarding friction compensation using fuzzy logic [3], artificial neural networks [4], neuro-fuzzy [5], PID, disturbance observer based models [6]. In all the Artificial Intelligent based [3] friction compensators researchers have been developed friction compensated control systems such as friction compensated position controllers or friction compensated velocity controllers where frictions are gray elements to the algorithm developer. They haven't estimated pure frictional factors which can be used independently in any system, except in DOB based friction compensators [6]. When comparing to other torques, frictional torque can be neglect in large scale motors. However, for highly precise and highly accurate applications, friction should be practically analyzed. In this paper authors have proposed a novel technique to estimate position dependent static friction which had been never done before in any of above available methods. Static friction of motors is continuously varying with the rotor position respectively to the stator because of the continuous change of material in contact due to rotation and nonalignment of the coupled loads. Repeat of frictional values are expected in the forthcoming rotations also. Hence static friction should be a unique in same orientations when the rotor is attempting to rotate on a one direction. However one orientation can be included two static friction values depending on the direction.

In this research authors have developed a method of estimating position based static friction using disturbance observer for any DC motor with high reliable algorithm. Research has been conducted for a small (inertia = 0.000091 kgm^2) [7] DC motor and position based static friction have been estimated using the developed algorithm and results are shown.

II. DC MOTOR FRICTION

Static friction and viscous friction are the major factors of friction in a DC motor. Other frictional components are relatively negligible with comparing to motor torque. Supply current is consumed by accelerating the load, static friction, and viscous friction. Motor torque could be derived as follows (1) [8].

$$T_m = J\,\frac{d\omega}{dt} + B\dot{\theta} + T_f \tag{1}$$

Where T_m could be derived from motor current and motor constant as in equation (2).

$$T_m = k_t I_a^{ref} \tag{2}$$

T_f	:	static friction
T_l	:	load torque
T_m	:	motor torque
J	:	inertia constant
$\dot{\theta}$	:	rotor speed
B	:	viscous friction coefficient
k_t	:	motor constant
I_a^{ref}	:	motor current

Viscous friction depends on the rotor speed and static friction depends on the surface properties of the contact bodies of the motor. If the velocity is zero at no load condition according to the equation (1) and (2), static friction is directly proportional to the motor current.

III. Measurement of Static Friction Torque Using DOB

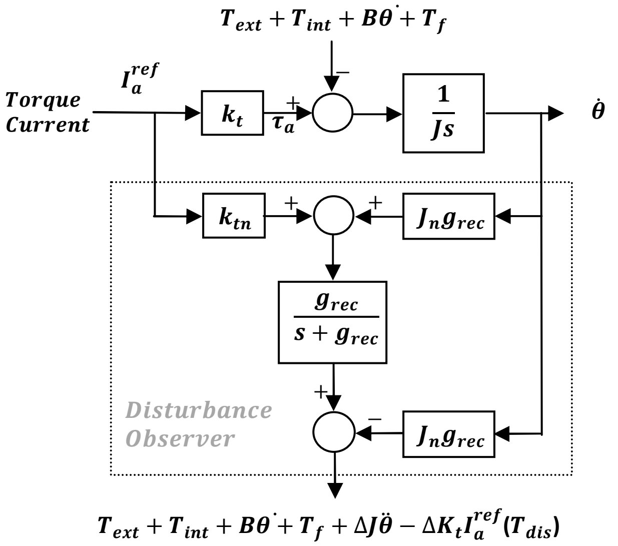

Fig. 1. Estimation of Disturbance Torque using DOB

Load torque and motor torque are the two torques applied on the electric motor when it is operating. Equation (3) to (10) shows the derivation procedure of the disturbance observer. If the inertia of the rotor is J, load torque could be expressed as in (3).

$$J\ddot{\theta} = T_m - T_l \tag{3}$$

T_{dis}	:	disturbance torque
T_{int}	:	Interactive torque
T_{ext}	:	external torque
J_n	:	nominal motor inertia
k_{tn}	:	nominal motor constant
Δk_t	:	self motor constant variation
ΔJ	:	self inertia variation
$\ddot{\theta}$	:	rotor acceleration

Equation (4) shows the load torque

$$T_l = T_{int} + T_{ext} + T_f + B\dot{\theta} \tag{4}$$

In (5) and (6) parameters are subjected to change.

$$J = J_n - \Delta J \tag{5}$$

$$k_t = k_{tn} - \Delta k_t \tag{6}$$

$$T_{dis} = T_{int} + T_{ext} + T_f + B\dot{\theta} - \Delta J\ddot{\theta} + \Delta k_t I_a^{ref} \tag{7}$$

From equation (4) and (7) the disturbance torque T_{dis} could be rewritten as,

$$T_{dis} = T_l + \Delta J\ddot{\theta} - \Delta k_t I_a^{ref} \tag{8}$$

From equation (7) and (2),(3)

$$T_{dis} = k_t I_a^{ref} - J\ddot{\theta} + \Delta J\ddot{\theta} - \Delta k_t I_a^{ref} \tag{9}$$

By substituting terms in equation (5) and (6) in equation (9)

$$T_{dis} = k_{tn} I_a^{ref} - J_n\ddot{\theta} \tag{10}$$

When angular acceleration and motor current are known parameters, it is possible to calculate the disturbance torque (T_{dis}) from the block diagram in fig.1. Equation (10) could be represented as shown in fig.1.This implementation is known as the disturbance observer. The low pass filter is included to remove undesirable high frequency responses due to the differentiation stages of the DOB.

When no load is applied, disturbance observer estimates the frictional constituents as shown in (11). Measuring of static friction was done by starting the motor from the standstill. Here it was assumed that, estimated parameters for J and K_t are accurate [8]. Therefore, $\Delta K_t \rightarrow 0$ and $\Delta J \rightarrow 0$, as explained in (5) and (6). T_{int} is not presence since the apparatus is single DOF actuator system. T_{ext} is considered as zero at no load condition.

$$T_{dis} = B\dot{\theta} + T_f \tag{11}$$

Initially 0.001A current is commanded to the motor and subsequently, current is increased by the steps of 0.001A. When a motion is detected, the torque output of the disturbance observer was recorded. So this torque is considered to be static frictional torque of that particular position.

IV. DISTURBANCE OBSERVER BASED POSITION CONTROLLER

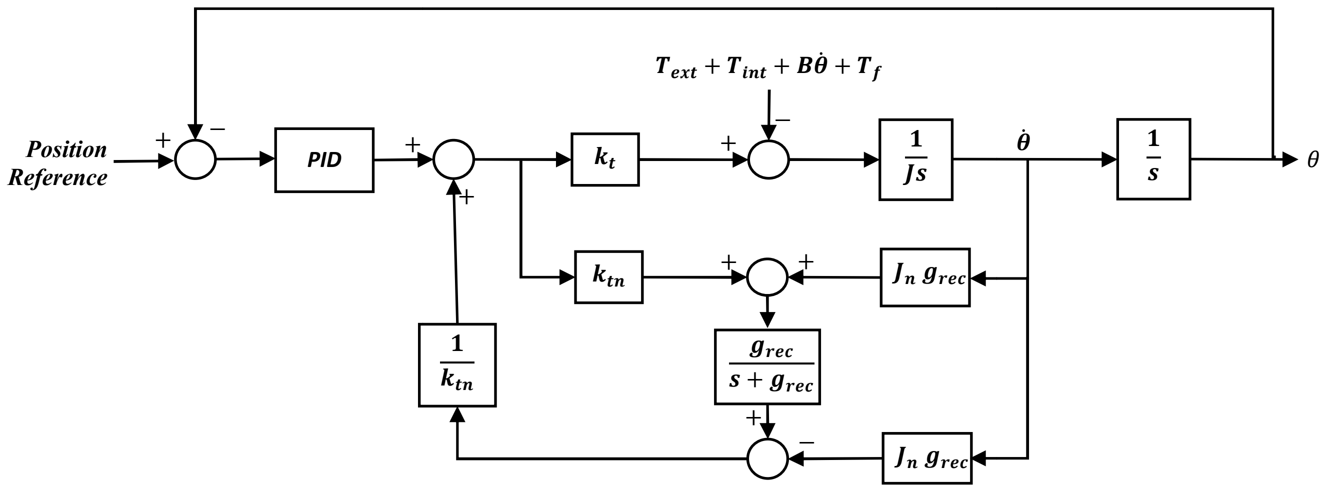

Fig.2. Disturbance Observer based Position Controller

DOB based position controller was used to place the rotor precisely at the required position with lowest possible time. It took around 8 hours to complete one rotation with DOB position controller. Time requirement for one rotation with conventional PID controller is more than it with DOB controller According to the pre estimations. Method used in this research is shown in fig.2. Algorithm was developed using the above block diagram and it was verified using proper testing procedure. Randomly positions were commanded to the system and by the use of response, it was verified that rotor has exactly followed the positions. Furthermore, action and the performance of the developed position controller are verified by the output position variation. When angle 180^0 (step) is commanded the response of the DOB based position controller is shown in fig.3.

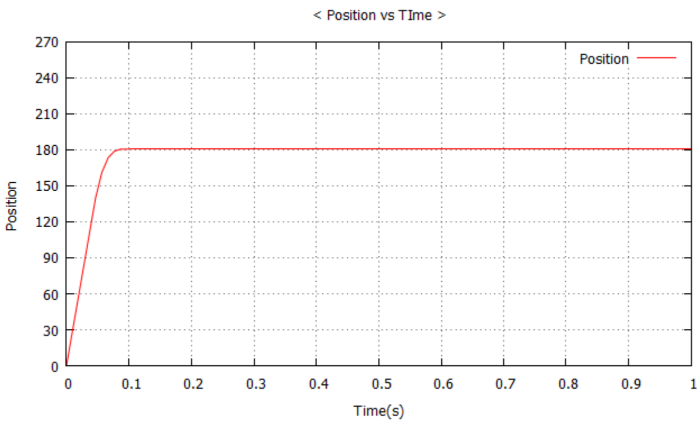

Fig.3. Position Response of the Position Controller for Commanded Position 180^0.

V. HARDWARE SETUP

Hardware setup of the system is shown in fig.4. LPC 1768 Mbed microcontroller has been identified as a proper device to implement the algorithm. Current sensor unit with differential amplifiers was used for the current measurements. Incremental encoder of 2500ppr was used for position identification and SD card reader is attached using SPI protocol for collecting data.

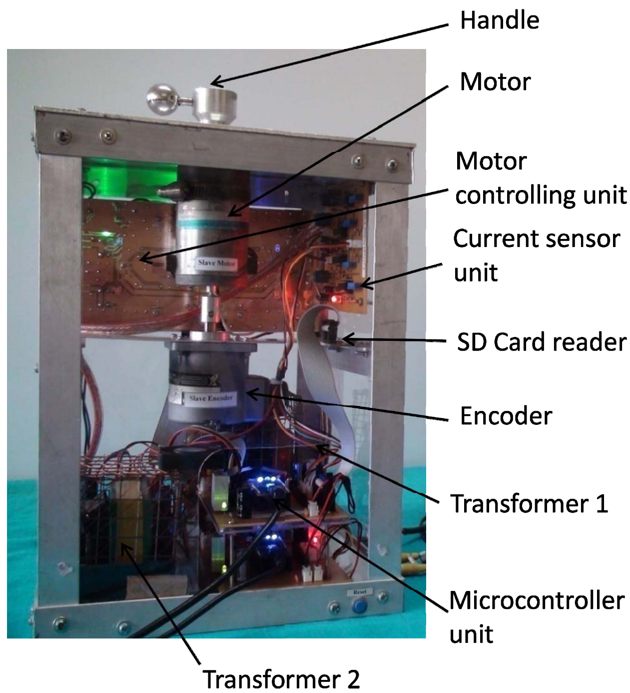

Fig.4. Hardware Configuration

VI. HOMING THE MOTOR CONTROL SYSTEM

Friction values should be measured with respect to a reference point since the positioning is doing by the incremental encoders. Index (Z) of the incremental encoder is selected as the homing feedback. The algorithm used for homing is explained as shown in fig.5.

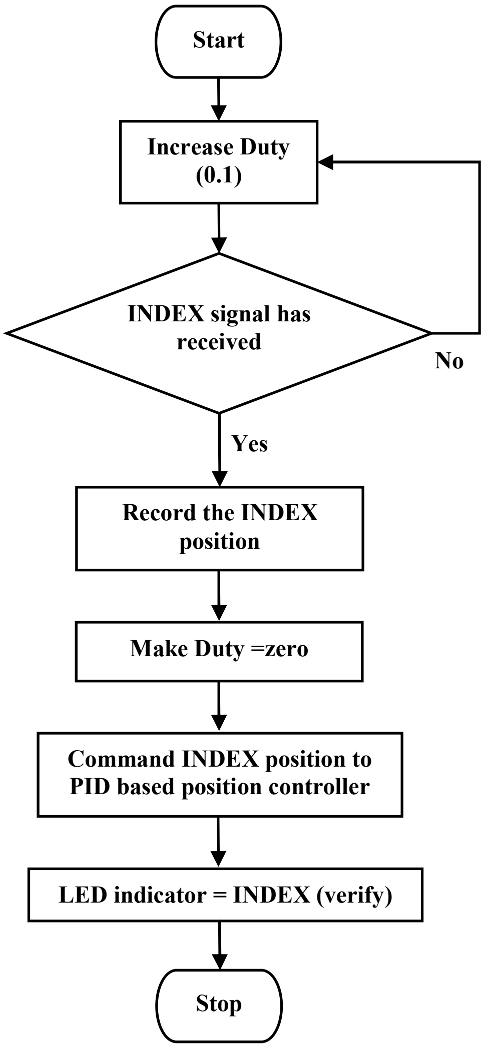

Fig.5. Move to the Index Position

VII. AUTONOMOUS POSITION BASED STATIC FRICTION TORQUE ESTIMATION

2500 ppr encoder with quadrature multiplication delivers a total of 10000 pulses per revolution resolution. An autonomous static friction estimation is needed as duplicating the procedure for 10000 position is practically impossible. We proposed an autonomous positioning algorithm as shown in fig.6 to accomplish this task.

In this process selected reference point to start is the index position of the encoder. Firstly the algorithm should support to move on to the index position. So method shown in fig.5 is applied to complete the first step and index position (Home) is being selected as the position zero orientation. Then to measure the static friction of first position, current command to the PID based current controller was increased gradually from starting 0.001A, by the steps of 0.001 A until it achieves a change in position. DOB output value just before the position change is selected as the static friction value of the first point. In the same cycle of the algorithm, current controller should be disabled and current command should assign to the zero as explained in fig.6.

It's not advisable to assume that the rotor is standing at the preferred consecutive position after estimating the first friction value. Rotor could be rotated far beyond the consecutive point. Therefore the rotor should be located to the next position. Position command was fed to the DOB based position controller after increasing by a unit step. Most of the time, position controller was able to achieve the commanded position. There would be few positions which will not be able to stabilize in the absence of the feedback. Therefore motor duty ratio is zeroed and that specific point is attempted to achieve with 1000 attempts. If the position is not achievable even after the 1000 attempts, the specific point is neglected in the algorithm.

If commanded position was achieved even after the waiting period, algorithm allows moving to the next estimation. At the same time position controller should be disabled and current position should be assigned to the position variable. This process can continue until the autonomous system collects the required amount of data by only changing the encoder max variable.

It takes around 2.88 seconds on average to estimate a one value of the static friction; all together it took around 8 hours to collect data for one rotation in autonomous mode.

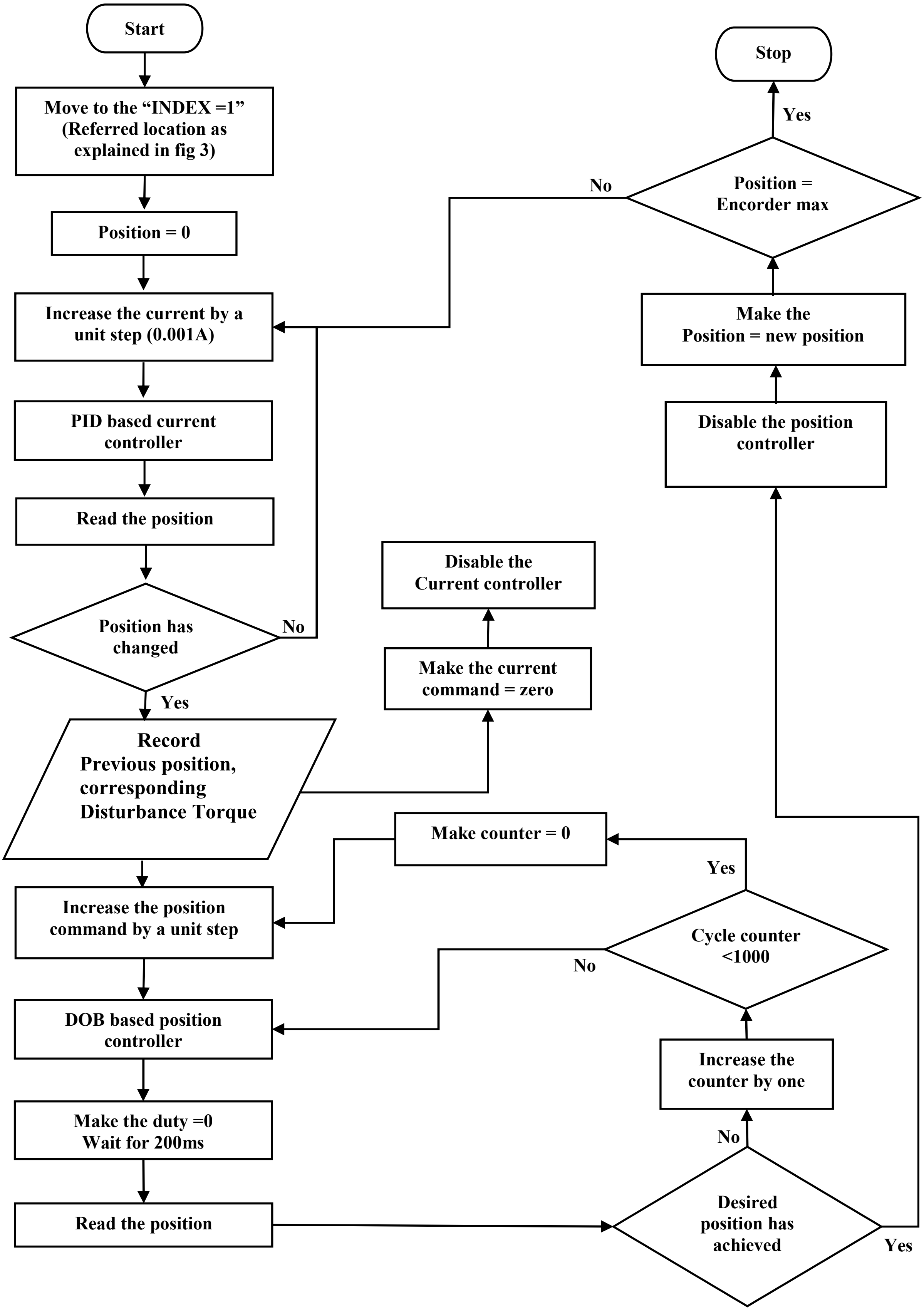

Fig.6. Autonomous Static Friction Estimation Algorithm

VIII. RESULTS

Mbed microcontroller was running with a Real Time Operating System (RTOS). Controller was run by a high priority thread while a low priority thread was given for data recording. Graphs were plotted using GNUPLOT software.

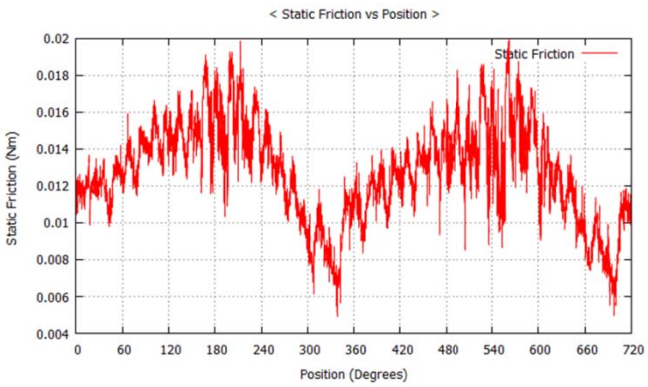

Fig.7. Static Friction Variation of the Motor for Clockwise Rotation

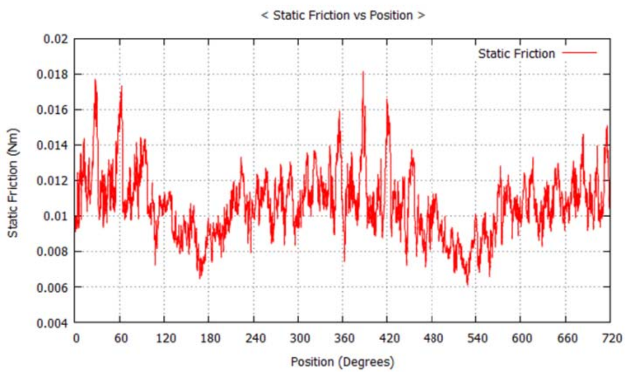

Fig.8. Static Friction Variation of the Motor for Anticlockwise Rotation

Fig.7 shows the static friction variation of the DC motor for clockwise direction. According to the data, static friction is varying around an average of 0.0124 Nm for the clockwise direction with the position. The data set shows a 20.11% coefficient of variance and 54.32% maximum deviation from the average. Correlation of two rotations is 0.934 according to the collected data. Fig.8 shows the static friction variation for the anticlockwise direction. Average value of the static friction for anticlockwise direction is 0.0108 Nm. Coefficient of variance is 16.54% and whilst maximum deviation from the average is 62.92%. Collected data for anticlockwise direction shows a correlation of 0.836.

Static friction for the clockwise and anticlockwise direction has a considerable difference according to the results. When compensating the friction for DC motors these scenarios should be taken in to the consideration. Above estimated values can be directly used for compensating the friction of the selected motor.

IX. CONCLUSION

Results show a considerable variation of the static friction with the position for both clockwise and anticlockwise directions. For precise applications, estimating an average value for static friction is not advisable since it is having rotor wide variation. Similarity of the rotor wide static friction variation pattern for consecutive rotation could be verified using strong correlations. However, for small *friction : motor torque* ratios position based friction estimation could be neglected. Developed static friction estimating algorithm could be used to identify an average value for static friction. Fixed static friction value could be used when the effects of the friction is considerably low when compared to the motor torque.

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