Azimuth Gearbox Windup and Drive Friction Measurements
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Introduction

During the data collection campaign of last June, data were collected on the response of the azimuth drive train. In this report, the focus is on data collected using open-loop measurements of the drive system encoders when driven by a triangular torque command. For the tests described here, the elevation axis was fixed with the brakes set.

Input-output Data

In this series of tests, a triangular torque demand was used to drive the azimuth axis, while data were collected on the one available motor position encoder (Heidenhain RON905), and the absolute encoder. It was found that due to hysteresis (and other) effects, the telescope "walked" off to one side more easily than the other. It is unclear whether this is due to an unbalanced friction condition in the drivetrain, differences in torque bias, individual motor torque output constants, or windup in the utility maypole imputing an uncontrolled torque in to the telescope. All tests were conducted at the 110° repose position to try to minimize this last effect. Also, the telescope tended to store the input torque in inertia and build up to larger and larger motions. In order to safely perform the tests, an offset was introduced in the torque demand to minimize the walking and all tests were terminated after a few cycles to avoid dangerously large excursions of the telescope. Finally, the tests were conducted with varying peak torques and with/without the anti-backlash bias torque turned on.

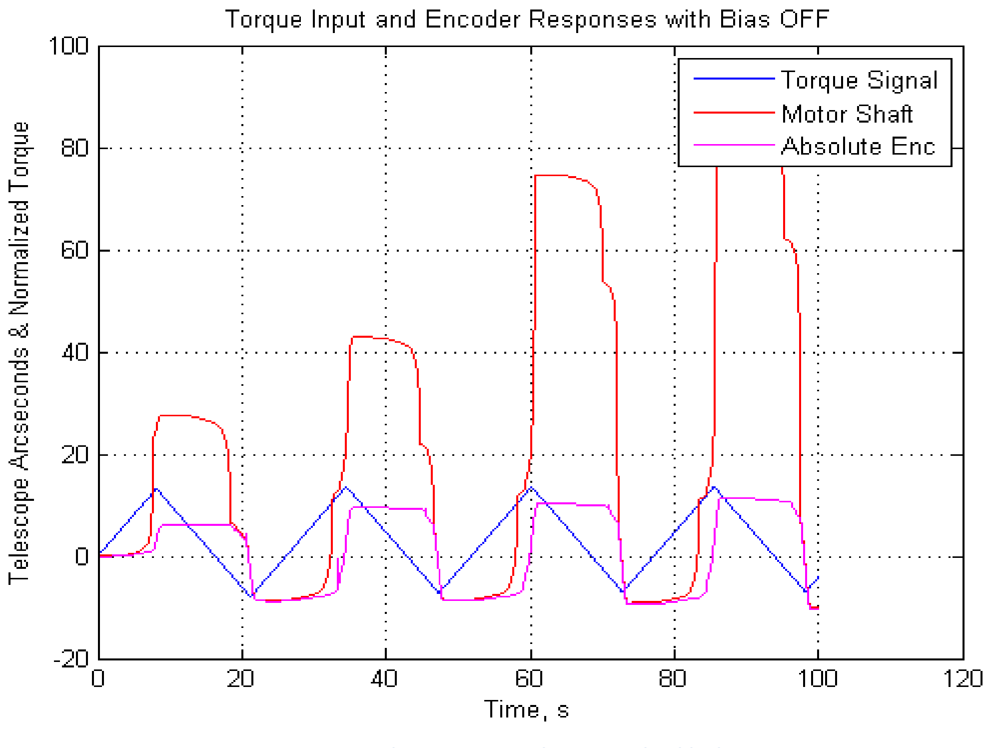

Figure 1. Encoder Outputs without Anti-backlash

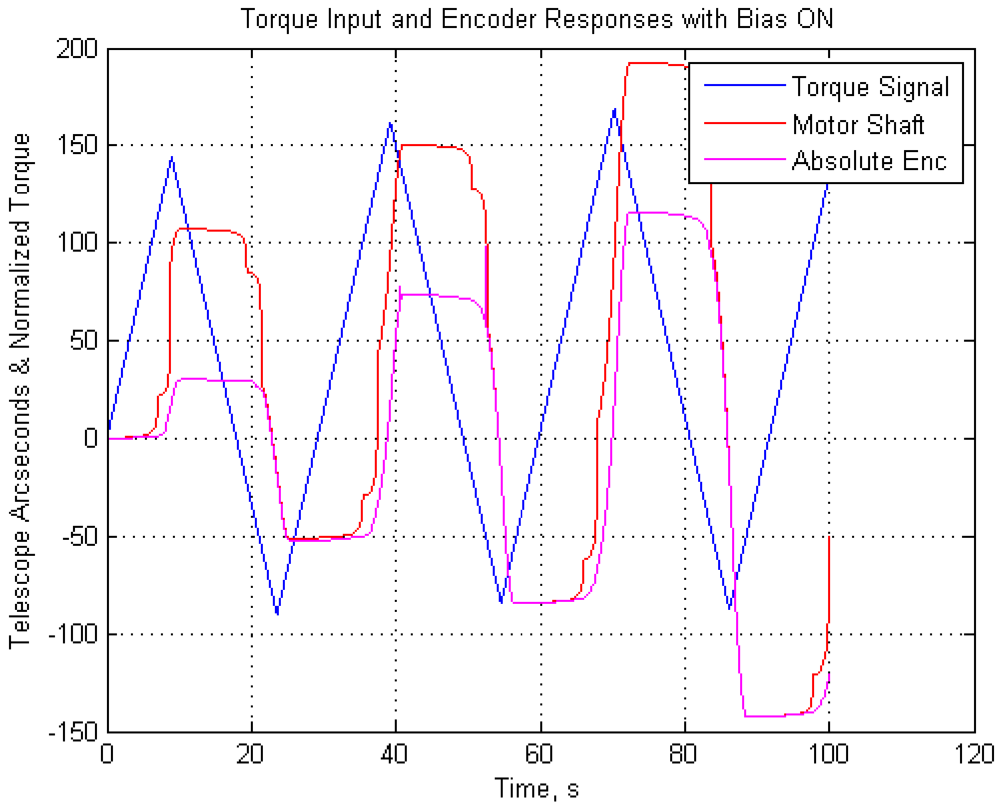

Figure 2. Encoder Outputs with Anti-backlash

For both tests, the difference in the range of motion between the absolute encoder and motor shaft, in telescope arcseconds is -71.3” and -76.5”, with anti-backlash off and on, respectively. In both the above plots, I have normalized the torque input signal to the range of the absolute encoder motion to make the relationship between the input torque and displacement clearer.

Obviously anti-backlash helps a lot in keeping the motor and telescope displacements tracking well with each other; it’s not perfect – this has consequences for control loop stability. The velocity loop demand driven by the absolute encoder creates output torques imperfectly tracked to the telescope position due to the elasticity of the connection between the motor and azimuth encoder. Limit cycling is only one of the several negative features of this arrangement. More extensive study and modeling the physical gearbox meshing and compliances will help flesh out understanding of what implications for smooth tracking are during the servo upgrade process.

Of more immediate moment for design purposes is the information available from the torque demand and encoder outputs when anti-backlash is applied. The friction can be estimated from this data, as well as the gearbox compliance and gear face contact details as the motor torque brings the gears in and out of mesh.

Below, we focus attention on the first ~25s of the test with the anti-backlash present. The torque/position profile gives us information about the behavior of the drivetrain that is well worth detailed study.

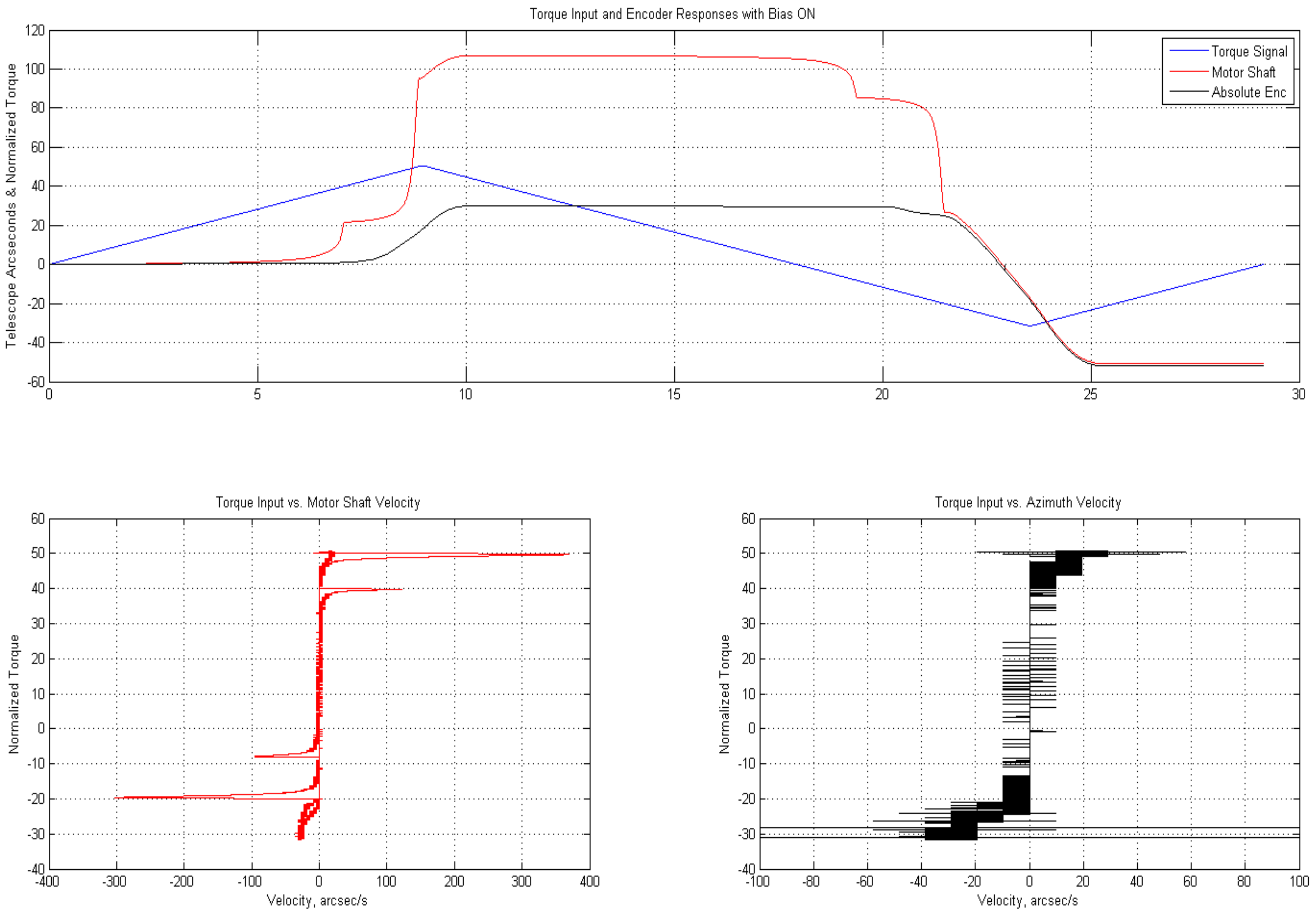

Figure 3. Encoder Positions and Velocities versus Torque

Now the time response of the motor shaft encoder and absolute encoder outputs are depicted in telescope arcseconds, with velocities scaled to arcseconds/s. I have normalized the torque amplitude to the amplitude of the absolute encoder position signal to make the velocity plots scale sensibly. Above, we see that the azimuth axis barely exits the static friction zone, since we never achieved any appreciable velocity. The motor shaft is more interesting: it exhibits a double force/velocity characteristic that shows very clearly the windup in the gearboxes.

Taking the time response from time 0 towards 5s, the motor achieves no velocity, even though the torque is increasing. At about 6s, the motor begins to move until the intermediate gear and its shaft come into mesh and begin winding up, so shaft velocity goes towards zero until windup of the intermediate gear and pinion gear are complete. Now the absolute encoder records motion starting at about 7s. The torque signal begins dropping soon after, so the motor stops moving over the 8-10s period. The azimuth axis likewise stops moving until enough torque in the other direction has accumulated to unload the intermediate gear and wind up in the other direction. This intermediate mesh and windup occurs over the period of about 18-21s, when the motor shaft encoder and azimuth encoder begin to move together. Once the torque input signal drops below the static friction level, they again show no displacement. This is only somewhat like the classic friction model shown below:

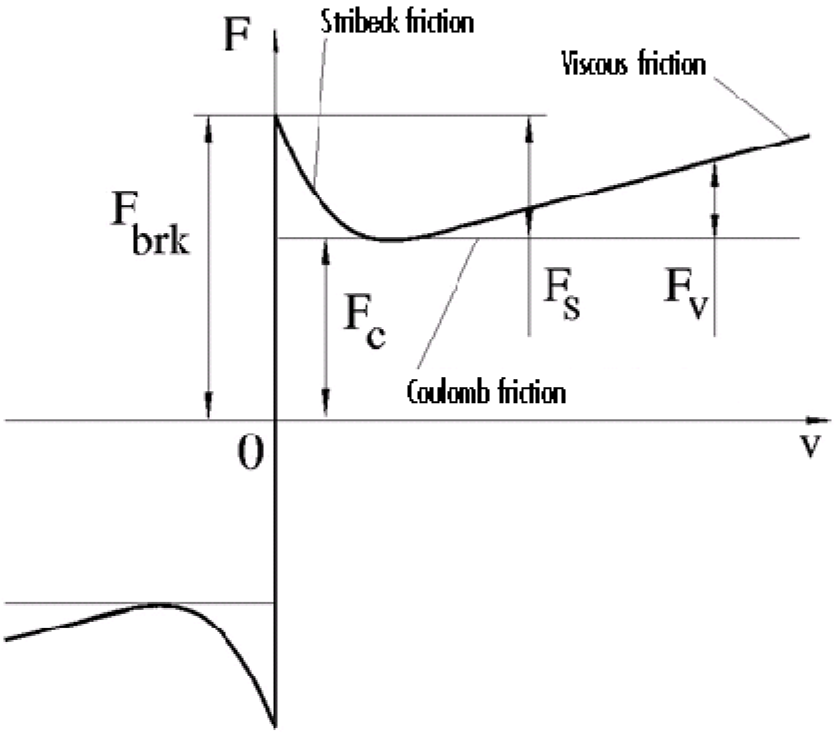

Figure 4. Classic Friction Model with annotations.

The friction force is modeled above as a function of relative velocity and is assumed to be the sum of Stribeck, Coulomb, and viscous components, where:

F is the friction force
Fbrk is the breakaway force where motion begins
Fc is the Coulomb friction
Fs is the Stribeck force
Fv is the viscous friction

Conclusion

The data acquired for this report are of insufficient quality to fully characterize any of the more subtle friction effects in the azimuth drive train. It's clear that a more careful round of testing is needed to capture all the low-level behavior. I'm especially interested in learning more about the velocity output at the absolute encoder, since that is where the servo loop will be getting feedback. The windup and gear-mesh effects in the gear train have an enormous influence on the ultimate tracking smoothness that can be achieved, and should be fully understood before attempting to design the servo loop feedbacks (e.g. do we need a friction compensator in the control loop?).

The data presented here is of value in building a reasonably accurate model of the gearbox and telescope using Simulink's mechanical modeling environment. I think time spent putting together a mechanical model to represent the windup and friction, even at low fidelity, will help to develop design scenarios to converge on the correct servo loop topology. Given the strange double windup in the motor shaft encoder output, I will invest some time to build this model to make sure there aren't any "gotchas" coming up in the development cycle.