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Using Lag Compensator in Orbit Feedback

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Abstract
Growing demand on the beam orbit stability requires higher loop gain inside the operational bandwidth. However, increasing the gain leads to the increase of the unity gain frequency and problems with systems stability due to the additional phase shifts caused by the trims (power supplies, eddy currents in vacuum chambers, etc.) and filtering of beam position data. Conventionally employed systems have 20 dB/decade slope near the unity gain providing 90 degrees phase shift which is sufficient for stability. Increase of the slope to 40 dB/decade by adding additional pole into the signal chain increases the phase shift to 180 degrees and makes system unstable. Utilizing one or more lag compensators allows to increase the gain while keeping phase margin acceptable. The paper provides more details on the proposed solution as well as simulations of how the transients will be modified.

Implementation of lag compensator

Rejection of the disturbance in the linear system feedback is proportional to the gain of the open loop. If the open loop gain is described by a transfer function G(s) the suppression of the disturbance is given by formula:

$$P(s) = \frac{1}{1+G(s)} \tag{1}$$

Increase of the implemented gain is limited by the requirement of the system stability. The phase shift caused by different elements of orbit feedback (trims with power supplies [1], eddy currents in vacuum chamber [1], filters implemented in the beam position monitors [2], latency in the signal propagation chain [3]) can turn negative feedback into positive one and make system unstable. Typically, the transfer function of the orbit feedback system is described by few poles. The lowest frequency pole is user defined and might be at zero frequency if integrator is utilized. The second pole is defined by hardware and is the main limiting factor in the system bandwidth. Therefore, at high frequencies the loop gain is inversely proportional to the frequency

$$|G(f)| \cong \frac{f_c}{f} \tag{2}$$

where f_c is crossover frequency where gain is unity. Since the slope of the Bode plot is usually fixed (-20 dB/decade for single pole), increase in suppression of the high-frequency disturbances requires increase of the crossover frequency.
Usage of lag compensation provides higher low-frequency gain [4]. The transfer function of lag compensator is

$$D(s) = \alpha\frac{Ts+1}{\alpha Ts+1},\ \alpha > 1 \tag{3}$$

where α is the ratio between zero/pole breakpoint frequencies and is time constant. At DC the lag compensator provides additional gain $\alpha > 1$. But it also creates negative phase shift. For α=10 phase shift is almost 60 degrees and can create long ringing response or even cause instability. This drawback can be overcome by using more compensators with different time constants. This will increase the slope of the Bodes diagram above 20 dB/decade but keep phase margin acceptable as it can be seen in Fig. 1.

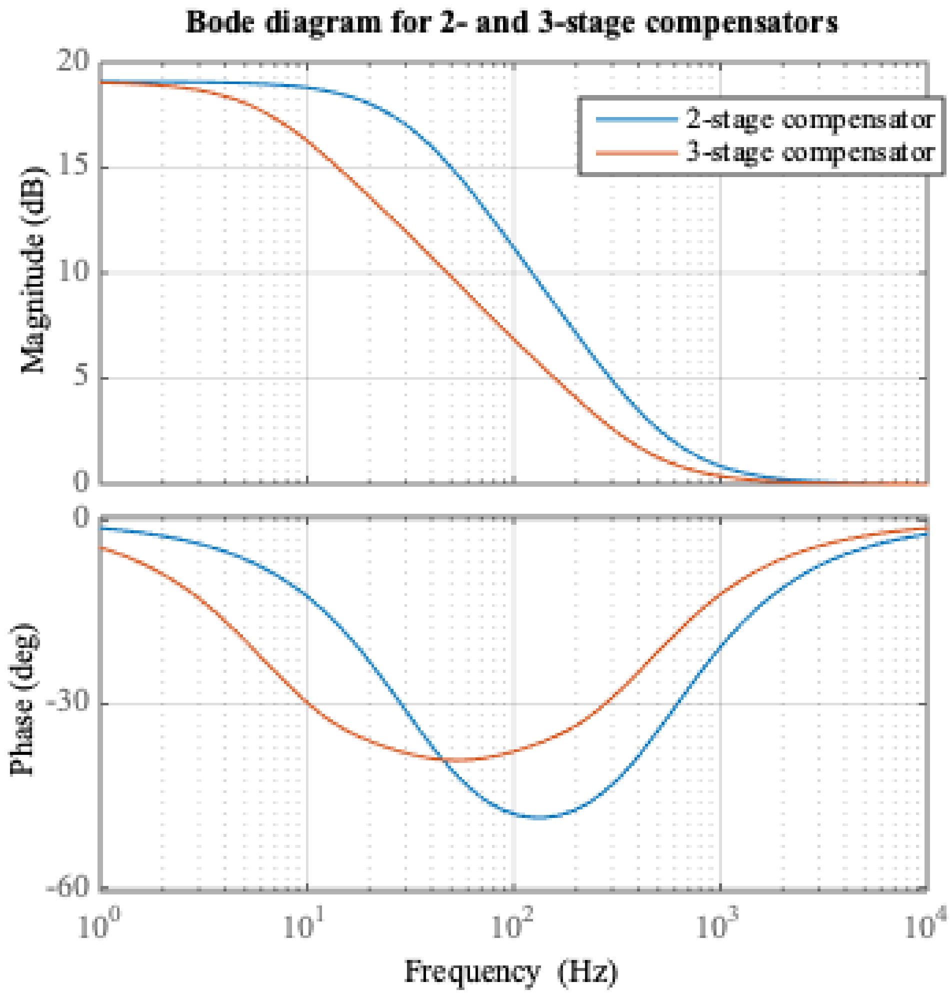

Figure 1: Bode plot of the open loop with two and three lag compensators. Total gain increase is the same but maximal phase shift different for three-stage it is 40 degrees and for two-stage it is 50 degrees.

Fig. 2 shows implementation of stages lag compensator the single input – single output (SISO) system with integrator in error amplifier and single pole at 800 Hz. Three stages providing 20 dB gain at DC were used. Fig. 3 shows noise suppression and phase of the residuals

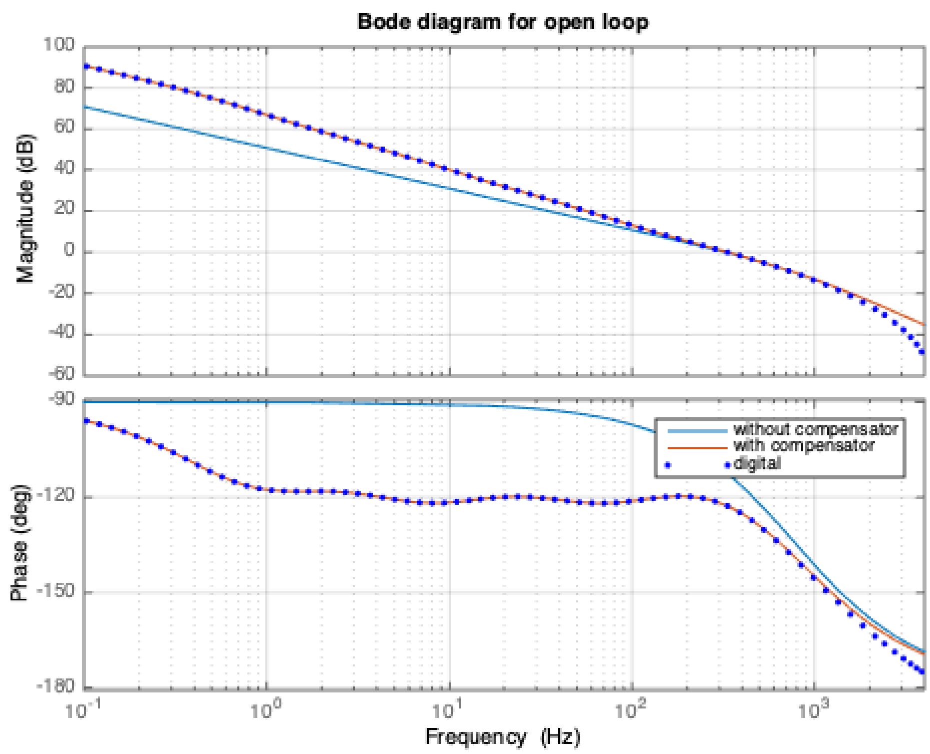

Figure 2: Example of the open loop gain with integrator and a pole at 800 Hz. Additional gain at low frequencies is about 20 dB, the phase margin is about 60 degrees with and without compensator. Dots correspond to the digital system with 10 kHz sampling rate.

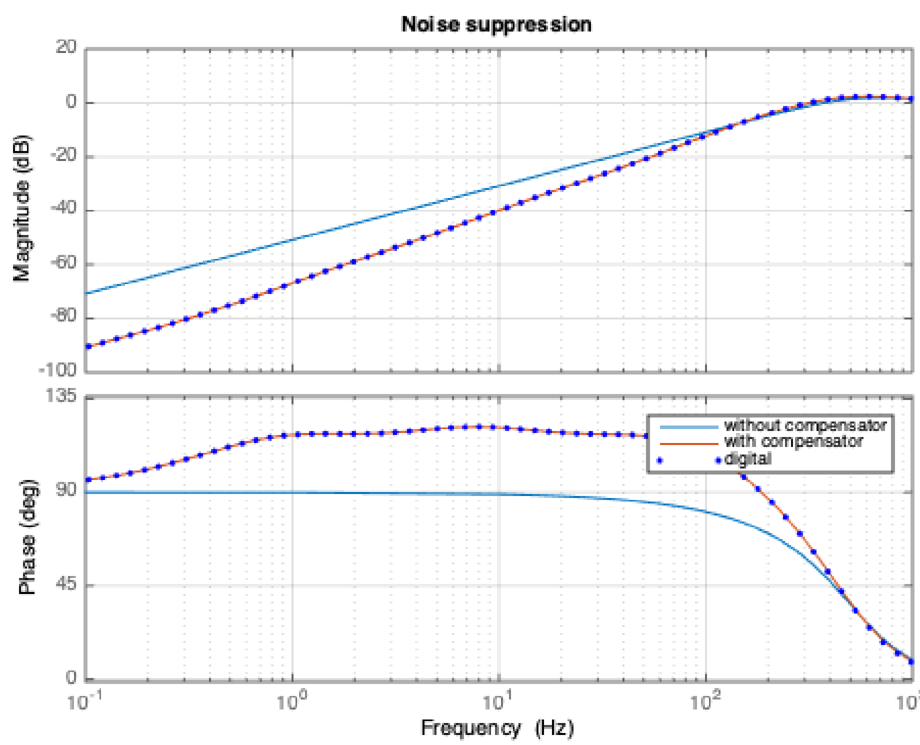

Figure 3: Noise suppression plot for closed loop.

While the stability of the system does not change much with introduction of the lag compensator the transient response changes noticeably. As Fig. 4 shows the overshoot increases from 2% to 16 % for system with lag compensator and longer tail appears.

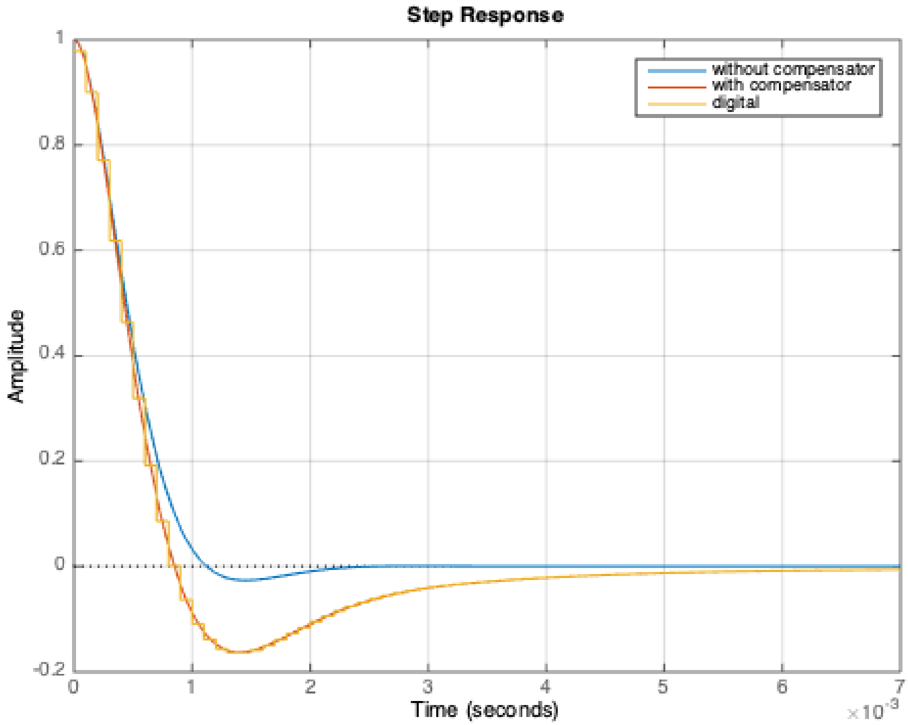

Figure 4: Transient response to the disturbance of the feedback system.

Conclusion

Implementation of the lag compensator allows to increase of the low-frequency disturbances without increase of the feedback bandwidth. Such solution does not change system stability but affect slightly transient dynamics.

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