EECE 460

# Control of Optical Storage Drive

Control System Design Project

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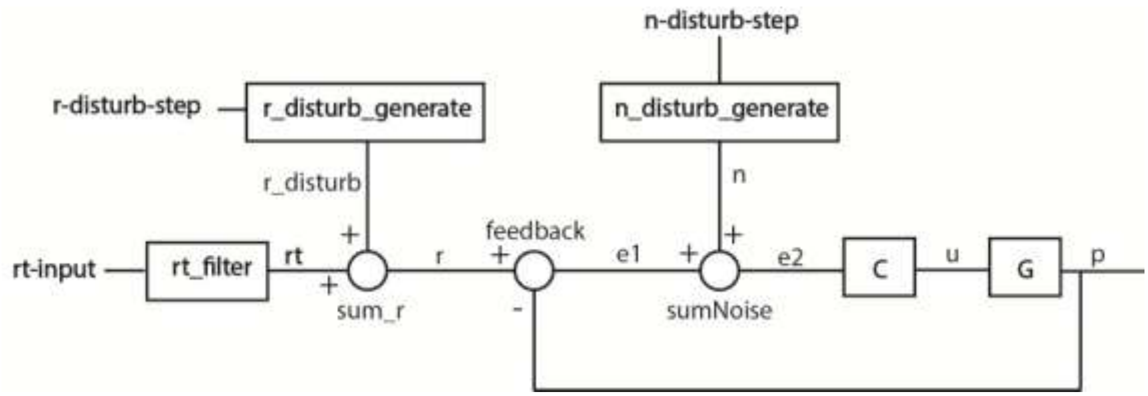
4/10/2013

# Contents

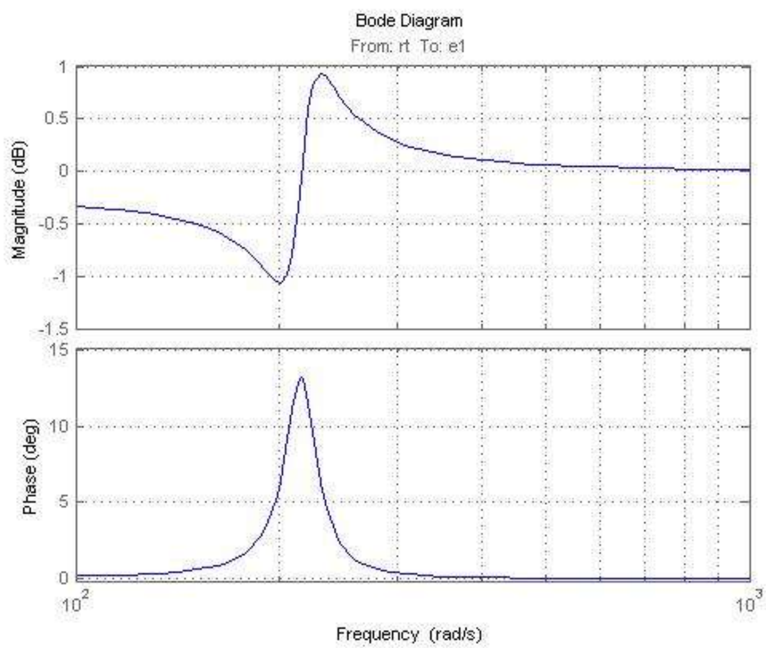
## Construction of Plant Model

The provided model from the project description generates the following model in Matlab with addition of <rt_filter> to filter the abrupt step change from the known <rt-input> signal:




Modular transfer function blocks on the above diagrams are created in Matlab script and connected together. See Matlab code for detail.

With the controller not implemented (C = 1), the transfer function from <rt> to <e1> is plotted below.



# Design Goal to Specifications

## Design Requirements

| | Ref # | Requirement | Spec Ref # |
|---|---|---|---|
| Part A | D1 | Zero tracking error in steady state | S1 |
| | D2 | Continuous read out (error tracking <370nm) given low frequency input disturbance of 3 micrometer | S2 |
| | D3 | Continuous read out (error tracking < 370nm) given high frequency noise disturbance of 100nm | S3 |
| | D4 | Controller output is limited to +/- 2V | S4 |
| | D5 | Follows step change in known <rt-input> signal with <5% overshoot | S5 |
| | D6 | Show response of control system to <rt-input> step change of 1mm. Also show response to above disturbances by generation of disturbance signal from <r_disturb_generate> and <n_disturb_generate> | S6 |
| Part B | D7 | Achieves zero steady state error in presence of large <r-disturb> eccentricities at 15Hz. Show response to $< rt - disturb \geq 10^{-3}\sin(15 * 2\pi)$. Meet Part A requirements | S7 |

## Design Specifications

| | Ref # | Specifications |
|---|---|---|
| Part A | S1 | Sensitivity function of system $\frac{e1(0)}{r(0)} = S_0(0) = 0$ |
| | S2 | $\left\|\frac{e1(s)}{r(s)}\right\| = \|S_0(s)\| \leq 0.1233 = -18\text{dB for f} \leq 200\text{Hz}$ |
| | S3 | $\left\|\frac{e1(s)}{n(s)}\right\| \leq 3.7 = 11\text{dB for f} \geq 3000\text{Hz}$ |
| | S4 | Check step response from <rt-input> to <u> to ensure maximum gain <= 2/0.001 = 66.02dB, assuming maximum 1mm step change is allowed for <rt-input> |
| | S5 | Check step response from rt(s) to e1(s) or p(s) to ensure < 5% overshoot |
| | S6 | Check response of system to <rt-input> step change of 1mm and disturbances by generation of disturbance signal from <r_disturb_generate> and <n_disturb_generate> to ensure error tracking within 370nm |
| Part B | S7 | $\frac{e1(15*2\pi)}{r(15*2\pi)} = \|S_0(15 * 2\pi)\| = 0$ and plot response to $< r > = 10^{-3}\sin(15 * 2\pi)$. Tracking error < 370nm also in presence of disturbance generated by <r_disturb_generate> and <n_disturb_generate>. |

# Affine Parameterization Design

Affine parameterization used to design the closed loop due to ease of analysis.

$C = \frac{QG_o}{1-CG_o}$, $Q = F_Q G_o^i$, $T_o = QG$, $S_o = 1 - QG_0$

$S_{io}$ and $S_{uo}$ are not considered since there is no disturbances at associated places in the system.

## Design for S1 and S2

| Required Specification | Achieved |
|---|---|
| $\lvert S_o(0)\rvert = 0$ | $\lvert S_o(0)\rvert = 0$ |
| $\lvert S_o(s)\rvert \leq -18\text{dB for f} \leq 200\text{Hz}$ | $\lvert S_o(s)\rvert \leq -19\text{dB for f} \leq 200\text{Hz}$ |

Given open plant model is stable and non-minimum phase with order of 2 in denominator. The plant is inverted to make $G_o^i = [G_o]^{-1}$. $F_Q$ is made to have relative order of 2 to make Q proper.

$$F_Q(s) = \frac{(2500 * 2\pi)^2}{s^2 + 0.7 * 2500 * 2\pi * s + (2500 * 2\pi)^2}$$

Natural frequency was adjusted until gain satisfied the low frequency disturbance requirement below 200Hz. Original natural frequency near 200Hz did not satisfy the requirement, so it was shifted to higher value of 2500Hz. Numerator of $F_Q(s)$ is chosen for $F_Q(2500 * 2\pi) = 1$ for DC zero tracking error.

$$S_o = 1 - QG_0 = 1 - F_Q$$
$$\lvert S_o(0)\rvert = 0$$
$$\lvert S_o(200 * 2\pi)\rvert = 0.1122 = -19\text{dB}$$

See Figure 1. r to e1 bode plot on page 10.

## Design for S3

| Required Specification | Achieved |
|---|---|
| $\left\lvert\frac{e1(s)}{n(s)}\right\rvert \leq 3.7 = 11\text{dB for f} \geq 3000\text{Hz}$ | $\left\lvert\frac{e1(3000 * 2\pi)}{n(3000 * 2\pi)}\right\rvert = 0.5758 = -4.79\text{dB}$ |

Bode plot for f > 3000Hz was checked first to see if any design changes need to be made to satisfy the specification. The response is a low pass and for f>3000Hz, gain is < 0.5758 = -4.79dB, which satisfy the specification of < 11dB.

See Figure 2. n to e1 bode plot on page 10.

## Design for S4

| Required Specification | Achieved |
|---|---|
| $\left\lvert\frac{u(s)}{rt\_input(s)}\right\rvert \leq 66.02dB$ | $\left\lvert\frac{u(s)}{rt\_input(s)}\right\rvert \leq 62.43dB$ |

Check step response from <rt-input> to <u> to ensure maximum gain <= 2/0.001 = 66.02dB, assuming maximum of 1mm step change is allowed for <rt-input>.

Original unfiltered signal achieves a gain of 104.76dB from step response which exceeds the specification. Fast poles are desirable for faster system response and thus faster settling time to step input changes. <rt-filter> is implemented with poles at 40Hz to reduce the gain to 1.75/0.001 = 62.43dB.

See Figure 3. r to u step response on 11.

## Design for S5

| Required Specification | Achieved |
|---|---|
| $rt(s)$ to $e1(s)$ overshoot $< 5\%$ | Filtered $rt(s)$ to $e1(s)$ overshoot $= 0\%$ |

Check step response from rt(s) to e1(s) or p(s) to ensure < 5% overshoot.

System was check with step response plot to see if there needs to be any adjustment for < 5% overshoot. From unfiltered <rt> step input, the overshoot seen at <p> was measured to be 4.6%.

See Figure 4. unfiltered rt to p step response on page 11.

Filtered <rt-disturb> signal (for limiting controller output) further decreases the overshoot to 0%. In both cases, specification was met.

See Figure 5. Filtered rt to p step response on page 12.

## Design for S6

| Required Specification | Achieved |
|---|---|
| Tracking error < 370nm in presence of r-disturb and n-disturb | Tracking error < 19.3nm with 200Hz r-disturb and 3000Hz n-disturb |

Check response of system to <rt-input> step change of 1mm and disturbances by generation of disturbance signal from <r_disturb_generate> and <n_disturb_generate> to ensure error tracking within 370nm.

Filtered rt step changes generate a maximum of 32.1 micrometer tracking error. See Figure 6. filtered rt to e1 step changes on page 12 for behaviour at e1 with step changes produced from feeding 2Hz square wave into <rt-input>.

Single input disturbance r-disturb generates a maximum of 16.4nm tracking error using <r-disturb-generate> block. See Figure 7. r-disturb-step to e1 low frequency disturbance response on page 12 for behaviour of a single input disturbance generated by feeding a step input into <r-disturb-step>.

Single noise measurement disturbance generates a maximum of 20.3nm tracking error using noise generation block <n-disturb-generate>. See Figure 8. n-disturb-step to e1 high frequency disturbance response on page 13 for behaviour of a single measurement noise disturbance generated by feeding a step input into <n-disturb-step>.

2Hz step changes in presence of 200Hz input disturbance and 3000Hz noise disturbances are simulated. Added tracking error of input and noise disturbances could reach a maximum tracking error of 16.4nm+20.3nm = 36.7nm, but due to phase differences as result of system filtering, tracking error reaches 19.3nm at above mentioned frequencies. See Figure 9. e1 probe with rt step changes and input and noise disturbances on page 14 for behaviour of 2Hz rt step changes with 200Hz input disturbances and 3000Hz noise disturbances.

## Design for S7

| Required Specification | Achieved |
|---|---|
| $\lvert S_o(15 * 2\pi)\rvert = 0$ | $\lvert S_o(15 * 2\pi)\rvert = 2.9190 * 10^{-4}$ = -70.70dB (due to Matlab rounding) |
| Tracking error < 370nm in presence of Part A disturbances | Not able to complete with 15Hz disturbances due to Matlab transfer function inaccuracy after calculation of Qa and Qb. Other responses are same as the old system. |

From specification, we see that:

$$S_o(15 * 2\pi) = 1 - T_0(15 * 2\pi) = 0$$

$$T_0(15 * 2\pi) = 1$$

An additional disturbance rejection at f = 15Hz to achieving 0 tracking error in presence of 15Hz disturbance was achieved by addition of complex zeros at 15Hz. Using the general formula for achieving disturbance rejection at specific frequencies, the Q(s) was modified by putting the complex zeros to the original Q(s) and adding another term that achieves perfect plant inversion at 15Hz. Additional 2nd order filter (with damping adjusted until system resembles the Part A system at other frequencies) was added at 15Hz to counter balance the gain and phase from the complex zeros so that the system at other frequencies would not notice much difference.

$$Q(s) = F_Q(s)[G_o(s)]^{-1}$$

$$Q_2(s) = Q_a(s) + Q_b(s)$$

$$Q_a(s) = Q(s)\frac{(s^2 + (15 * 2\pi)^2)}{(15 * 2\pi)^2}\frac{(15 * 2\pi)^2}{(s^2 + 0.000001 * 15 * 2\pi * s + (15 * 2\pi)^2)}$$

See Figure 10. $Q_a$ comparison with original Q bode plot with complex zeros and resonant poles added at 15Hz on page 14.

$$Q_a(15 * 2\pi) = 0$$

Due to Matlab computation, $\lvert Q_a(15 * 2\pi)\rvert = 3.1605 * 10^{-9}$ instead.

$$Q_b(s) = F_{Q2}(s)[G_o(s)]^{-1}$$

$$F_{Q2}(15 * 2\pi) = 1$$

$$Q_b(15 * 2\pi) = [G_o(15 * 2\pi)]^{-1}$$

$$Q_2(15 * 2\pi) = 0 + [G_o(15 * 2\pi)]^{-1}$$

$$T_0(15*2\pi) = Q_2(15*2\pi)G_o(15*2\pi) = 1$$

$Q_b(s)$ was designed with a resonant band pass filter with unity gain and zero phase shift at the 15Hz frequency point. The relative order of $F_{Q2}(s)$ was chosen to be 2 in order to make $Q_b(s)$ proper.

$$F_{Q2}(s) = \left[\frac{0.1*s}{s^2 + 0.1*s + (15*2\pi)^2}\right]^2$$

See Figure 11. Fq2 band pass filter bode plot on page 15.

$$Q_b(s) = \left[\frac{0.1*s}{s^2 + 0.1*s + (15*2\pi)^2}\right]^2 [G_o(s)]^{-1}$$

$F_{Q2}(s)$ band pass filter damping was adjusted together with $Q_a(s)$ 15Hz low pass damping to reduce abrupt changes near 15Hz in $S_o(s)$.

See Figure 12. $Q_b$ comparison with $G^{-1}$ bode plot on page 15 to observe $Q_b(15*2\pi) = [G_o(15*2\pi)]^{-1}$.

See Figure 13. r to e1 with 15Hz disturbance rejection on page 16 for similarity of the transfer function everywhere except at 15Hz due to added zeroes.

Gain check for $|S_o(15*2\pi)| = 2.9190*10^{-4} = -70.70\text{dB}$ which was due to $|Q_a(15*2\pi)| = 3.1605*10^{-9}$ instead of 0.

Gain checks were made for f = 200Hz and 3000Hz to satisfy Part A disturbance requirements.

$$|S_o(200*2\pi)| = 0.1122 = -19\text{dB}$$

$$\left|\frac{e1(200*2\pi)}{n(200*2\pi)}\right| = 0.5758 = -4.79\text{dB}$$

The gains at these disturbance cut off frequencies are same as achieved specifications S2 and S3.

$$\left|\frac{e1(3000*2\pi)}{n(3000*2\pi)}\right| = 0.5758 = -4.79\text{dB}$$

$$|S_o(200*2\pi)| = 0.1122 = -19\text{dB}$$

Response of the new system was not totally accurate due to poor accuracy of transfer function in Matlab, however it should follow familiar response as the old system.

Figure 1. r to e1 bode plot

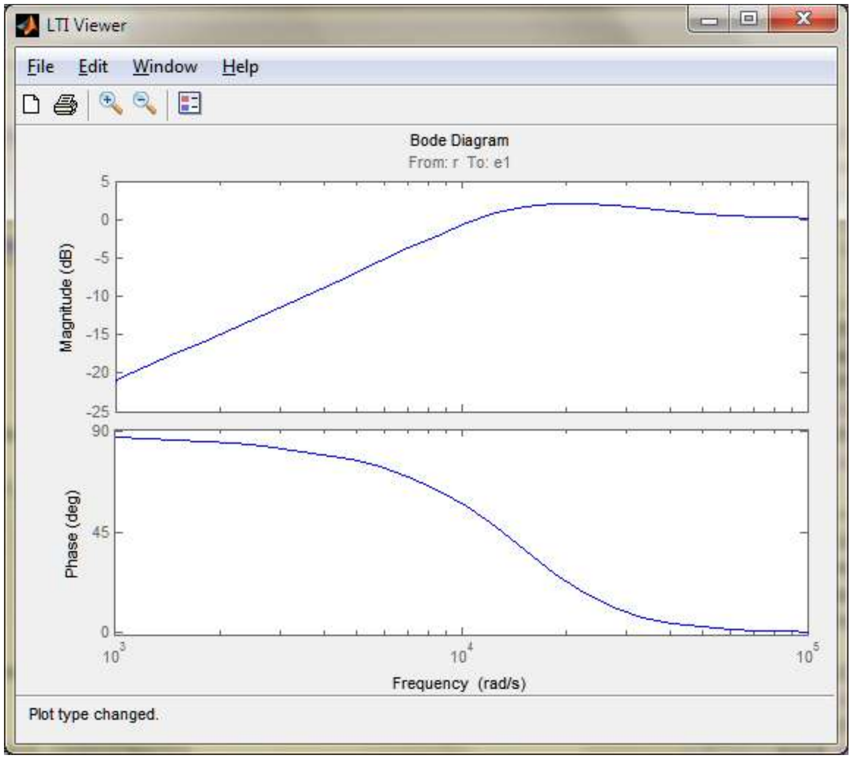



Figure 2. n to e1 bode plot

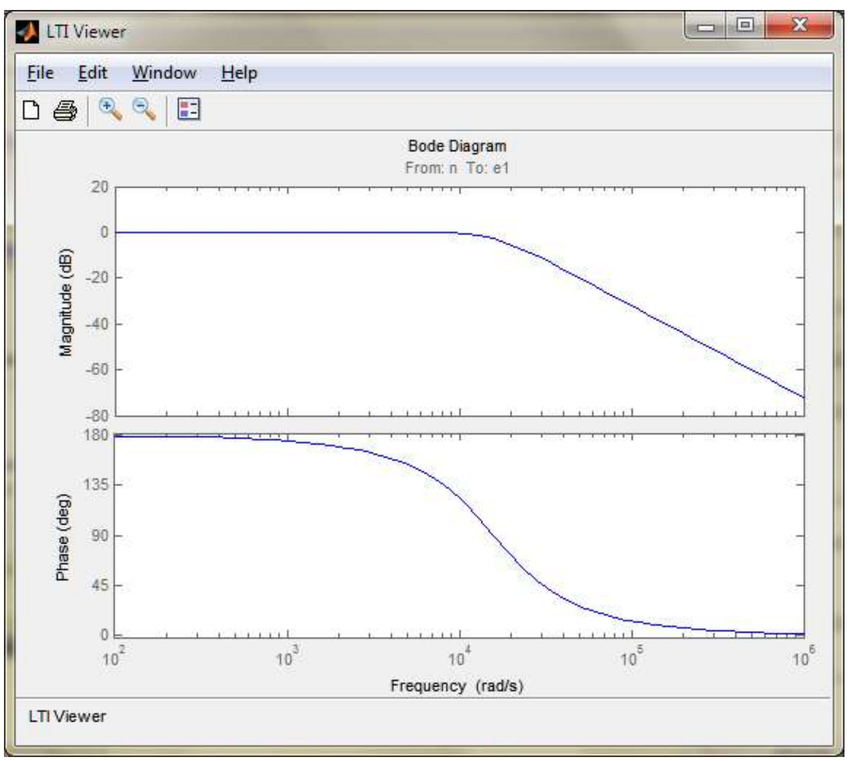


Figure 3. r to u step response

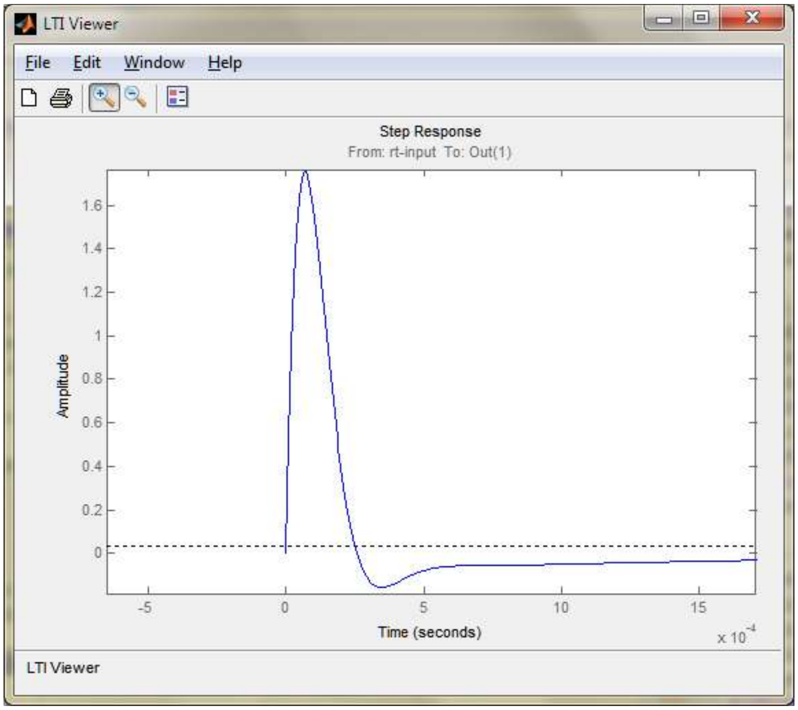



Figure 4. unfiltered rt to p step response

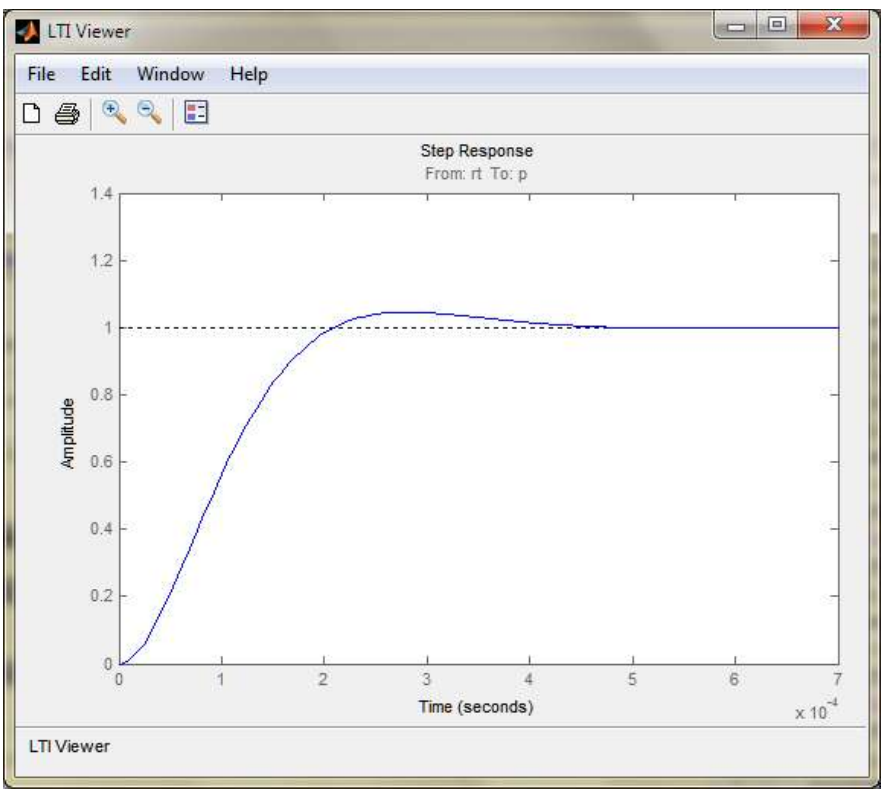


**Figure 5. Filtered rt to p step response**

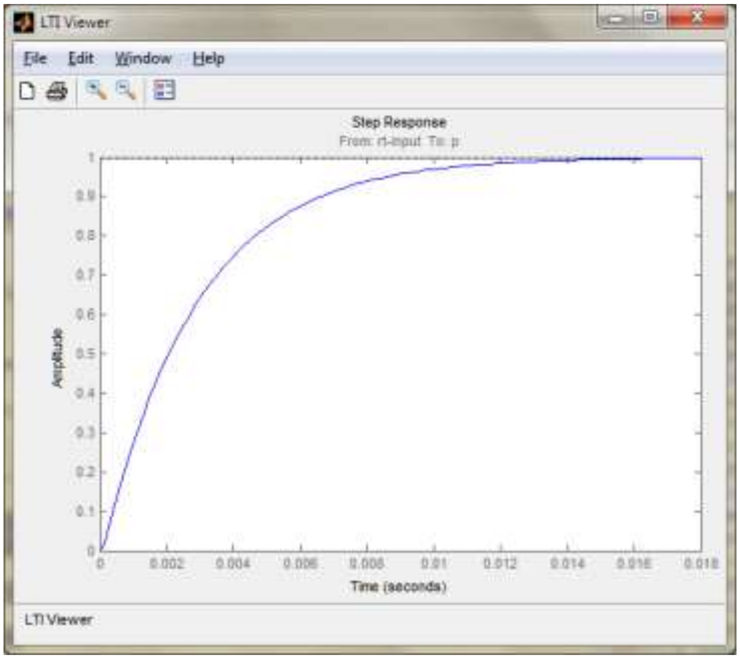



**Figure 6. filtered rt to e1 step changes**

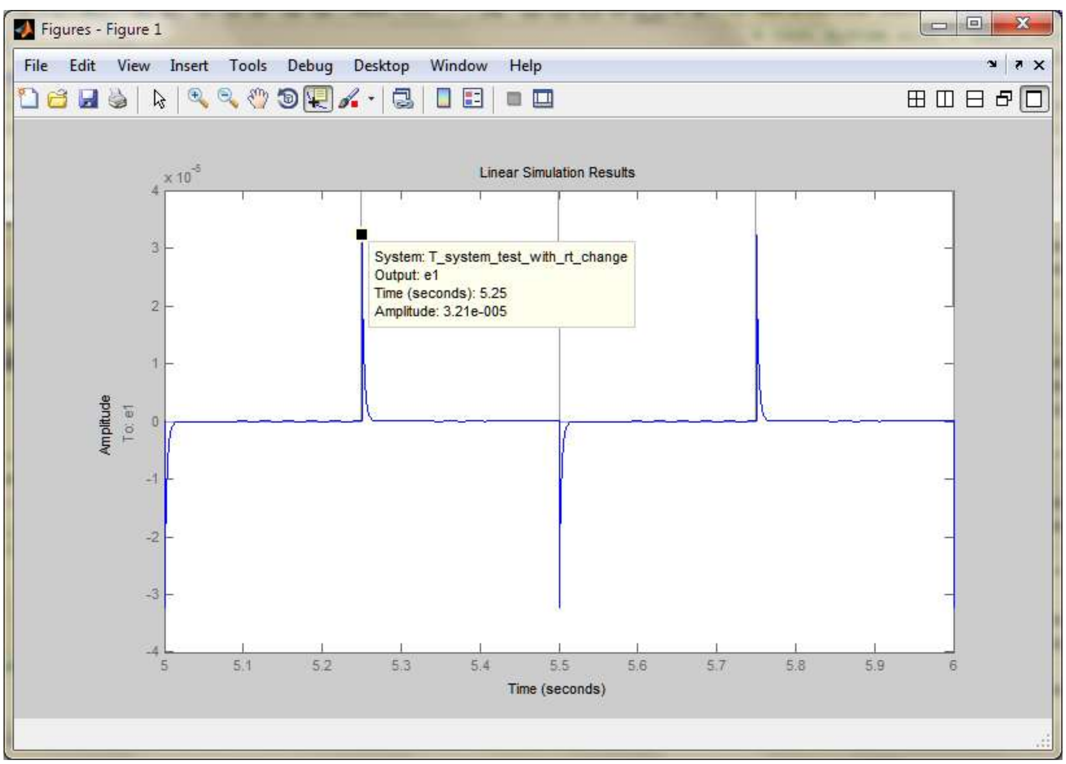


**Figure 7. r-disturb-step to e1 low frequency disturbance response**

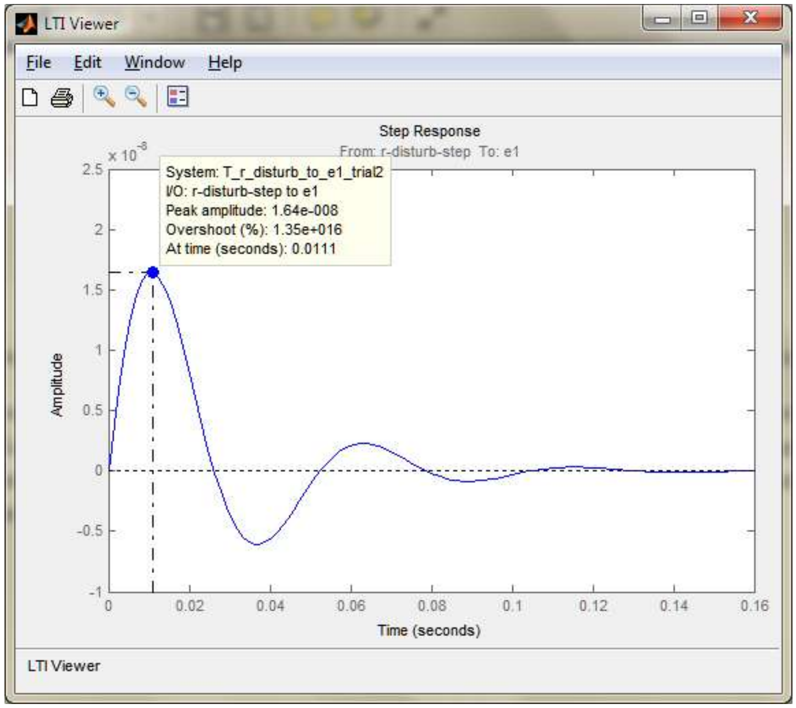



**Figure 8. n-disturb-step to e1 high frequency disturbance response**

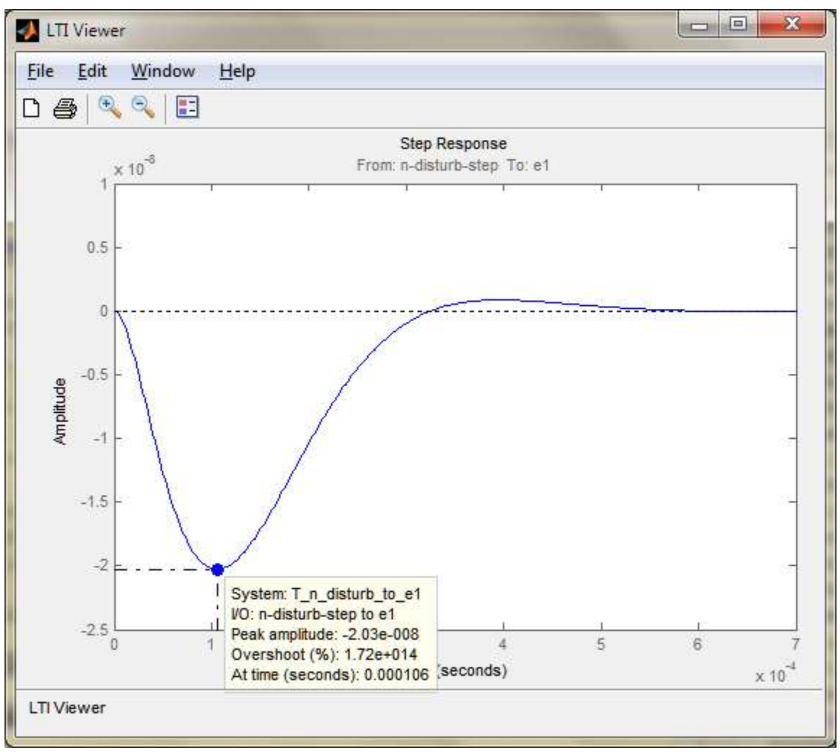


Figure 9. e1 probe with rt step changes and input and noise disturbances

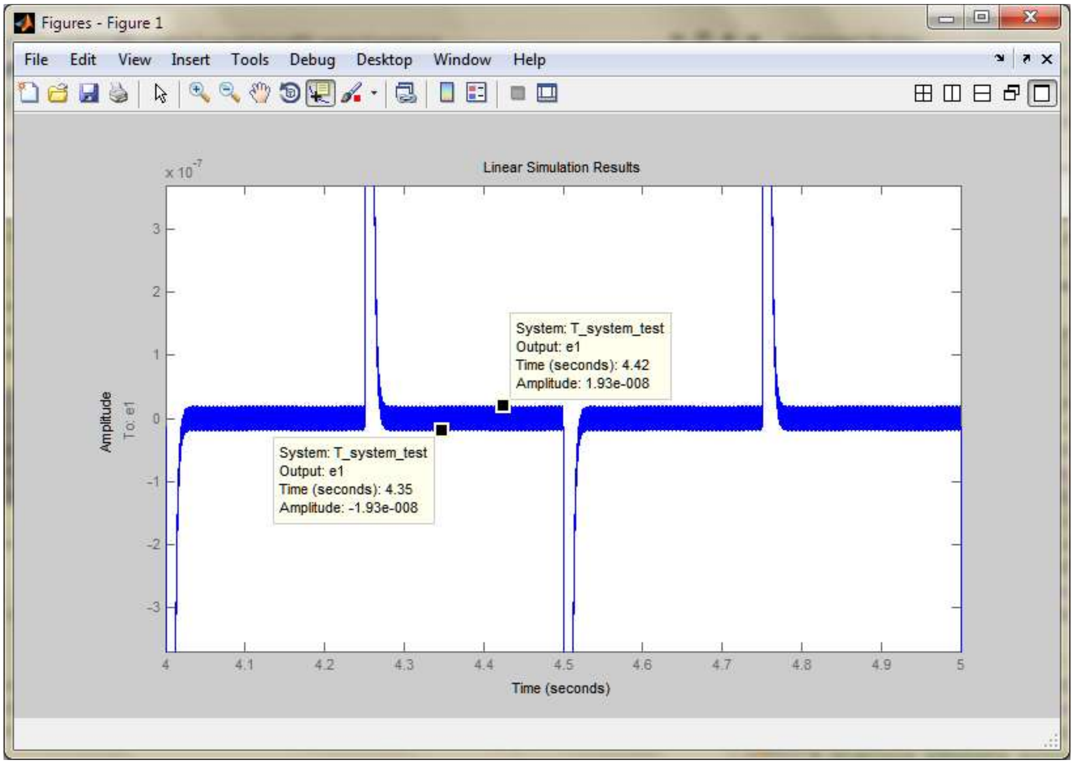



Figure 10. $Q_a$ comparison with original Q bode plot with complex zeros and resonant poles added at 15Hz

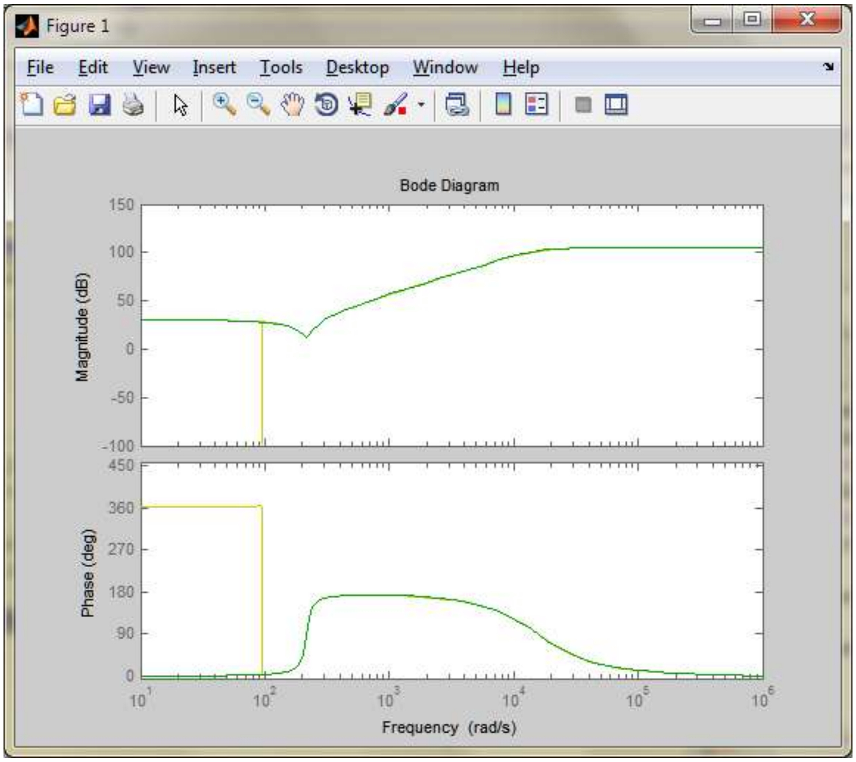


Figure 11. Fq2 band pass filter bode plot

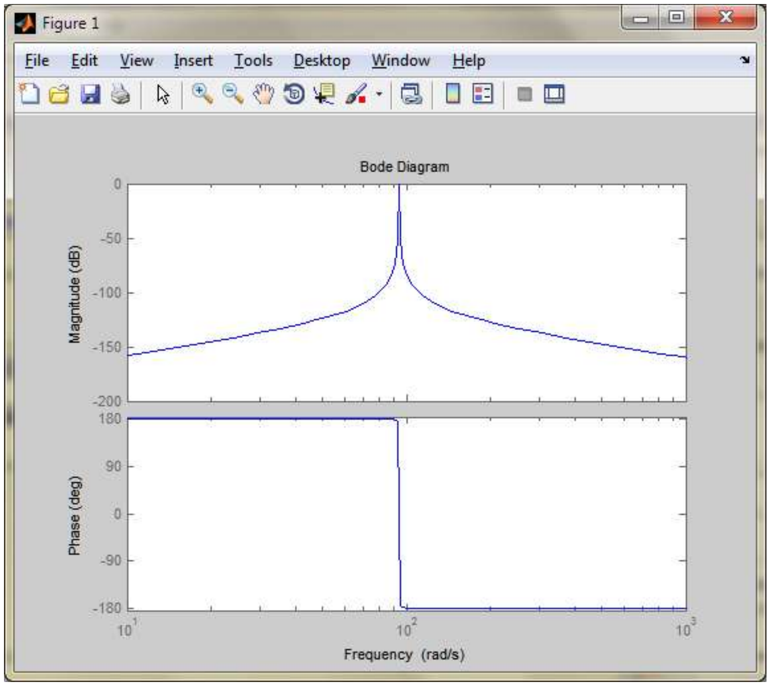
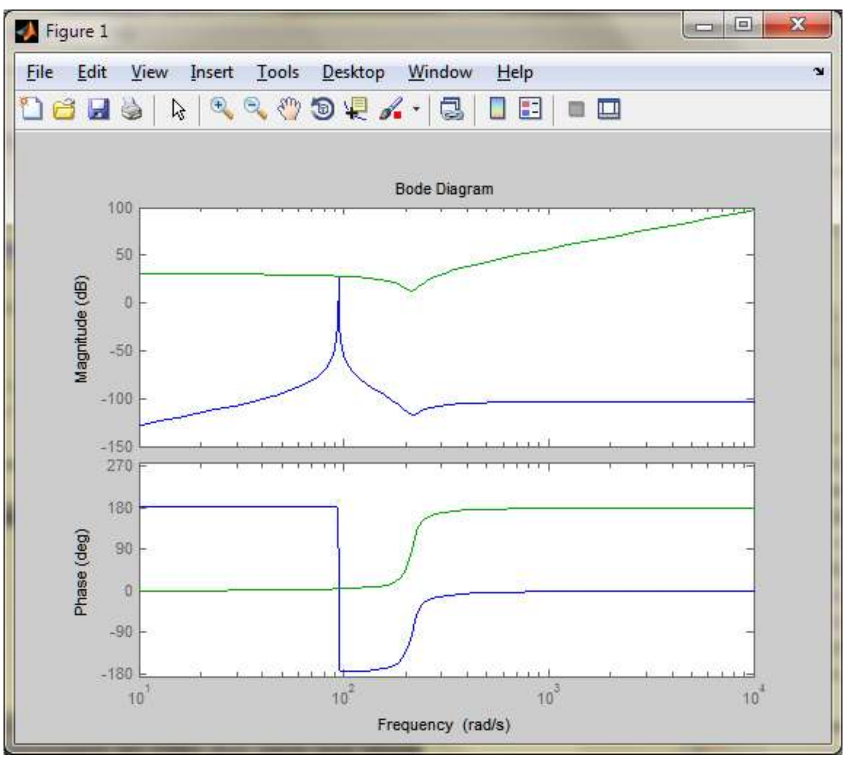
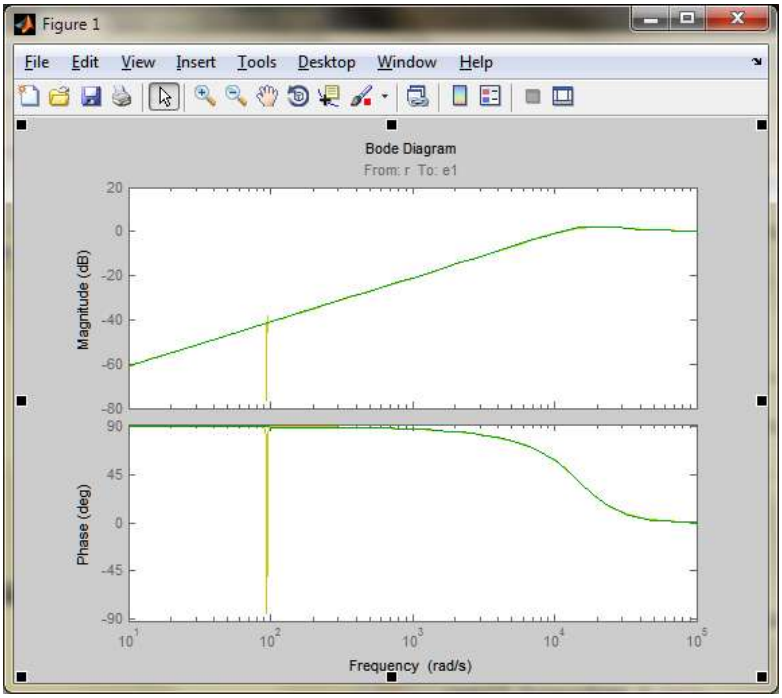



Figure 12. $Q_b$ comparison with $G^{-1}$ bode plot




(blue is the band pass filter for 15Hz, green is the open plant inverse)

Figure 13. r to e1 with 15Hz disturbance rejection




(yellow is the new system with 15Hz disturbance rejection, green is the old system)

Figure 14. n to e1 with revised Q for 15Hz disturbance rejection