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A First Study of MMA Antenna Offset Performance

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Abstract
For scientific reasons, it must be possible to offset the MMA antenna pointing by 1.5 degrees within 1.5 seconds. To study the feasibility of this, a simple, lumped model of the antennas is set up and cascade controllers for velocity and position loops are added. It is found that the bandwidth of the position loop must be 3-4 Hz to achieve this. To avoid structural oscillations ("ringing") after the offset, specially shaped input trajectories must be applied. It seems likely that feedforward in combination with such shaped input curves will permit fast offsets in pointing. Further studies to explore this possibility are pending.

Keywords: Radio telescopes, antennas, servo system, pointing, structural dynamics, offsetting.

1. Introduction
The MMA array will have about 30 submillimeter antennas with diameters of 10 m. For calibration purposes, it is desirable to offset the antenna pointing by 1.5 degree to a precision of 3" within 1.5 seconds. The present note deals with the feasibility of this feature.

Switching performance depends on the acceleration capacity, and on the dynamics of the servo and the antenna structure. For this application, the acceleration capacity as defined by the motor torque is not a limiting factor.

Hence, the servo dynamics and the antenna dynamics, and the interaction between the two, will determine the performance. The dynamics of the structure plays a role in two ways. Firstly, the part of the dynamics that is seen by the servo defines how the servo can be designed and which servo bandwidth that is achievable. Secondly, both the part that is visible and the part that is invisible to the servo respond to servo actions and perform "ringing". Such ringing may influence pointing and image quality for a period of time after servo activity.

The present investigation has concentrated on the servo and its interaction with the structural dynamics. For these effects, a reasonably simple model of the antenna structure gives a good approximation to system performance. The high order ringing effects are deferred to a separate study based on a finite element model of the structure.

2. Simple model of Antenna Dynamics
For servo design purposes, the antenna dynamics may be represented by the model shown in Figure 1. The antenna is modeled by two lumped fly-wheels interconnected by a spring. The fly-wheels represent the motor and the antenna, and the spring represents all resilience acting in series[1,2]. The spring rate can be determined from the locked rotor resonance frequency.

For simplicity, the model depicted in Figure 1 does not include a gear. It can easily be added without changing the principles. Alternatively, all moments of inertia and other parameters can be referred to the same

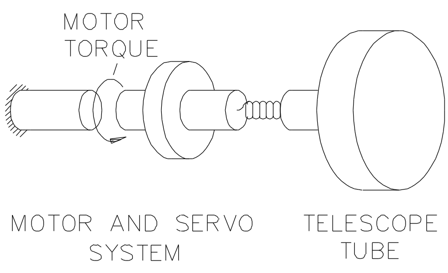

Figure 1. Simple model of antenna structure.

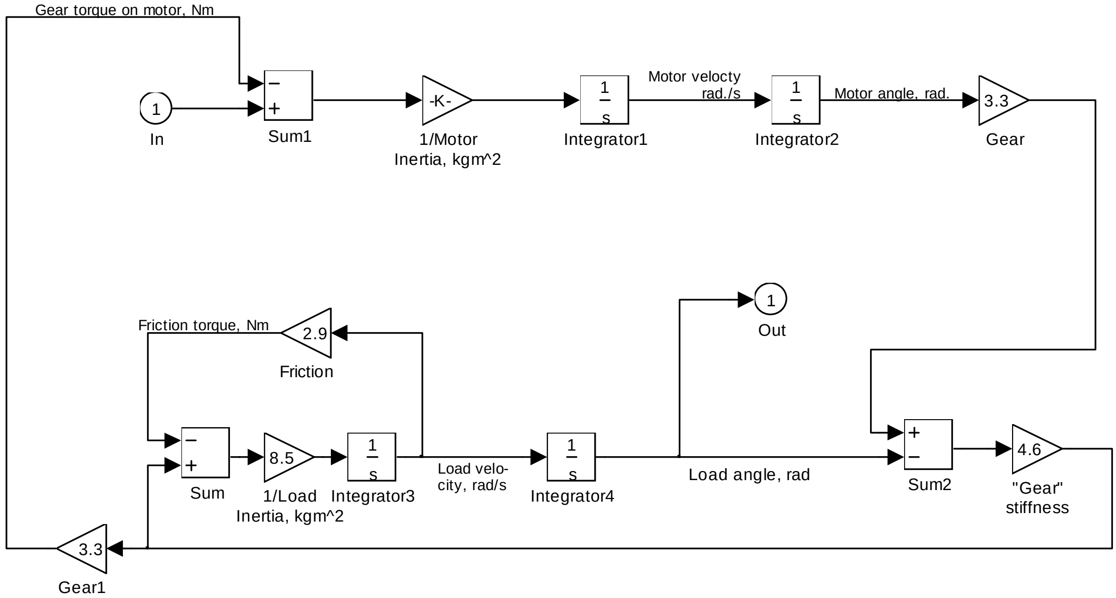

Figure 2. Block diagram of system schematically shown in Figure 1.

axis. Also, viscous friction is not shown. For the first linear considerations, viscous friction proportional to angular velocity is assumed to exist between load and ground leading to a damping ratio of about 0.02. Non-linear bearing friction will be considered later.

From Newton's second law, it is straightforward to formulate the system equations and to set up a block diagram of the system. A block diagram of the structure can be seen in Figure 2. The input is electric torque on the motor shaft. The motor velocity (~tachometer reading) or load position (~encoder reading) would be typical interface points for the servo.

For the present configuration, the following values have been used:

Motor inertia	0.0091	kgm^2
Load inertia	117000	kgm^2
Gear ratio	3000	
Series stiffness	462	MNm
Viscous friction	294000	Nms
L.r.r. frequency	10	Hz

The considerations are equally valid for designs with one or two motors per axis. If two motors are used, the motor inertia refered to above should be replaced by the sum of the moments of inertia of the two motors. In addition, it should be ensured that oscillations of the two motors against each other would not pose problems. This is outside the scope of the present study.

The system is of fourth order. It has an eigenfrequency of 15.6 Hz and two eigenvalues very close to zero, corresponding to free body motion.

3. Servo System

Generally speaking, two types of servo systems can be used for astronomical telescopes: cascade controllers and state-space controllers. The cascade controllers are typically of PI type with suitable compensation networks. These controllers are used on Single Input Single Output (SISO) systems. There are several cascaded loops, one inside the other. The state space controllers are multivariable. Numerous design possibilities exist, for instance using observers and pole-placement techniques.

An overwhelming part of the telescopes and radio telescopes in use today use cascade controllers. Attempts have been made to apply state space controllers but these appear not to have been successful. On the other

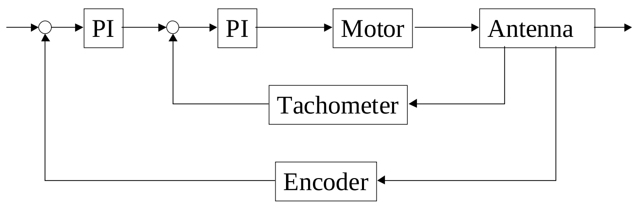

Figure 3. Overview of a conventional servo system for radio and optical telescopes. Compensation networks and current loop are not shown.

hand, modern control theory has already for a long time been based on state-space techniques. Hence, it is expected that at some time in the future, reliable state-space controllers for astronomical telescopes will find widespread use. However, due to the limited success so far, it was found to be conservative to base the considerations on traditional cascade controllers.

The servo system for the antenna is shown in Figure 3. The drive has torque motors with a current loop (not shown) to speed up the system by reducing the effect of the inductance in the motor windings. There is a tachometer loop with velocity feedback from the motor shafts. Experience shows that velocity feedback should be taken from the motor shaft to avoid stability problems from high-order resonances.

The encoder feedback should be taken as close as possible to the mechanical structure defining the antenna boresight, i.e. on the telescope tube (=load) of Figure 1. However, due to the distributed nature of the inertia, encoder feedback is in practice normally neither taken from the load nor the motor but rather "somewhere in between". This reflects the fact that the model shown in Figure 1 is highly simplified.

The tachometer and the position loops should be implemented digitally. The sampling rate should be about 1 ms and this value is so high that the system, for this introductory study, can be considered as continuous.

4. Design of Servo System

The models described are all linear. Hence, conventional linear tools can be applied for servo system design.

Figure 4 shows Bode plots for the tachometer loop. The solid curves are open-loop Bode plots with appropriate scaling. It is essentially a line falling 20 dB/decade because of the integrating effect of the motor. At high frequencies, the motor and the load become decoupled. This is seen as a decrease in inertia, and for high frequencies the amplitude ratio line is located higher than for low frequencies. The phase never goes below -90° and, ideally, any high bandwidth can be obtained even with a simple P controller.

In practice, secondary resonances in the structure limit the bandwidth of the tacho loop. Experience shows that the bandwidth achievable depends on the ratio between the moment of inertia of the motor and the load, re-

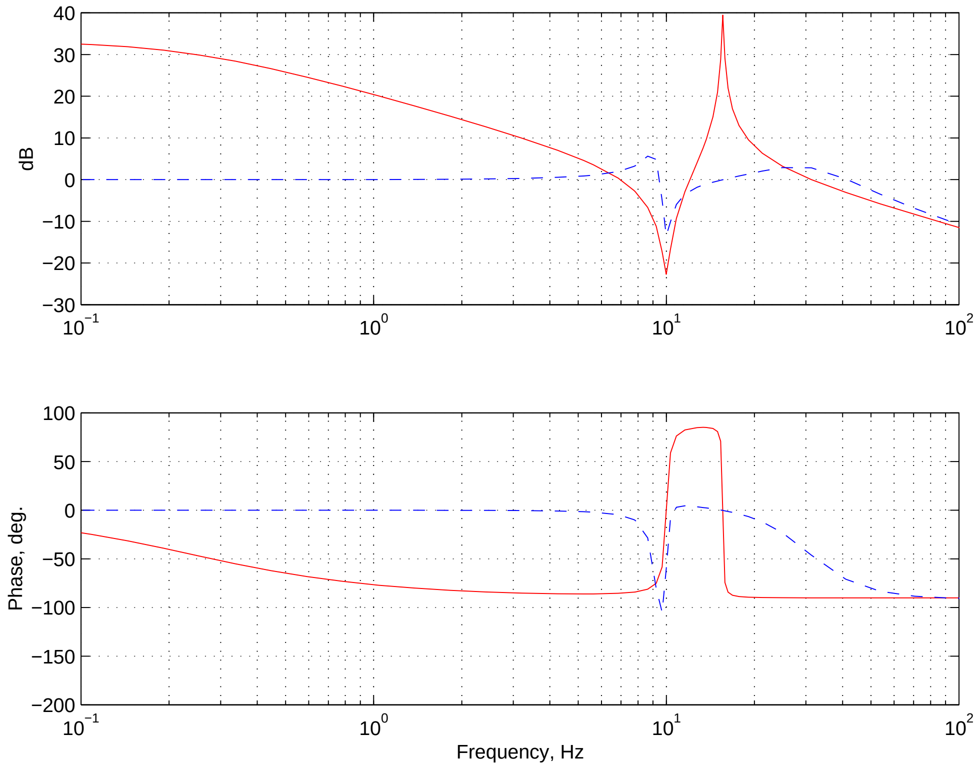

Figure 4. Bode plots for open and closed tacho loops, respectively. The open loop curves are solid, and the closed loop dashed.

ferred to the same axis. If the ratio is <<1, as for a direct drive, the bandwidth achievable is normally somewhat below the locked rotor resonance frequency. If the ratio is >>1, as for a small motor and a large gear ratio, a very high bandwidth above, say, 100 Hz is achievable.

For the present application, the ratio between the motor and load moments of inertia referred to the same axis is 0.7, i.e. close to a matched inertia condition. This is a value traditionally selected, partially for historical reasons. It corresponds to a matching of impedance in an electric network and is optimal from an energy transfer point of view. However, from a stabilization point of view it is unpleasant[3].

From experience it is reasonable to expect a bandwidth of about 50 Hz for the present system but it would require a finite element analysis to give a more clear answer. For the present analysis, it has been assumed that a bandwidth of 50 Hz is obtainable. The break frequency of the PI has been chosen to be 30 Hz. For these choices, the closed loop bode plots are shown dashed in the curves. There is a dip near the locked rotor frequency, corresponding to a peak in the amplitude ratio for the load (not shown).

The open position loop is shown in Figure 5. The encoder signal is here taken from the antenna load and not from the motor. Thus, the dip near the locked rotor resonance frequency found in the tacho loop now appears as a resonance peak. As for the velocity loop, the curve drops 20 dB/decade at low frequencies.

Due to the drastic phase shifts near the resonance peak, it is for this configuration, with conventional means, not possible to achieve bandwidths higher than 3-5 times below the locked rotor resonance frequency (10 Hz). For the present case, a PI controller with a break frequency of 0.8 Hz in series with a first-order lowpass filter with a break frequency of 4 Hz has been selected. This gives a closed loop bandwidth of about 2 Hz. The frequency response of the closed position loop is shown dashed in Figure 5.

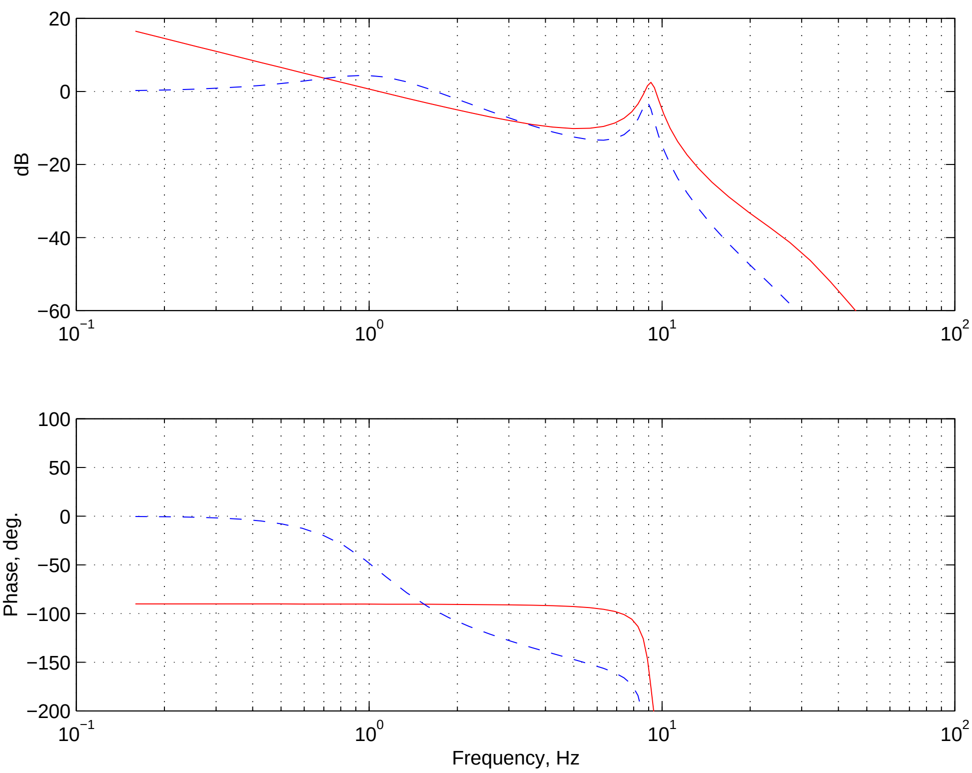

Figure 5. Open and closed loop frequency responses for the position loop. Encoder feedback is taken from the load. The open loop responses are solid and the closed loop plots dashed.

If the encoder is connected to the motor shaft, it is possible to obtain a faster servo system. The bandwidth can be 4-5 Hz. This is demonstrated in Figure 6, showing open and closed position loop frequency responses with encoder feedback from the motor.

As mentioned before, in practice the encoder signal is neither taken from the motor shaft nor the load but rather "somewhere in between". Hence, the two cases described constitute limit cases. It would take a more detailed model based on a finite element calculation to go into details.

In some cases it is necessary to force the bandwidth of the position loop to a value near or above the locked rotor resonance frequency. The remedy for this is to insert a notch filter in series with the controller. In this way, it is, in principle, possible to cancel resonance effects near the locked rotor resonance frequency. However, in practice this approach is often dangerous, in particular for physically large systems. Such a system can be highly susceptible to parameter changes causing drift, and the risk of instability is high. Also, for the azimuth movement, corrections must be made for parameter changes due to change in elevation angles. Hence this approach is not attractive for general use.

5. Performance Analysis

For this study, the linear model shown in Figure 7 is applied. The model can easily later be modified to include non-linear effects such as digitizing, saturation and dry friction. A step response of the complete system with position feedback from the load and a step of 1.5 degrees is seen in Figure 8. Due to the low bandwidth of the position loop, it takes about 2.2 seconds to reach the final position with a tolerance of 3 arcseconds.

Although some "ringing" occurs, the step response shows that the major problem in this configuration is the low bandwidth of the position loop. On the other hand, the bandwidth would need an improvement of only a factor about 1.5. This is roughly the uncertainty in the servo system design of this study. Hence, system performance is marginal and it would take a more detailed study to determine whether the specification can be met.

It can also be seen that with position feedback from the load, ringing may not be a problem.

For the configuration where the position feedback is taken from the motor, the step responses shown in Fig-

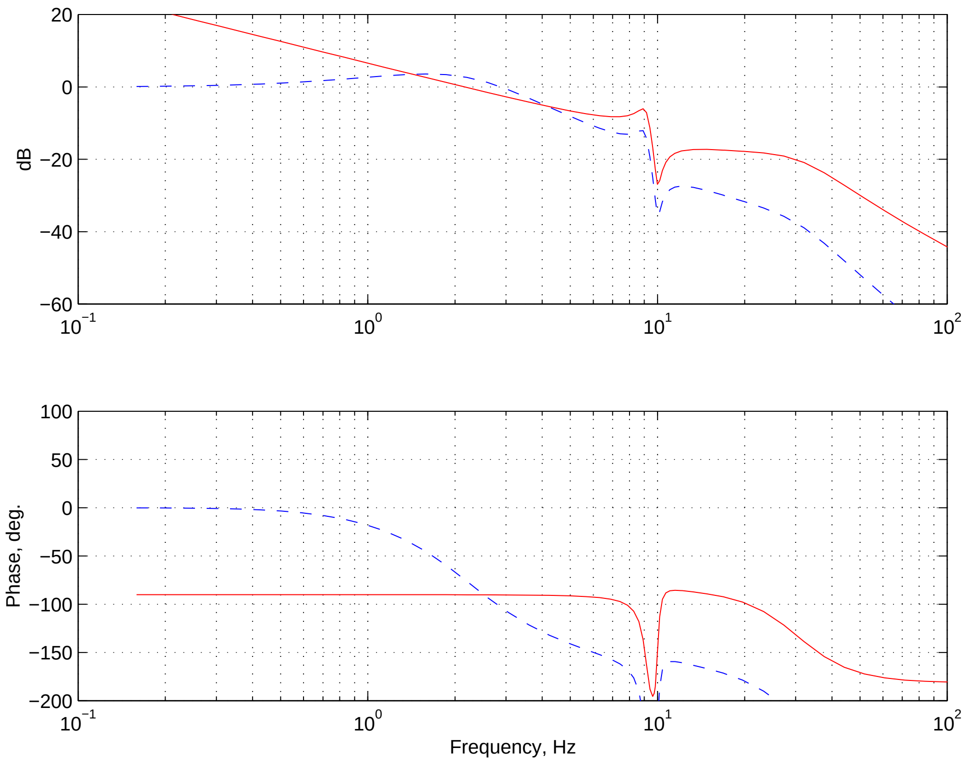

Figure 6. Open and closed loop frequency responses for the position loop. Encoder feedback is taken from the motor shaft. The open loop responses are solid and the closed loop plots dashed.

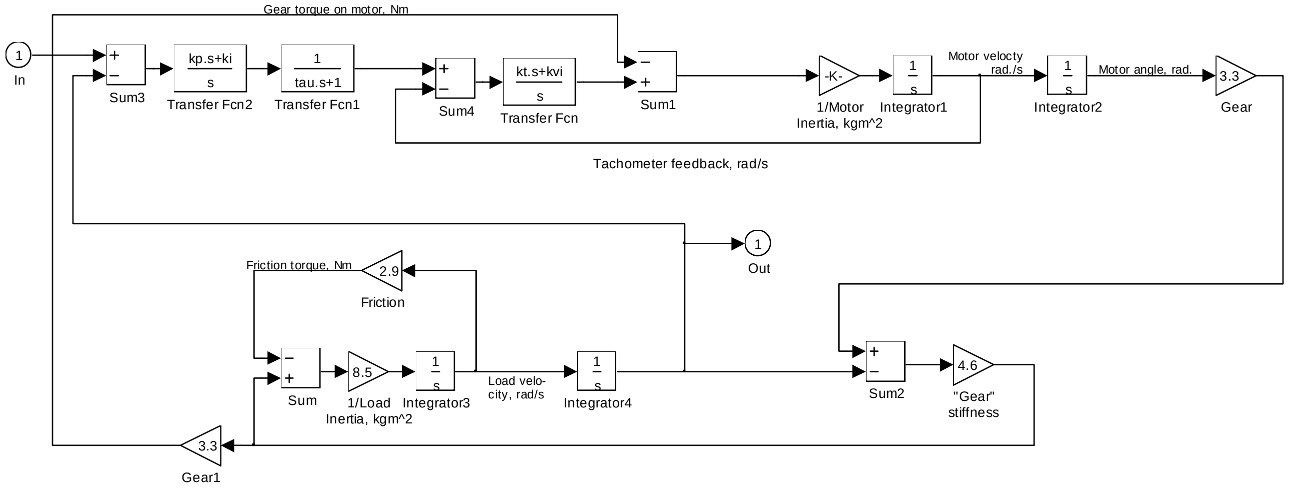

Figure 7. Block diagram of complete, linear model applied for this study. The diagram is shown with position feedback from the load. Alternatively, the feedback can be taken from the motor shaft.

ure 9 are obtained. The system is now faster than for Figure 8 but heavy ringing takes place due to the fact that the load movement is outside the servo loop.

6. Suppression of Ringing

In practice, the system will have a performance somewhere between that of Figure 8 and Figure 9. Hence ringing may be a problem and it is of interest to discuss methods of suppressing such effects.

Two approaches can be identified. The first is to change the system dynamics actively or passively. One or more damping loops can be added. This can be accomplished using observers to identify the unmeasured states or by adding load feedback from accelerometers. Such an approach has been used for some optical telescopes[1,4] but may not be attractive for the present application due to its complexity.

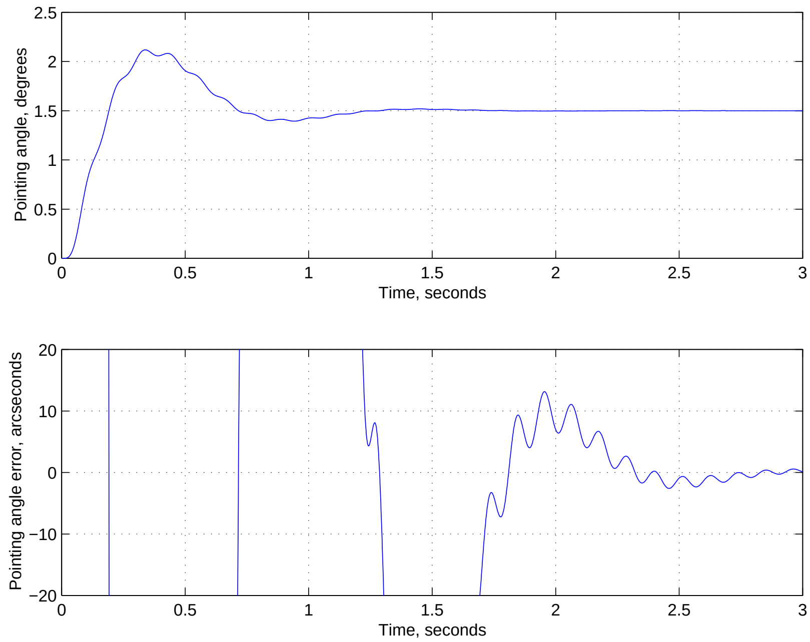

Figure 8. Step response of complete system. Encoder feedback is here taken from the load. It can be seen that the system is inherently too slow and that ringing is not critical.

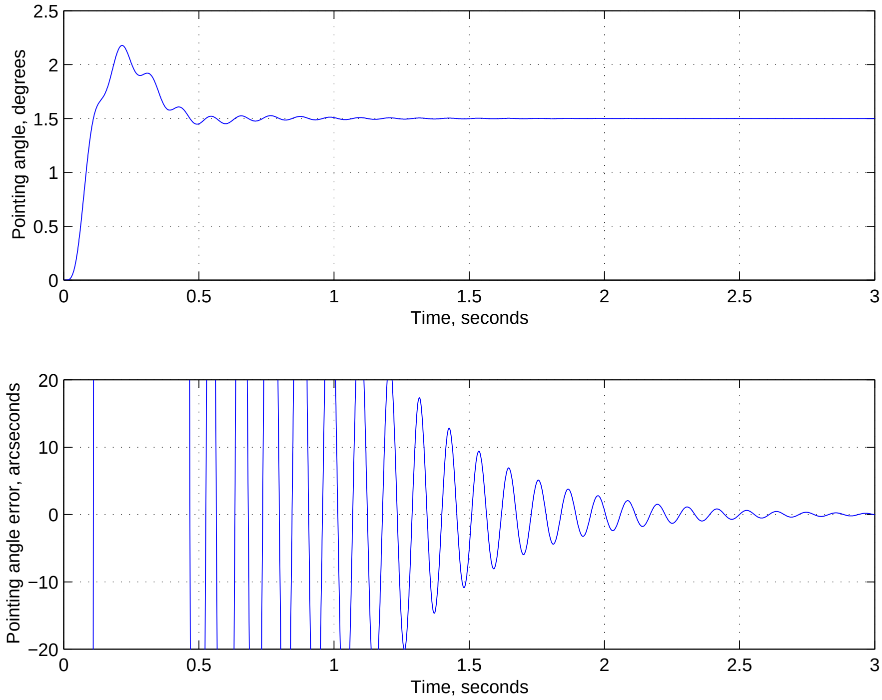

Figure 9. Step responses for a system with position feedback from the motor. The curves above show the movement of the load. Intense ringing occurs.

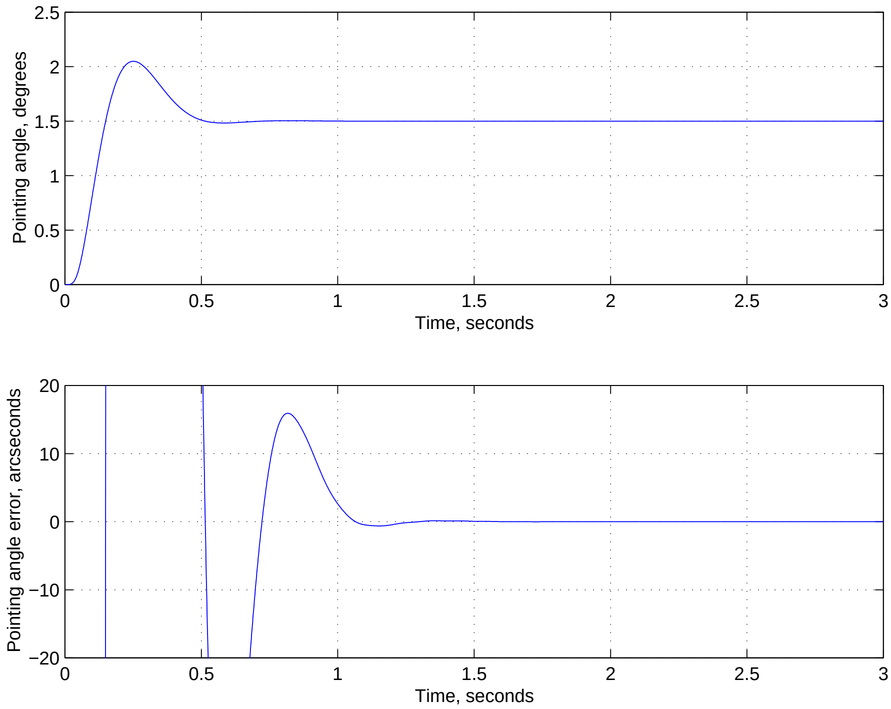

Figure 10. Step responses for a system with position feedback from the motor. The curves above show the movement of the load. The input curve is shown in Figure 11. Ringing is completely avoided.

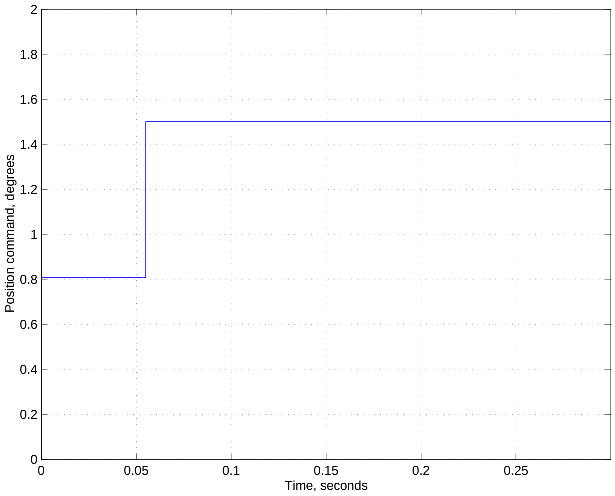

Figure 11. Shaped input curve applied to the position loop for the step responses in Figure 10.

The other method is to apply special shaped inputs to avoid or suppress ringing. There are important applications for this approach within the fields of hard disk drives and spacecraft orientation mechanisms. Hence, a considerable amount of research has been done within this area.

The simplest shaped input techniques merely apply smooth curves. For optical telescopes it has for some time been general practice to round the corners of the input trajectories using polynomia. Von Hoerner has proposed half sine waves to accomplish the same[5]. Other methods apply input trajectories with only little power at the locked rotor resonance frequency [6,7,8,9,10].

The most promising method seems to be the approaches that first excite ringing and secondly cancels it[11,12,13,14,15,]. For a single oscillation mode, as assumed in this context, the approach simply subdivides a step into two. The first step excites the vibration and the second one cancels it. This can be seen in Figure 10 that is based upon an input shape as shown in Figure 11. In practice the method is somewhat more complex since ringing may occur at more than one frequency.

Shaped inputs may be applied in a feedforward mode, i.e. matching input curves may be applied simultaneously for both torque, velocity and position. This approach has not been investigated in great detail yet. However, it seems promising since the filtering effect of the slow position loop is avoided.

To demonstrate the potential of such an approach, shaped input curves as shown in Figure 12 have been generated. The position loop of the system was opened and the shaped velocity reference curve was used as input to the tachometer loop. Since the tachometer loop has a high bandwidth, it is possible to move the antenna quickly.

The resulting trajectory is seen in Figure 13. It is seen that the antenna moves 1.5 degrees within about 200 ms. Although there will be other limiting factors not included in the model (such as tachometer errors and secondary resonances), these curves indicate that a combination of shaped inputs with feedforward techniques has a high potential and should be studied further.

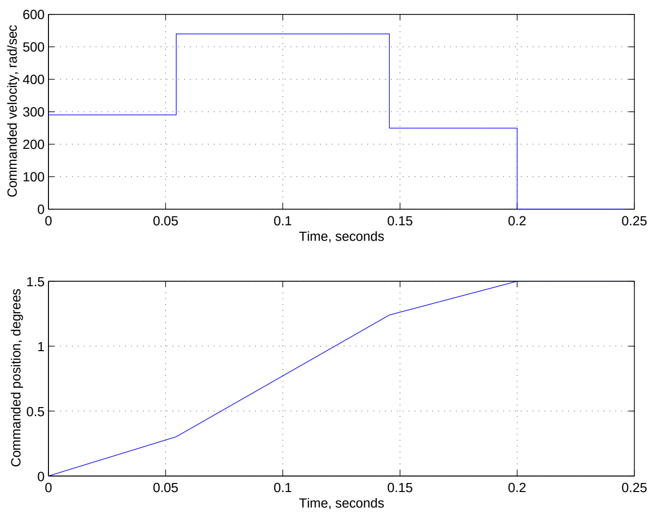

Figure 12. Shaped input curves for velocity (top) and positon (bottom).

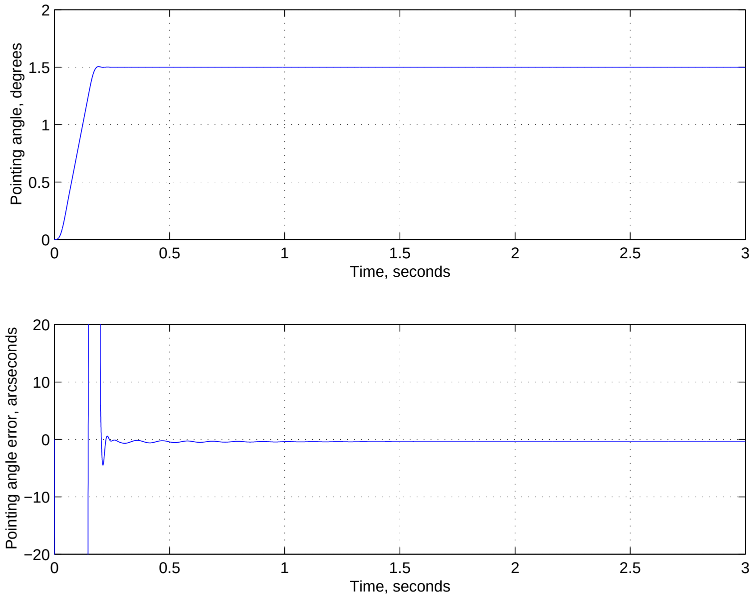

Figure 13. Responses for a system with tachometer loop only. The velocity profile of Figure 12 has been applied as input. The upper curve is load position, and the lower curve is load position from which the position profile of the lower curve of Figure 12 has been subtracted and appropriately scaled. No ringing occurs in spite of the short transition time.

7. Conclusions

An introductory study of antenna offset performance has been carried out. On the basis of a simple model of the antenna dynamics, the following conclusions can be drawn.

- It is important that the position loop has a high bandwidth. A bandwidth of 3-4 Hz is desirable. A finite element model must be available to determine whether this is achievable. Also, it is essential that the lowest eigenfrequency is not below 10 Hz.

- Various shaped torque techniques exist to suppress ringing. These techniques have been demonstrated to perform well.

- Feedforward in combination with shaped torque techniques seems highly promising and could lead to better performance than specified. An analysis of this possibility must be based on a finite element model.

- A further analysis including non-linear effects should be carried out.

8. References

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