

Servo drive chain evaluation test set-up and configuration methodology

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Abstract— The evaluation test bench set-up for servo drive chain consists of various servo sub-modules viz., generic motion controller, servo drive amplifier, brushless AC servo motor, torque coupler, gear reducer and shaft encoder assembly for position feedback is considered. The module interfaces are established for efficient use in commissioning, diagnosing and qualifying the antenna tracking chain. Design methodology demonstrated and specifications of systems were derived. Design specifications of drive chain are configured through software tools for optimizing rate loop and position loop. The transient behaviour and response of servo system using Proportional Integral Derivative controller in time as well in frequency domain is analyzed. Stability conditions are simulated and verified. The test set up energised and test results of different inputs verified and following error minimised by tuning/optimising the system.

Keyword - PID controller, IRS series, Servo drive chain, Optimisation, Gear reducer, Shaft encoder.

I. INTRODUCTION

The antenna tracking chain (antenna servo system) for any satellite is one of the most critical front end hardware and control algorithms (software control) which consists of mechatronics system for meeting stringent tracking specifications. At satellite ground station; satellites are tracked and data received on a round the clock basis from IRS (Indian Remote Sensing) and Non-IRS series of satellites. In such scenarios, any failure/break-down in tracking chain will lead to considerable amount of data loss and station efficiency obviously decreases. Thus, to reduce the minimum down-time and to make an immediate attempt to improve system failures, work bench evaluation test set-up is developed for diagnosing faults, abnormalities, observations in tracking chain and re-qualifying the respective servo control modules (antenna servo hardware & software) on priority basis is achieved. This evaluation test set-up is also used for antenna system commissioning, improvements and any spare/ new modules qualification apart from exact fault finding and restoration.

In [8], [10] explained the servo control system-three important parameters discussed viz., Current, Speed and shaft Position of Motor. Thus, in closed loop control domain, three parameters (current, speed and position) forms torque loop, velocity loop and position loop [5], [6] which are essential for accurate, precise control and positioning of antenna towards required direction of target/ Satellite.

In [7], various control techniques PI to H_∞ were mentioned for applying and obtaining accurate control over target based on accuracies and dynamics.

In [3], the drive chain modules selection and sizing criteria considered for approaching and implementing test set-up.

The antenna tracking chain flow diagram comprising essential three loops is exhibited in Fig. 1.

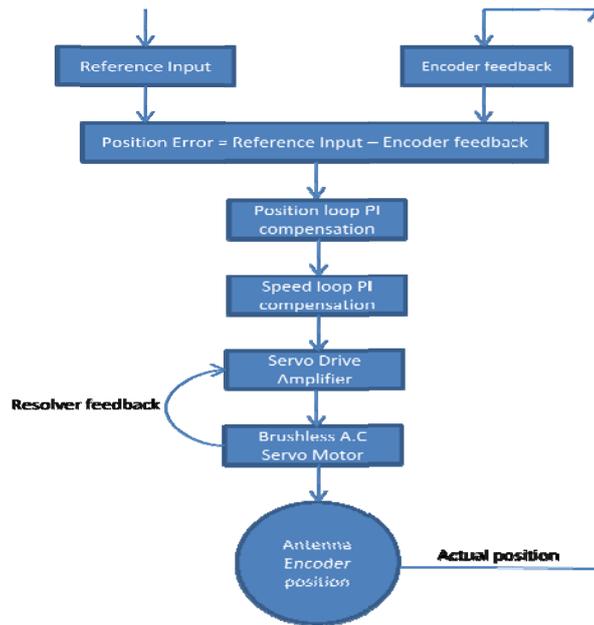


Fig.1. Loop control flow diagram

The flow chart diagram shows position feedback from antenna which compared with reference position and obtained error is compensated in position loop PI controller to provide the speed input to velocity loop which intern encloses torque loop and regulates the current (A) requirements. In case of practical scenario, to support and track the real-time pass, two drive chains are provided for each axes to minimise the drive gear back-lash so that drive gear error can be maintained within the station beam width and should not affect the target tracking. Thus, the output of speed loop is bifurcated into two output commands by adjusting the biased voltage, which can be either fixed or dynamically varying commands in case of digital programmable systems as per the torque bias adjustment scheme as depicted in Fig. 2.

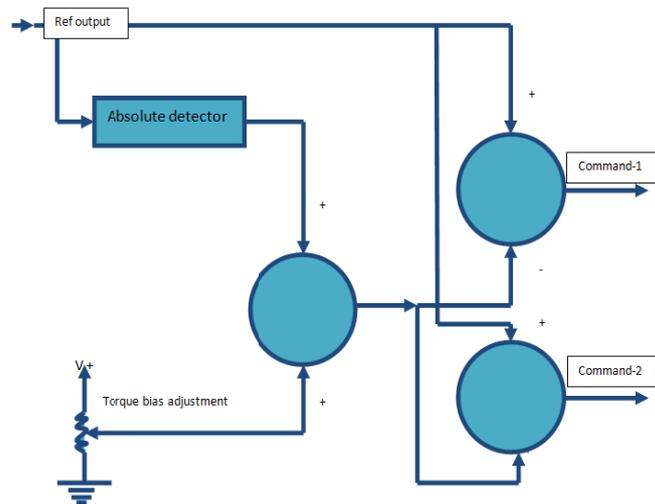


Fig. 2. Torque bias adjustment for dual-drive system

II. FORMULATING & METHODOLOGY

The design methodology of servo control module begins with actual loads acting on antenna servo system [13]. Following loads which oppose the movement of antenna are:

1. Gravity load (Self Weight).
2. Inertia and Frictional loads (due to angular acceleration).
3. Wind loads.

In order to achieve the total mechanical drive torque of the system, it is essential to compute wind torque, inertial torque, & frictional torque of the system.

Therefore, total drive torque expressed is:

$$T = T_w + T_i + T_f \quad Nm \tag{1}$$

Where in

T_w = Torque required to overcome wind loads

T_i = Torque required to overcome inertia of the body due to self weight.

T_f = Torque required to overcome friction in the body due to rotation.

The mechanical forces and respective torques are estimated and the required mechanical torque and is derived to be 2550 Newton-metres which includes wind torque, frictional torque and inertial torque. Having estimated total mechanical drive torque, the electrical torque required has to be derived. The electrical torque depends on gearing mechanism engaged between mechanical load (antenna) and electrical AC motor and antenna load torque.

The gearing ratios is expressed as:

$$\text{Gearing ratio } N = \frac{\omega_m}{\omega_o} \quad (2)$$

Where, ω_m and ω_o are the speed of motor and load, respectively.

Now, reflected torque and inertia to the motor can be calculated from load inertia J_o' and torque requirement at the load T_o' by the following expressions,

$$J_o = \frac{J_o'}{N^2} \quad (3)$$

$$T_o = T_o' / N\eta \quad (4)$$

Here, efficiency of convertor is η . These mathematical relations were converted to linear motion form and the total motion required by motor shaft is combination of inertial, frictional and damping torques.

The gearing ratio is derived to be 900:1 based on the inertia principle between load and servo motor. Further, speed of the electrical motor depends on the speed of the tracking antenna which is following the satellite target from ground. The drive should supply the peak and rms current supply of the system [3], [9].

$$I = \frac{T}{K_t} \quad (5)$$

Where K_t =torque constant of motor. Therefore, drive should be able to supply the voltage expressed:

$$V = RI + K_e \omega_m \quad (6)$$

R = resistance of motor, K_e = back emf constant of motor, I = motor peak current and ω_m is maximum speed of motor.

Due to the variation of the load and possible overcurrent trip, often it is desirable to use maximum motor speed and peak and rms torques of the motor rating instead of calculated requirement of the system. Hence, the safety margin is considered totally.

Therefore, considering all the design parameters, the requirements which are derived and design specifications are consolidated in Table-1.

TABLE 1

| <i>Description</i> | <i>Quantitative specification</i> |
|-------------------------------|--|
| Servo bandwidth | 0.9 Hz |
| Total Mechanical torque | 2550 N-m |
| Gearing Ratio | 900:1 |
| Motor Torque | 1.9N-m |
| Motor cont. speed requirement | 20*900/6 = 3000 rpm |
| Encoder display resolution | 0.001 [22 bit encoder (360 /2 ²² -1)] |
| Drive switching frequency | 8 kHz (10 times of machine frequency) |
| Antenna Max. Velocity | 20 deg/sec |
| Antenna Acceleration | 5 deg/sec ² |

For better gearing efficiency, planetary gearing mechanism is chosen. Based on the mechanical system parameters, the following are the specifications drawn for Servo Motor and drive amplifier.

Motor torque required to deliver the mechanical drive torque (2550N-m) is 2.55N-m (2550/900*0.90). This is achieved by considering 90% efficiency of Motor with the mentioned gear ratio. Accordingly, Motor & Drive Amplifiers specifications derived are tabulated in Table-2.

TABLE 2

| <i>Parameter</i> | <i>Values</i> |
|-------------------------------|---------------|
| Continuous Stall torque | 2.55 N-m |
| Continuous Current | 4 A |
| Peak torque | 6 N-m |
| Peak Current | 10.1 A |
| Torque constant(N-m/amp) | 0.58 |
| Rated speed @160 volts | 3000 rpm |
| Voltage constant (Vpk / Krpm) | 49.4 |
| Resistance | 5.6 ohms |
| Inductance | 11.57 Mh |

Here, in evaluation test set-up case, single drive chain is considered for practical demonstration as the other chain is replica of first one. The control loops (position & velocity) are represented in closed loop control environment for a continuous system and the mathematical representation of complete system with essential position tracking loop is exhibited in fig. 3.

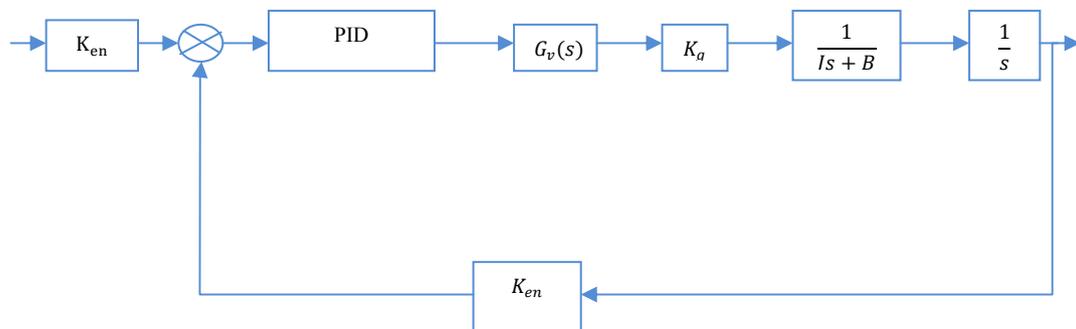


Fig. 3. Position control system representation

- Where, P = Proportional
- I = Integral
- D = Derivative
- Kg = Gearing ratio
- Ken = Encoder constant
- J = Antenna inertia
- B = Coefficient of friction

$G_v(s)$ is the gain of the rate loop and it is computed from rate loop model as exhibited in fig. 4, below:

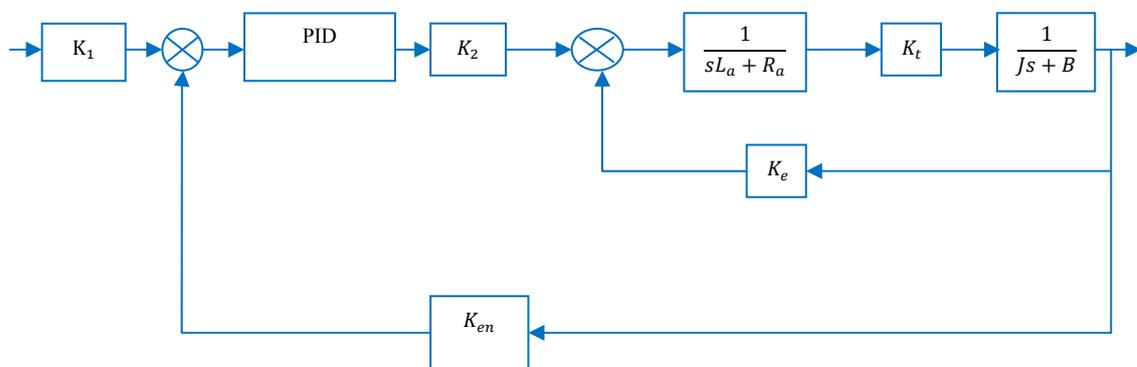


Fig. 4. Velocity loop representation

Where:

- La = Armature inductance
- Ra = Armature resistance
- Kt = Motor torque constant
- Ke = Back emf of the motor
- K1 = Tacho voltage constant
- K2 = Drive amplifier constant
- J = Motor inertia
- B = Coefficient of friction

For better sensing and impact of angle reading resolution a brush less AC Servo motor with resolver feedback is considered for precise position control. Resolver is a analog device which is inbuilt with motor having one primary and two secondary windings with orthogonal arrangements for precise position measurement in harsh and rough weather conditions when compared to other methods of position sensing described in articles [1], [2]. The antenna tracking position loop diagram is also represented in Z-domain as depicted in fig. 5, below.

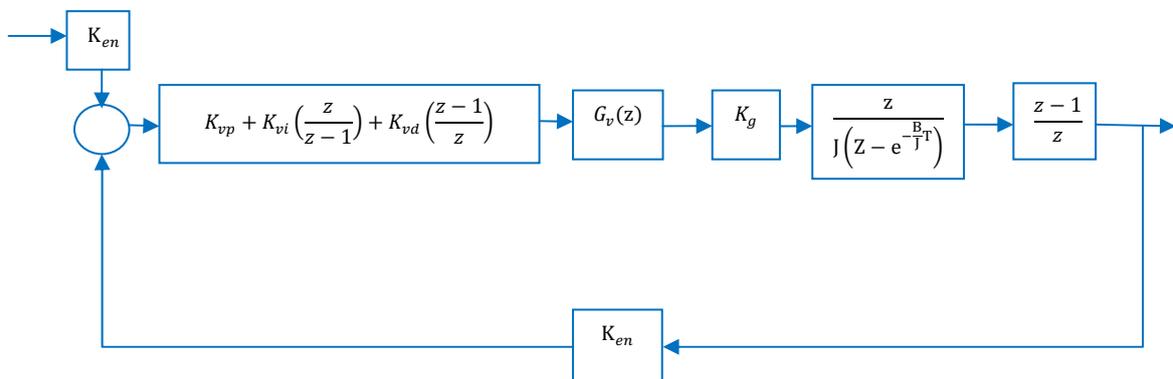


Fig. 5. Z-domain position loop representation

Where, Velocity loop gain is denoted with $G_v(z)$ and it is computed from velocity loop and gain is expressed as:

$$G_v(z) = \frac{K_1 K_2 G_t(z) [K_{vp} + K_{vi} (\frac{z}{z-1}) + K_{vd} (\frac{z-1}{z})]}{1 + K_1 K_1 K_2 G_t(z) [K_{vp} + K_{vi} (\frac{z}{z-1}) + K_{vd} (\frac{z-1}{z})]} \dots (7)$$

As per the design specifications, the PID controller is analysed, transient and steady state behaviour of the system is demonstrated here. To obtain and represent the servo control loops, the electrical representation of equivalent circuit of servo motor, drive amplifier and antenna system were carried and transformed mathematical representations into S-domain as described in introduction section for position and rate loops of the system. Further, the design calculations and specifications are used to represent system transfer function. Thus, the rate loop block reduction is as given in Fig. 6.

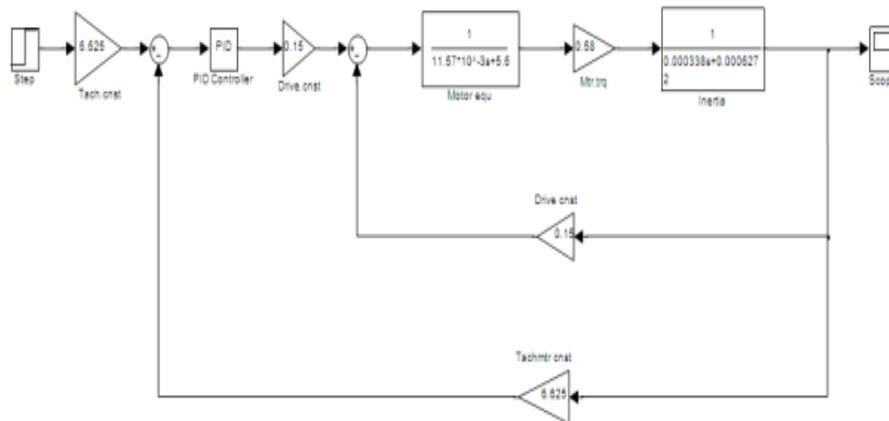


Fig. 6. Rate loop block reduction in MATLAB

The above block diagram is further reduced to obtain the velocity loop gain/ transfer function. The rate loop transfer function of the system expressed as:

$$\frac{(sK_p + K_i + K_d s^2) \times 0.5763}{s(44.428 \times 10^{-8} s^2 + 21.5 \times 10^{-5} s + 0.029) + (sK_p + K_i) \times 0.087 \times 6.625} \dots \tag{8}$$

Gain of the rate loop:

$$G_v(s) = \frac{5.767 \times 10^{-4} s^2 + 3.456 s + 1.152}{44.406 \times 10^{-8} s^3 + 7.913 \times 10^{-4} s^2 + 0.3548 s + 1.1526} \dots \tag{9}$$

The velocity loop inside the position loop enhances the system stability. The position loop block reduction comprising velocity gain is as exhibited in Fig. 7.

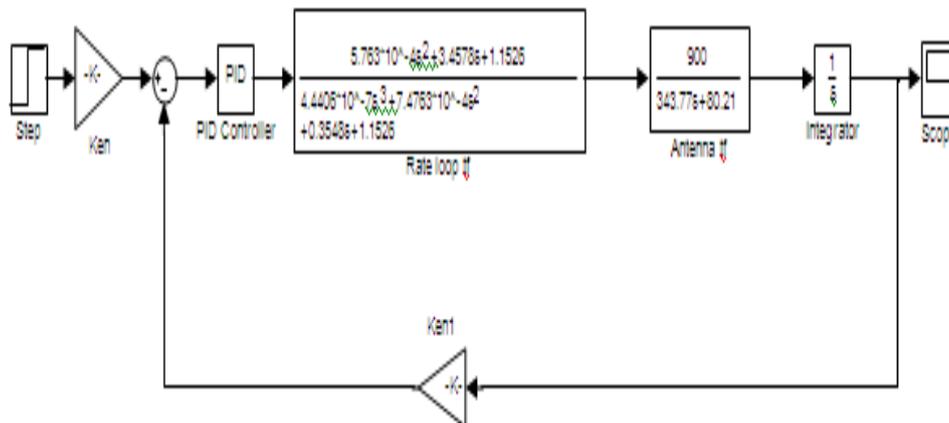


Fig. 7. Position loop reduction block in MATLAB

The speed loop incorporates the current loops. The ultimate performance of the servo is decided by the position loop controller [12]. It encloses the speed loop with its output, forming speed demand. The position error is computed as the difference between command position and measured position. The position feed-back is taken from the encoder by default. In case of fault in the encoder the position loop is closed by the position, sensed through resolver in the motor. The position error (demand position - actual position) is filtered through a position loop compensator. This system transfer function is as indicated below.

$$\text{Gain of the position loop } G(s) = \frac{2.854 \times 10^{-5} s^4 + 0.342 s^3 + 1026.564 s^2 + 684.28 s + 114.04}{1.5274 \times 10^{-4} s^6 + 0.27199 s^5 + 122.0074 s^4 + 424.94 s^3 + 1119.01 s^2 + 684.28 s + 114.048} \tag{10}$$

III. TRACKING CHAIN EVALUATION TEST SETUP

As discussed the importance of evaluating test set-up mechanism for system failures/ break-downs, the practical implementation of tracking chain evaluation test set-up is developed and demonstrated here. Hardware components comprise various sub-systems viz., controller, drive amplifier, Brushless servo motor and gear reducer and encoder feedback. The complete position loop system of BLDC servo motor [4] is considered, interfaces between motor and drive amplifier is identified and established accordingly to form current and velocity loops. The encoder feedback is taken and given as input to controller to form the position loop. The detailed interfaces are as indicated in fig. 8.

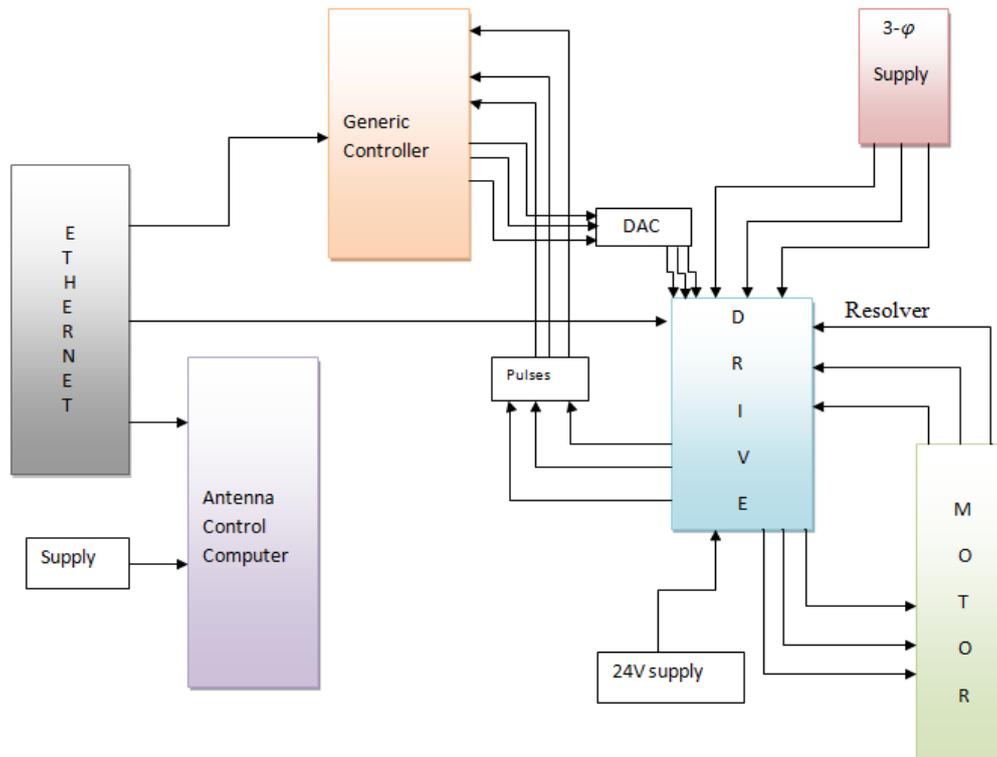


Fig. 8. Interface diagram of servo control system

As the identified electronic modules are having Ethernet interfaces, monitoring and control is possible. The drive amplifier and controller configuration is done by accessing Ethernet facility. The 24V is utilized for brake release of motor and drive enabling also and 3-phase supply is used as input to drive amplifier which is then rectified to 300V D.C input to IGBT based Inverter Bridge.

The hardware test-setup of the control system which is implemented is as shown in Fig. 9.

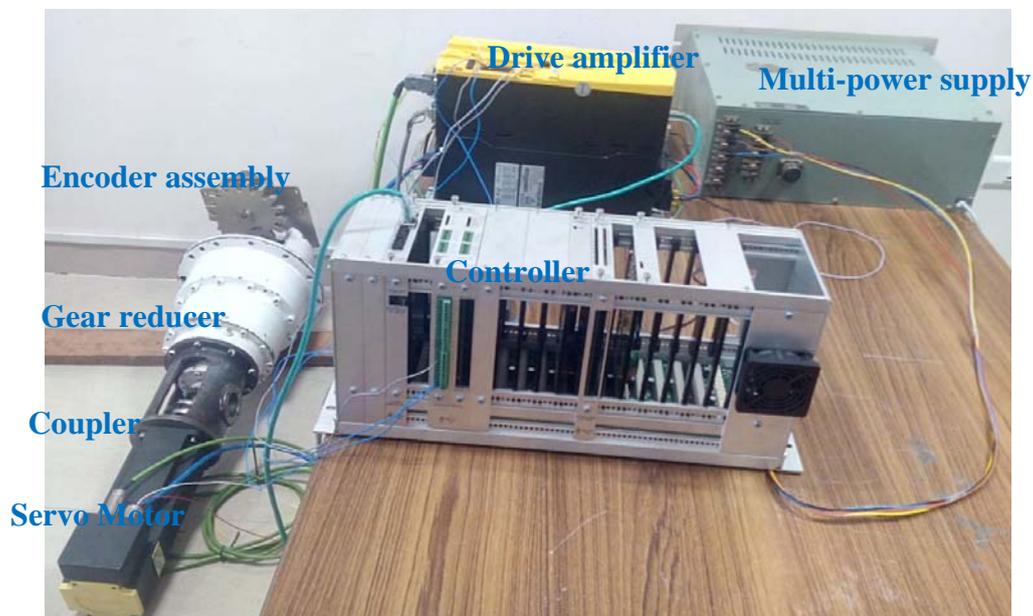


Fig. 9. Hardware test set-up of servo control system

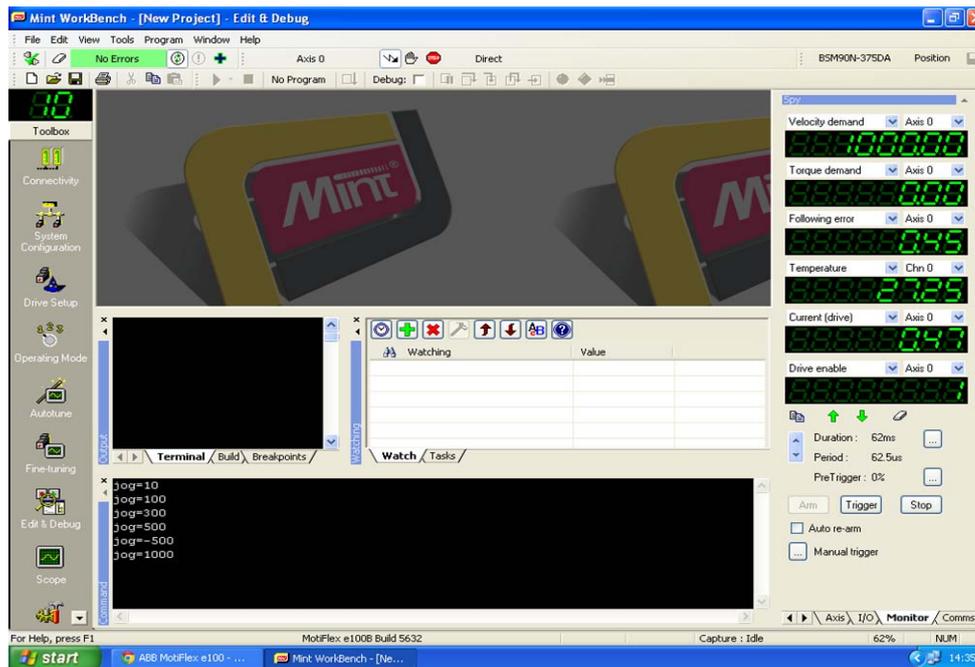


Fig. 10. Rate loop mode real-time monitoring

The drive amplifier design specifications, drive configured with mint work software tool. Rate loop test is conducted and motor demand and actual velocities, following error, enabling status were verified in rate loop test mode and test results monitored and exhibited in Fig. 10.

From the results fig. 10, it is noted that the demand and actual velocities are as expected with minimal following error 0.45 counts only for move of 1000 counts demand. As the test is rate loop test mode, the torque demand is reported to be zero and current drawn for system is only 0.47A with operating temperature of about 27.25°C.

IV. PRACTICAL, SIMULATION RESULTS & DISCUSSION

(A) Experimental Results:

The test set-up test results are obtained and real-time testing and monitoring results which were exhibited in fig. 10 shows the demanded and commanded velocities are very close and following error is about 0.45 counts which is equal to close zero position value of shaft. Because for one revolution of shaft/ 360° movement of motor shaft, resolver produces 16384 counts. i.e., for at least 1° of motor shaft movement, a minimum of 45 counts required. Further, the response of the motor is observed by giving different inputs to the system i.e step input, sinusoidal input, and parabolic input. These results represent the actual position and command position of the motor with respect to time which is as exhibited in Fig. 11a, 11b, 11c respectively.

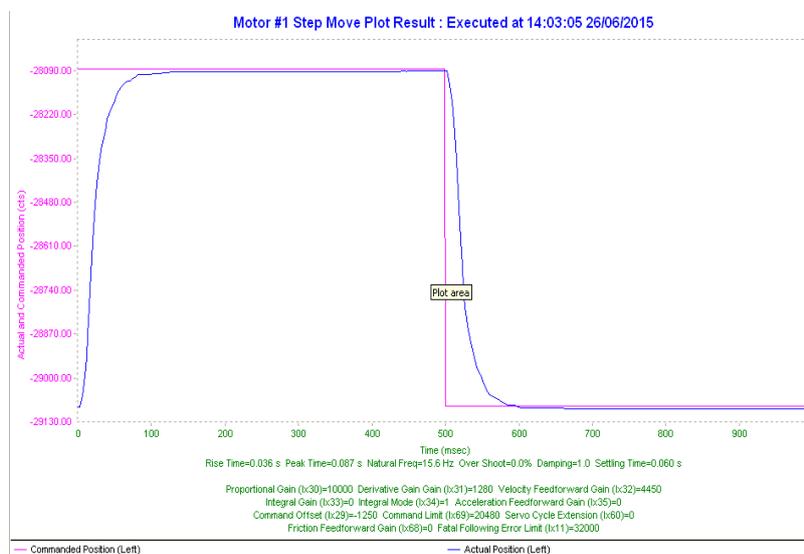


Fig. 11 a. Response of the step input

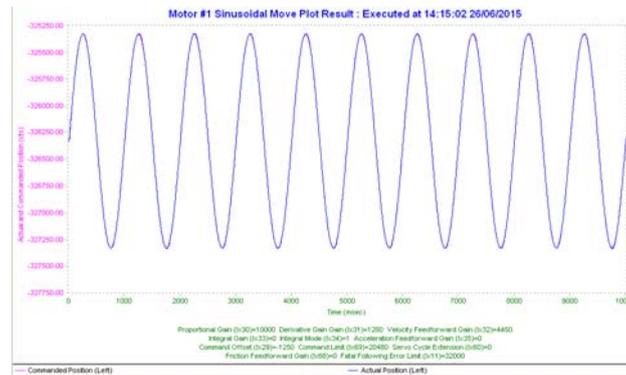


Fig. 11b. Response of the sinusoidal input

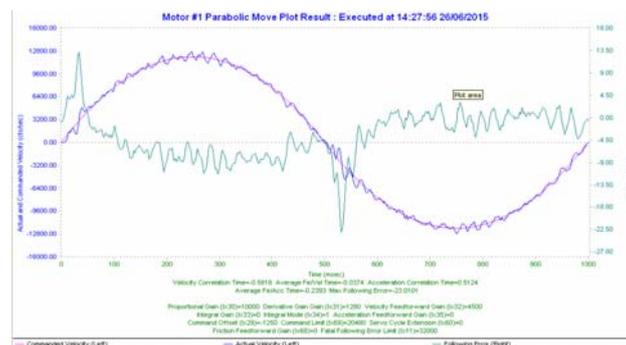


Fig. 11c. Response of the parabolic input

From the above test results, it is seen that the rise time, peak time and settling time of the system is extremely well and as expected and near ideal values achieved. The commanded and actual positions are very close to each other with small following error of about 23.01 counts which is a very small value. The system is not having any overshoot due to non-presence of frictional component. Since, the test is conducted without antenna load as the aims of the article is to test, verify and configure the servo system sub-modules and evaluate the system in off-line mode, as the diagnosing and normalising the system in real-time which is quite not possible. In this test set-up, any antenna servo system failures can be simulated, monitored, diagnosed and configured. Hence, servo drive chain evaluation and restoration can be done practically.

(B) Simulation results & analysis

The simulation results for rate loop and position loops are obtained and exhibited in Fig. 12, Fig. 13, Fig. 14 & Fig. 15 respectively. The position loop results in time domain as well as frequency domains obtained shows that the rise time of the system is fast enough about 0.39 sec, overshoot is 23% due to which settling time resulted into 3.2sec. The bandwidth of the system becomes 0.89Hz. The system has considerable phase and gain margins 74° and 63dB respectively.

The transient behaviour of system is demonstrated. Accordingly, stability conditions fulfilled and the system is optimized using Ziegler-Nichols PID tuning method [11]. It is very clear from the rate loop step response Fig. 12, that the rate loop is having higher bandwidth than position loop, it is good to have higher bandwidth rate loop in point of view of attenuating effect of torque disturbances and less bandwidth of position loop as it encloses the rate loop.

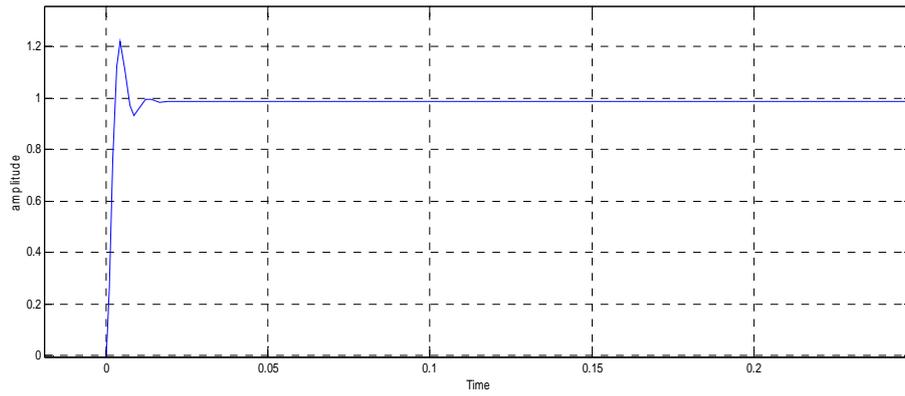


Fig. 12. Step response of rate loop

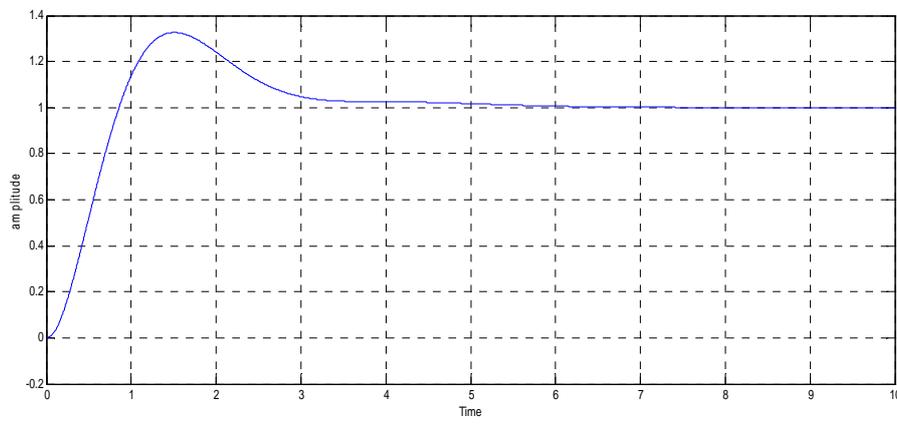


Fig. 13. Step response of position loop

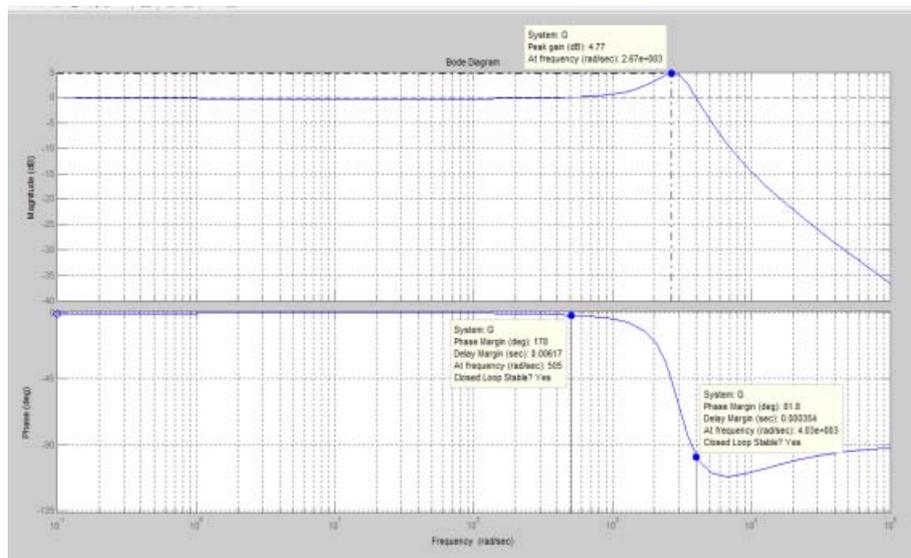


Fig. 14. Bode plot response of rate loop

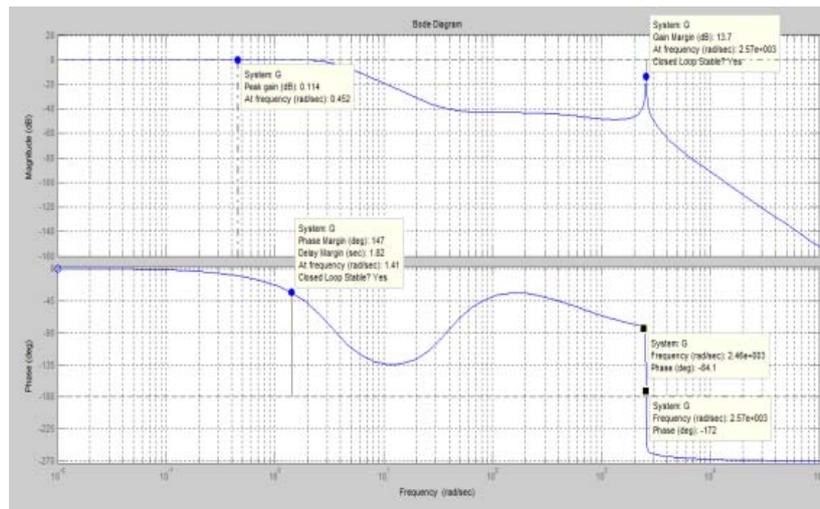


Fig. 15. Bode plot response of position loop

The position loop simulation results viz., rise time, overshoot, settling time, bandwidth; phase and gain margins are tabulated in Table-3 below:

TABLE 3

| <i>Description</i> | <i>Particulars</i> |
|---------------------|--------------------|
| System rise time | 0.39 Sec |
| Overshoot | 23 % |
| Settling time | 3.2 Sec |
| Bandwidth | 0.9 Hz |
| Phase margin | 74° |
| Gain margin | 63 dB |
| Bandwidth of system | 0.89 |

The experimental and simulation results and analysis shows that the obtained performance of the system is excellent in dynamic error and also in steady state performance. Design specifications and practical performance is very close in values as expected. The system produced absolutely stable performance and also this was verified with frequency domain analysis having adequate phase and gain margins as noted in above table-3. The test set-up is very much useful in isolating the tracking chain faults and then rectifying, re-configuring, verification and restoration of the system.

V. CONCLUSION

The servo control methodology is evolved for better and precise control. Evaluation test set-up is implemented for fault isolation, testing, commissioning and configuring the servo drive chain parameters. The specifications of servo sub-modules are derived as per the design requirements as described. The simulation of tracking chain is achieved and system behaviour is analysed in Matlab/ Simulink. A hardware test setup for tracking chain simulation/ evaluation is integrated, interfaces between sub-systems were implemented and testing is conducted and results were demonstrated. The unique evaluation methodology/ developed hardware test set-up is beneficial for fault diagnosis, analysis and rectification. The hardware test set-up will be very much useful for antenna tracking chain verification, re-configuration, restoration and tracking chain qualification thereby reducing the minimum down-time of the real-time antenna servo system.

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