Investigation of Feedback Control for Klystron Ripple

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Abstract

The variations of the phase and amplitude of klystron output due to the change in klystron cathode voltage is investigated in this note. The mechanism and the effectiveness of the feedback control to suppress the variations are given. To understand the limitation of the feedback, both proportional controller and proportional-integral controller used in feedback loop are simulated and analyzed respectively for superconducting cavity and normal conducting cavity. The tolerances of the droop and ripple in cathode voltage are shown according to the data and results obtained. All the simulations and calculations are performed with MATLAB. The data and results are listed in detail so as to enable comparison with further studies and measurements at ESS.

INTRODUCTION

In accelerator, the klystron suffers the droop and ripple effect resulting from the modulator (klystron cathode voltage supplier), while the droop and ripple in klystron cathode voltage leads to a phase and amplitude modulation on klystron output. At ESS, there might be potentially serious droop and ripple because of long pulse up to 3 ms. It is important for us to know to what extent the droop and ripple affects the klystron output, and how much we can tolerate.

PHASE AND AMPLITUDE VARIATIONS

Electron beams generated from electron gun are firstly accelerated by the cathode voltage V and then modulated by the RF signal at input cavity. After passing through the drift space of the length L, the beams finally induce the required RF signal at output cavity. The RF output phase varies if there is any change in the time to travel through the drift space, which is highly affected by the change in cathode voltage. There is also variation in amplitude as a result of the change in klystron cathode voltage. Some calculation and measurement data indicate that 1% change in cathode voltage results in a phase variation of more than $10°$ and an amplitude variation of 1.25%[1]. It appears that the phase is much more influenced by the ripple than the amplitude. Therefore, we will mainly discuss the phase variations in this paper.

SUPPRESSION OF VARIATIONS

The amplitude and phase variations of klystron output resulted from modulator droop and ripple can be suppressed in feedback loop by a factor of G+1, where G is the loop gain. However, the feedback gain G cannot be increased without limit due to the loop delay. The low gain limits the feedback performance and leaves steady errors. The integral gain is then introduced to eliminate the steady error and also the low frequency noise, but have a poor performance at high frequency. More details will be given in following sections.

Loop delay and loop gain

The block diagram of a simplified feedback loop for cavity phase and amplitude (or I & Q) control is given in Figure 1, where the klystron, cavity and detector are all simulated as the one-order low pass filters [2, 3], and only proportional controller is considered. The loop delay is generally of the order of µs in LLRF system, which is the key factor causing loop instability and limiting loop performance. If

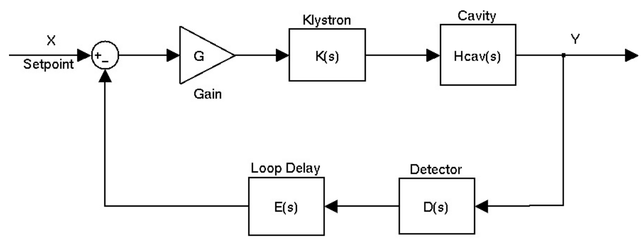

Figure 1: Block diagram of simplified feedback loop

we note that the 3-dB cut-off frequencies of klystron and detector are usually much higher than the cavity, the block diagram can be further simplified with neglecting the effect from klystron and detector in the loop. As a result, the cavity transfer function $H_{cav}(f)$ and the open loop transfer function $H_o(f)$ in Figure 1 can be written as [2]:

$$H_{cav}(f) = \frac{f_{hbw}}{jf + f_{hbw}}, \tag{1}$$

$$H_o(f) = GH_{cav}e^{-j2\pi\tau f}, \tag{2}$$

where f is the frequency variable, and f_{hbw} is the cavity half bandwidth.

Close loop instability can be concluded from the characteristics of open loop transfer function, which occurs when:

$$|H_o(f)| \geq 1, \tag{3}$$

$$\varphi = -\pi + n \cdot 2\pi, \quad n = 0, \pm 1, \pm 2, ... \tag{4}$$

Combining the Equation 1, 2, 3 and 4, we can calculate the critical frequency where the phase equals $-180°(-\pi)$ and the critical loop gain where the magnitude equals 0 dB. The lower the delay is, the higher the critical loop gain will be. Consequently the better feedback performance could be achieved.

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The loop delay τ is set to 2µs in the following sections, and correspondingly the critical gains are 241 and 12 for superconducting cavity and normal conducting cavity respectively, while the critical frequency is 125kHz for both.

It is at risk to have loop gain below but close to critical gain, which might cause big overshoot. In practice, at SNS the average loop gain is about 50 for superconducting cavity and 6 for normal conducting cavity [4], which are far away from critical gains. In JPRAC where only the normal conducting cavities are used the average loop gain is about 5 [5]. In FLASH, the loop gain is 70 ~ 100 [2, 6].

Suppression of the klystron output variation by proportional gain

The influence of the ripple and droop of the modulator on klystron is equivalent to adding a noise to the klystron output. The block diagram of the feedback loop with noise is given in Figure 2, which is applicable for both phase and amplitude loops (or I &Q loops). The noise inside the cavity bandwidth is fully passed to the cavity in open loop via the path from r to y, while suppressed by a factor of G+1 (G is the loop gain) in closed loop. The larger the loop

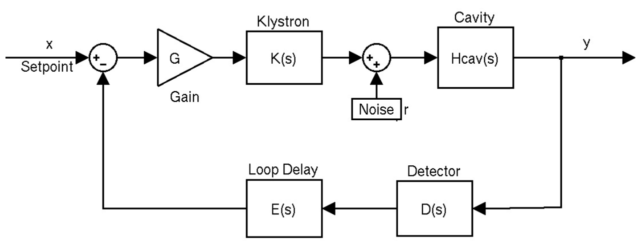


Figure 2: Block diagram of feedback loop with noise

gain, the better the loop performance against noise. The characteristics are shown in Figures 3. However, it is also found that larger gain induces bigger overshoot and longer oscillation.

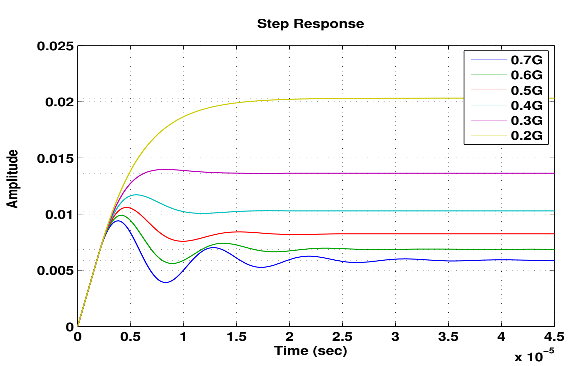


Figure 3: Closed loop noise suppression for superconducting cavity(G=241)

With only the proportional controller, it is hard for the normal conducting cavity to deal with large perturbation (with a loop gain of 6, for example, a perturbation of 15° phase variation can be only suppressed to 2.5°). What's worse, it leaves big steady error. These are the reasons why the integral controller needs to be introduced as well in the feedback control.

Suppression of the klystron output noise by proportional-integral controller

As mentioned above, to eliminate the steady error and better suppress the noise, apart from the proportional controller we also have to employ the integral controller. The larger the integral gain is, the better the noise suppression performance of the integral controller will be at low frequency. However, larger integral gain consumes more phase margin, thereby increasing the risk of raising the instability. The block diagram of the feedback loop with PI (proportional-integral) controller is almost the same with Figure 2 but replace Gain module G with PI module $K_p(s + K_i)/s$. In the feedback loop with PI controller, the open loop transfer function can be written as:

$$H_o(f) = K_p\left(1 + \frac{K_i}{j2\pi f}\right) H_{cav}(f)\, e^{-j2\pi\tau f} \qquad (5)$$

Figure 4 shows the frequency response of the PI open loop transfer function under different integral gain, with 2µs delay for all cases. It can be seen that the instability arises inevitably as the integral gain gets larger and larger. In practice, the integral gain is set to $2\pi f_{hbw}$ so as to keep a constant loop phase and larger phase margin.

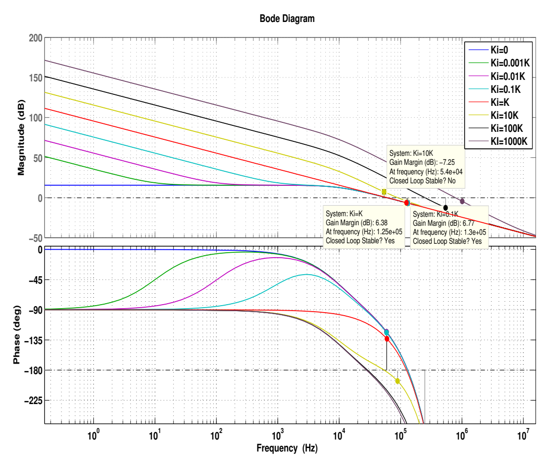
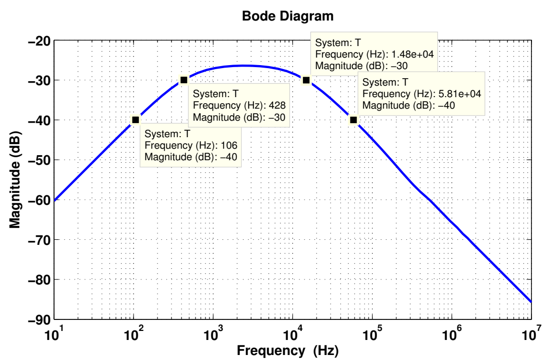


Figure 4: Phase margin reduced in open loop under different integral gains(2µs delay, $K = 2\pi f_{hbw}$)

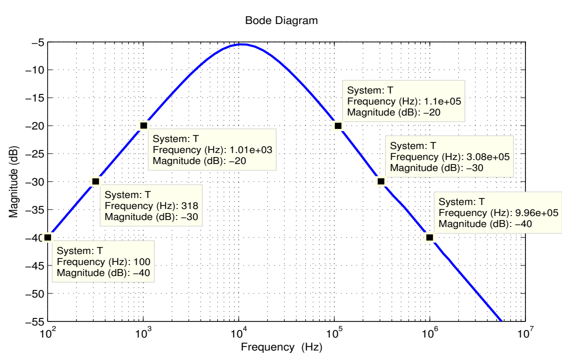
Having set the proper proportional and integral gains, it makes possible to look into the closed loop performance against the noise. As there exists many factors affecting the feedback performance such as unpredicted noise, cavity detuning and passband modes, a worse situation of proportional gains of Kp=1 for normal conducting cavity and 20 for superconducting cavity in simplified close loop is taken for analysis, while the integral gains are set to $K_i = 2\pi f_{hbw}$ for both. The noise suppressions in closed loops as a function of frequency are given in Figure 5 for superconducting cavity and normal conducting cavity separately.

It is found from Figure 5 that with integral controller the feedback loop can suppress effectively the low frequency noise but the performance degrades as frequency increases, while the far higher frequency noise is filtered by cavity itself. Assuming that $15°$ phase variation is induced by 1% change of the cathode voltage, and $0.5°$ phase variation is to be achieved under feedback control, we can obtain the noise tolerance as listed in Tables 1 and 2. .

For the modulator ripple, the problematic frequencies are usually less than hundred kHz. It is valuable for us to focus on the rising part of the curves in figures above and the corresponding results in tables. To control the phase variation within $0.5°$, it seems better to keep the modulator ripple $<1\%$ at low frequency (<1 kHz), while $<0.1\%$ for normal conducting cavity and $<0.5\%$ for superconducting cavity at higher frequency (>1 kHz). For the ripple with frequency below 100 Hz, it is possible to leave the ripple at around 3% or even higher for much lower frequencies.



(a)



(b)

Figure 5: Noise suppression performance of PI feedback closed loop as a function of frequency for (a): superconducting cavity($K_p = 20, K_i = 2\pi \times 518$) and (b): normal conducting cavity($K_p = 1, K_i = 2\pi \times 10^4$)

CONCLUSION

The modulator droop and ripple of 1% induces more than $10°$ in klystron output phase and 1.25% in amplitude (2.5% in power). The PI feedback loop has trouble to deal with the noises with high amplitude and high frequency due to loop delay and the necessity to keep proper phase margin. It would be better to keep the modulator droop and ripple $<1\%$ in low frequency range (<1 kHz), while $<0.1\%$ for normal conducting cavity and $<0.5\%$ for superconducting cavity in higher frequency range (>1 kHz). For the modulator droop and very low frequency ripple below 100 Hz, the tolerance for the ripple could be up to 3% or even higher, but it consumes more power and more phase dynamic range. It is essential to reduce the droop and ripple as much as possible.

Table 1: Noise tolerances of PI feedback closed loop at different frequencies for superconducting cavity

Frequency range /kHz	Loop gain available	Tolerance in cathode voltage
<0.1, or >58	>100	>3.3%
$0.1 \sim 0.4, 15 \sim 58$	$30 \sim 100$	$1\% \sim 3.3\%$
$0.4 \sim 15$	$20 \sim 30$	$0.7\% \sim 1\%$

Table 2: Noise tolerances of PI feedback closed loop at different frequencies for normal conducting cavity

Frequency range /kHz	Loop gain available	Tolerance in cathode voltage
<0.1, or > 1000	>100	>3.3%
0.1˜0.3, 300˜1000	$30 \sim 100$	$1\% \sim 3.3\%$
$0.3 \sim 1, 100 \sim 300$	$10 \sim 30$	$0.33\% \sim 1\%$
$1 \sim 100$	$2 \sim 10$	$0.07\% \sim 0.33\%$

REFERENCES

[1] R. Zeng, A. J. Johansson, K. Rathsman,and S. Molloy, ”Influence of the Droop and Ripple of Modulator on Klystron Output,” ESS Technical notes ESS/AD/0033, European Spallation Source AB, 2011.

[2] M. Hoffmann, ”Development of a multichannel RF field detector for the Low-Level RF control of the Free-Electron Laser at Hamburg,” PhD thesis, Hamburg University of Technology, 2008.

[3] T. Schilcher, ”Vector Sum Control of Pulsed Accelerating Fields in Lorentz Force Detuned Superconducting Cavities,” PhD thesis, University of Hamburg, 1998.

[4] Hengjie Ma, Mark Champion, Mark Crofford et al., ”Low-level rf control of spallation neutron source: System and characterization,” *Phys. Rev. ST Accel. Beams*, 9(3):032001, Mar 2006.

[5] S. Michizono, S. Anami, M. Kawamura, et al., ”Digital rf control system for 400-mev proton linac of jaeri/kek joint project,” In *Proceedings of the 2002 Linear Accelerator Conference*, 2002.

[6] V. Ayvazyan, S. Choroba, Z. Geng et al., ”Optimization of Filling Procedure for TESLA-type Cavities for Klystron RF Power Minimization of European XFEL,” In *Proceedings of 1st International Particle Accelerator Conference: IPAC’10*, 2010.