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 $\pi$ modes.

The resonant frequency of the a-cavity ($\omega_a$) should be detuned in order to compensate for the reactive component of the beam loading, while that of the c- ($\omega_c$) and s-cavities ($\omega_s$) should be kept at the operating frequency ($\omega_{rf}$) [2]. Since the s-cavity has a very high $Q$-value, $\omega_s$ 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:

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

$$p^2 + \frac{\omega_c}{Q_c}p + \omega_c^2)X_c(p) + p^2 (k_a X_a(p) + k_s X_s(p)) = 0,$$  \hspace{1cm} (2)

$$p^2 + \frac{\omega_s}{Q_s}((1+\beta_s)p + \omega_s^2)X_s(p) + k_s p^2 X_c(p) = \omega_s \frac{R_s}{Q_s} pI_g(p),$$  \hspace{1cm} (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. $\beta_s$ is the input coupling to the s-cavity. (The input power is fed through the s-cavity.) From the definition of $x_a$ (above), the shunt impedance of the s-cavity ($R_s$) is related to that of the a-cavity ($R_a$) as $\omega_a R_s/Q_a = \omega_s R_s/Q_s$.

Equations 1 — 3 are solved as:

$$X_a(p) = \frac{A_b(p)I_b(p) + A_c(p)I_c(p)}{D(p)},$$  \hspace{1cm} (4)

$$X_c(p) = \frac{C_b(p)I_b(p) + C_c(p)I_c(p)}{D(p)},$$  \hspace{1cm} (5)

$$X_s(p) = \frac{S_b(p)I_b(p) + S_c(p)I_c(p)}{D(p)},$$  \hspace{1cm} (6)

where

$$D(p) = (p^2 + \frac{\omega_a}{Q_a}p + \omega_a^2)(p^2 + \frac{\omega_c}{Q_c}p + \omega_c^2)$$

$$\times (p^2 + \frac{\omega_s}{Q_s}(1+\beta_s)p + \omega_s^2) - p^2(p^2 + \frac{\omega_a}{Q_a}p + \omega_a^2)k_a^2$$

$$+ (p^2 + \frac{\omega_s}{Q_s}(1+\beta_s)p + \omega_s^2)k_s^2),$$  \hspace{1cm} (7)

$$A_b(p) = [(p^2 + \frac{\omega_c}{Q_c}p + \omega_c^2)$$

$$\times (p^2 + \frac{\omega_s}{Q_s}(1+\beta_s)p + \omega_s^2) - k_s^2 p^4] \frac{\omega_a}{Q_a} \frac{R_a}{Q_a},$$  \hspace{1cm} (8)
\begin{align}
A_g(p) &= k_a k_s p^2 \omega_s 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 R_a Q_a, \tag{10} \\
C_g(p) &= -k_s (p^2 + \frac{\omega_s}{Q_s} p + \omega_s^2) p^3 \omega_a R_a Q_a, \tag{11} \\
S_b(p) &= k_a k_s p \omega_s R_a Q_a, \tag{12} \\
S_g(p) &= [(p^2 + \frac{\omega_s}{Q_s} p + \omega_s^2) \\
&\times(p^2 + \frac{\omega_s}{Q_s} p + \omega_s^2) - k_a^2 p^4] \omega_a R_a Q_a. \tag{13}
\end{align}

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.](image)

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 \( X_a(p) \), \( \omega_s \), and \( \omega_a \), we obtain \( X_c(p) \) and \( X_s(p) \) from Eqs. 1 and 2. Since \( \omega_s \) is not included in these equations, \( X_c(p) \) and \( X_s(p) \) are independent of \( \omega_s \). In particular, the relative phases between the a-, c-, and s-cavities are independent of \( \omega_s \). Figure 2 (upper) shows the phase of each cavity relative to the generator power (\( \phi_{ag} \), \( \phi_{cg} \), and \( \phi_{sg} \)), as a function of \( \omega_s \). \( I_a(p) \) is calculated from Eq. 3. On the other hand, \( X_c(p) \) depends on \( \omega_s \). Although \( X_s(p) \) depends on \( \omega_s \), as shown in Eq. 2, the dependence is small, because the amplitude of \( X_s(p) \) is much smaller than that of \( X_c(p) \) for the operating mode. As a result, the relative phases between the c- and other cavities (\( \phi_{cg} \) and \( \phi_{cs} \)) depend on \( \omega_a \), as shown in Figure 2 (lower). The results suggest that \( \phi_{ac} \) or \( \phi_{ac} \) 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 \( \omega_s \), and (lower) as a function of \( \omega_a \).](image)

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

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

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 \( \phi_{sg} \) has an error of \( \pm 10 \) degrees. Similar result was obtained also when \( \phi_{ac} \) 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 \( \pm 10 \) degree in \( \phi_{sg} \) 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 $\omega_s$ or $\omega_a$. Therefore, this tuning method should not be adopted.

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

![Figure 3: Effect of the error in $\phi_{sg}$ for tuning method 1.](image)

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![Figure 4: Effect of the error in $\phi_{sg}$ for tuning method 2.](image)

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![Figure 5: Effect of the error in $\omega_s$ for tuning method 3.](image)

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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 $\omega_a$, $\omega_s$, 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 $\omega_a$, $\omega_s$, 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 $\phi_s$ 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.](image)

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