Tuning Control and Transient Response of the ARES for KEKB

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Abstract

This paper discusses the operating issues for an accelerator resonantly coupled with an energy storage (ARES) for KEKB. We have obtained transfer functions of the ARES. The tuning control methods are examined, while taking possible errors into account. The transient response of the ARES to a bunch-gap is also discussed.

1 INTRODUCTION

In a large e^+e^- storage ring with an extremely high beam current, the accelerating mode itself can excite a strong longitudinal coupled-bunch instability. In order to solve this problem for KEKB [1], an ARES scheme was devised [2]. The ARES is a three-cavity system where an accelerating (a-) cavity couples with an energy storage (s-) cavity operating in a high-Q mode via a coupling (c-) cavity in between. The c-cavity is equipped with a damper, which reduces the loaded-Q value of the c-cavity to below 100 to damp the parasitic 0 and π modes.

The resonant frequency of the a-cavity (ω_a) should be detuned in order to compensate for the reactive component of the beam loading, while that of the c- (ω_c) and s-cavities (ω_s) should be kept at the operating frequency (ω_{rf}) [2]. Since the s-cavity has a very high Q-value, ω_s must be controlled so as to compensate for any change due to thermal expansion or other effects. Therefore, two tuning control loops are required: one is for the a-cavity and the other is for the s-cavity.

It should be noted that the ARES will be operated under such a condition that the three cavities are resonantly coupled, and their Q-values are different from each other by three orders of magnitude. Therefore, the tuning system should be studied quantitatively, by taking any possible errors into account. In particular, (1) the two tuners are no longer independent: one tuning loop can affect the other, and (2) if a high field is excited in the c-cavity, a large amount of RF power is extracted to the c-cavity damper. It not only reduces the Q-value of the operating $\pi/2$ mode, but can damage the load which terminates the damper.

Another issue regarding the operation of the ARES is the transient responses. In particular, the response to a bunch-gap, which will be introduced to avoid ion-trapping, should be studied. The bunch-gap modulates the bunch position from the colliding point, resulting in a luminosity reduction. In addition, it modulates the power to the c-cavity damper: the peak power to the load can be increased.

2 TRANSFER FUNCTION OF THE ARES

In the coupled-resonator model, the ARES is expressed in terms of three simultaneous differential equations [2]. By Laplace-transforming them, we obtain the following algebraic equations in the Laplace region:

$$(p^2+\frac{\omega_a}{Q_a}p+\omega_a^2)X_a(p)+k_a p^2 X_c(p) = \omega_a\frac{R_a}{Q_a}pI_b(p), \quad (1)$$

$$(p^2+\frac{\omega_c}{Q_c}p+\omega_c^2)X_c(p)+p^2(k_aX_a(p)+k_sX_s(p)) = 0, \quad (2)$$

$$(p^2+\frac{\omega_s}{Q_s}(1+\beta_s)p+\omega_s^2)X_s(p)+k_s p^2 X_c(p) = \omega_s\frac{R_s}{Q_s}pI_g(p), \quad (3)$$

where $X_a(p)$, $X_c(p)$, $X_s(p)$, $I_b(p)$ and $I_g(p)$ are the Laplace transforms of the cavity voltage ($x_a(t)$, $x_c(t)$, $x_s(t)$), the beam current, and the generator current, respectively. (Here, x_a is the accelerating voltage, and x_c and x_s are defined in such a way that $|x_a^2|$, $|x_c^2|$ and $|x_s^2|$ are proportional to the stored energy in each cavity.) k_a and k_s are the coupling constant between the a- and c-cavities, and between the s- and c-cavities, respectively. β_s is the input coupling to the s-cavity. (The input power is fed through the s-cavity.) From the definition of x_μ (above), the shunt impedance of the s-cavity (R_s) is related to that of the a-cavity (R_a) as $\omega_aR_a/Q_a = \omega_sR_s/Q_s$.

Equations 1 — 3 are solved as:

$$X_a(p) = \frac{A_b(p)I_b(p)+A_g(p)I_g(p)}{D(p)}, \quad (4)$$

$$X_c(p) = \frac{C_b(p)I_b(p)+C_g(p)I_g(p)}{D(p)}, \quad (5)$$

$$X_s(p) = \frac{S_b(p)I_b(p)+S_g(p)I_g(p)}{D(p)}, \quad (6)$$

where

$$\begin{aligned} D(p) &= (p^2+\frac{\omega_a}{Q_a}p+\omega_a^2)(p^2+\frac{\omega_c}{Q_c}p+\omega_c^2) \\ &\times(p^2+\frac{\omega_s}{Q_s}(1+\beta_s)p+\omega_s^2) - p^4[(p^2+\frac{\omega_a}{Q_a}p+\omega_a^2)k_s^2 \\ &+(p^2+\frac{\omega_s}{Q_s}(1+\beta_s)p+\omega_s^2)k_a^2], \quad (7) \end{aligned}$$

$$\begin{aligned} A_b(p) &= [(p^2+\frac{\omega_c}{Q_c}p+\omega_c^2) \\ &\times(p^2+\frac{\omega_s}{Q_s}(1+\beta_s)p+\omega_s^2) - k_s^2p^4]p\omega_a\frac{R_a}{Q_a}, \quad (8) \end{aligned}$$

$$A_g(p) = k_a k_s p^5 \omega_a \frac{R_a}{Q_a}, \tag{9}$$

$$C_b(p) = -k_a(p^2 + \frac{\omega_s}{Q_s}(1+\beta_s)p + \omega_s^2)p^3\omega_a \frac{R_a}{Q_a}, \tag{10}$$

$$C_g(p) = -k_s(p^2 + \frac{\omega_a}{Q_a}p + \omega_a^2)p^3\omega_a \frac{R_a}{Q_a}, \tag{11}$$

$$S_b(p) = k_a k_s p^5 \omega_a \frac{R_a}{Q_a}, \tag{12}$$

$$S_g(p) = [(p^2 + \frac{\omega_a}{Q_a}p + \omega_a^2) \times (p^2 + \frac{\omega_c}{Q_c}p + \omega_c^2) - k_a^2 p^4] p \omega_a \frac{R_a}{Q_a}. \tag{13}$$

3 TUNING SYSTEM

Figure 1 shows a schematic view of the RF control system examined here. In addition to the tuning loops, it has a phase lock loop (PLL) and an auto level control loop (ALC) to keep the phase and amplitude of the voltage in the a-cavity $X_a(p)$ constant.

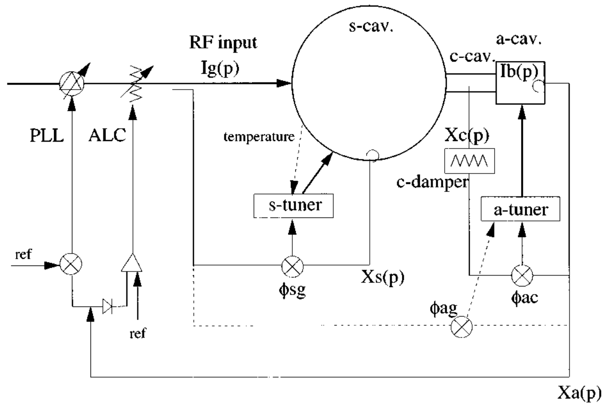

Figure 1: Block diagram of the tuning system with feedback loops examined for the ARES.

First, we consider the case in which the tuning controls for the a- and s- cavities are off, while PLL and ALC for the a-cavity are working. Given $X_a(p)$, ω_a, ω_c and ω_s, we obtain $X_c(p)$ and $X_s(p)$ from Eqs. 1 and 2. Since ω_s is not included in these equations, $X_c(p)$ and $X_s(p)$ are independent of ω_s. In particular, the relative phases between the a-, c-, and s-cavities are independent of ω_s. Figure 2 (upper) shows the phase of each cavity relative to the generator power (ϕ_{ag}, ϕ_{cg} and ϕ_{sg}), as a function of ω_s. ($I_g(p)$ is calculated from Eq. 3.) On the other hand, $X_c(p)$ depends on ω_a. Although $X_s(p)$ depends on ω_a, as shown in Eq. 2, the dependence is small, because the amplitude of $X_c(p)$ is much smaller than that of $X_a(p)$ for the operating mode. As a result, the relative phases between the c- and other cavities (ϕ_{ac} and ϕ_{cs}) depend on ω_a, as shown in Figure 2 (lower). The results suggest that ϕ_{ac} or ϕ_{cs} should be used for the a-cavity tuning control.

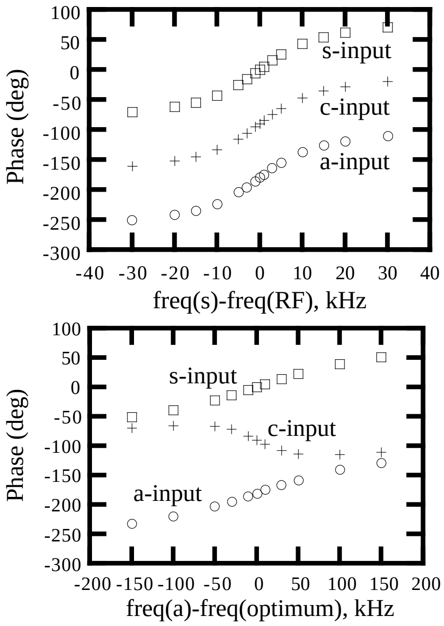

Figure 2: Phase in the cavity with PLL and ALC on: (upper) as a function of ω_s, and (lower) as a function of ω_a.

Next, we include the a- and s-tuning loops, while taking possible errors into account. Since the response of the PLL and ALC is usually much faster than the tuning loops, we simply assume that $X_a(p)$ is constant. We examined different methods for the tuning control, as follows (see Figure 1):

1. control the s-tuner according to ϕ_{sg}, and the a-tuner according to ϕ_{ac};
2. control the s- and a-tuners according to ϕ_{sg} and ϕ_{ag}, respectively; and
3. measure the temperature of the s-cavity and move its tuner accordingly, while the a-tuner is controlled according to ϕ_{ag}.

The last method uses a feed-forward method for the s-tuner, while the others are feedback loops based on the relative phases. Given $X_a(p)$, ω_c, and the errors for the tuning loops, we calculated solutions of Eq. 1 — 3 for $X_c(p)$, $X_s(p)$, ω_a and ω_s.

The generator power (P_g) and the extracted power from the c-cavity (P_c) are shown in Figures 3 to 5, corresponding to the tuning method of 1 to 3, respectively. Figure 3 shows the case of method 1. The increase of P_g and P_c from their minimum values is very small, even if ϕ_{sg} has an error of $\pm$ 10 degrees. Similar result was obtained also when ϕ_{ac} has the same amount of error. This phase accuracy can be easily achieved with an ordinary phase-detection system. This method can be used for the ARES.

Figure 4 shows the case of method 2. A phase error of $\pm$ 1.0 degree in ϕ_{sg} gives rise to an unacceptable increase of P_g and P_c. The extreme sensitivity to the phase error can be understood by considering the fact that the relative phase between the a- and s-cavity is insensitive to the frequency change (see Figure 2). Consequently, a small phase error significantly shifts ω_s or ω_a. Therefore, this tuning method should not be adopted.

Figure 5 shows the case of method 3. When ω_s shifts from ω_{rf} by $\pm$ 10 kHz, P_c increases significantly. In order to avoid any extraordinary heating of the load terminating the damper, ω_s should be controlled to within $\pm$ 10 kHz, which corresponds to a temperature change of $\pm$ 2 degrees. It is almost impossible to control ω_s with this accuracy: a large amount of heat flows from the cavity wall to the water cooling channel and a large temperature gradient exsits in the cavity.

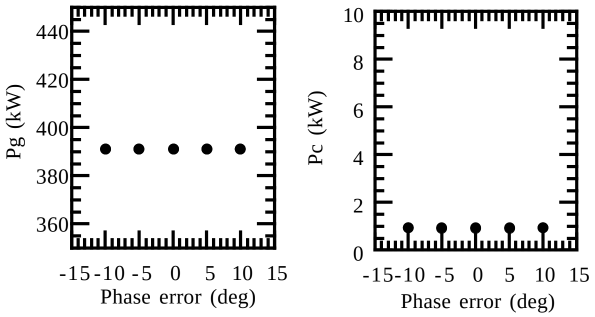

Figure 3: Effect of the error in ϕ_{sg} for tuning method 1.

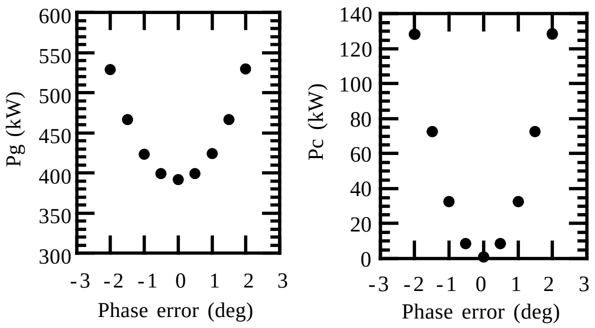

Figure 4: Effect of the error in ϕ_{sg} for tuning method 2.

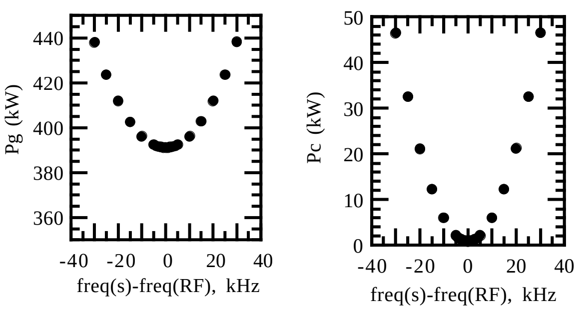

Figure 5: Effect of the error in ω_s for tuning method 3.

4 BUNCH-GAP TRANSIENT

The transient responses can generally be calculated from inverse Laplace transforms of Eqs. 4 — 6. Here, we calculate the bunch-gap transient. We assume that in N_b equally-spaced buckets M continuous buckets are filled with an equal charge (q) and the other $N_b - M$ bunches are missing.

To simplify the problem, we assume that the tuners and the feedback loops do not respond to the bunch gap. This is valid for KEKB: the response speed for the tuning control is 1–10 Hz and that for the ALC and PLL is about 1 kHz, whereas the revolution frequency is 100 kHz. We also neglect the effect of the bunch-position shift due to field modulation on the beam-induced voltage. Instead, we simply use equi-distant bunches with gaps and the Laplace transforms. This approximation is good for KEKB, since the bunch-position shift is small.

We calculated the gap transient in the following way. First, we calculate the operating parameters, such as ω_a, ω_s, and i_g, under a continuous beam loading of KEKB. Then, a beam spectrum with a 10% gap is applied to the system, while keeping ω_a, ω_s, and i_g constant.

Figure 6 shows the results. The modulation of the amplitude ($\Delta V/V$) and the phase ($\Delta\phi$) of the a-cavity are 0.8% and 2.6 degrees, respectively. The effective change of the bunch phase ($\Delta\phi_b$), which is given by $\Delta\phi_b = \Delta\phi + (\Delta V/V)\tan\phi_s$, is 2.7 degrees, where ϕ_s is the synchronous phase. The modulation of the a-cavity field is in good agreement with that calculated using a single-cavity approximation [3]. The extracted power P_c changes from 300 W with the beam to a peak of 2.5 kW at the gap. The response is fast because of the low Q-value of the c-cavity.

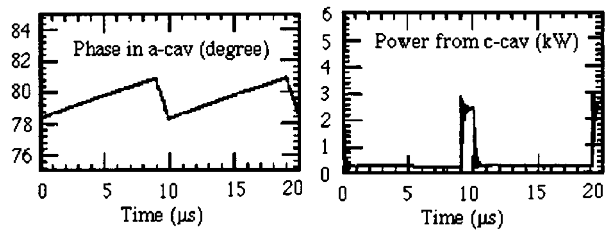

Figure 6: Transient response to a bunch gap in KEKB.

5 SUMMARY

We have studied the tuning control system and the bunch-gap transient on the basis of the transfer functions. We proposed the most promising tuning method for normal operating conditions with the ALC and PLL working. A remaining problem is to establish a recovery procedure: when we switch on the ARES under a circulating beam, we have to tune the cavities before the ALC and PLL are switched on under heavy beam loading. Further study in this respect is being conducted.

6 REFERENCES

[1] "KEKB B-Factory Design Report", KEK-Report 95-7.

[2] Y. Yamazaki and T. Kageyama, Part. Accel. 44, 107 (1994).

[3] K. Akai and E. Ezura, Proc. 4th European Part. Accel. Conf., p. 1141 (1994).