Tuner control system of spoke012 SRF cavity for C-ADS injector I at IHEP (Postprint)

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Abstract

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Full Text

Preamble

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Abstract

A new tuner control system for spoke superconducting radio frequency (SRF) cavities has been developed and applied to Cryomodule I (CM1) of the C-ADS Injector I at IHEP. We have successfully implemented the tuner controller and achieved a cavity tuning phase error of ±0.7° (peak-to-peak) in the presence of electromechanical coupled resonance. This paper presents preliminary experimental results based on the new tuner controller under proton beam commissioning.

Keywords: tuner control, spoke cavity, electromechanical coupled resonance
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1. Introduction

The China Accelerator Driven sub-critical System (C-ADS) is a proposed project to address nuclear waste management and safety operation for nuclear power plants in China. Injector I, part of the 25 MeV main linac for the C-ADS facility, will operate in continuous wave (CW) mode and provide a 10 MeV proton beam [1]. The first spoke SRF cavity, operating at 325 MHz with =0.12 (spoke012), has been developed by the Institute of High Energy Physics (IHEP), Chinese Academy of Sciences, with the first beam commissioning carried out in September 2015.

The spoke012 SRF cavity was selected for the C-ADS Injector I to accelerate protons. CM1 of Injector I, consisting of seven spoke012 cavities, has been constructed at IHEP. To control the resonant frequency of each cavity at 325 MHz, a new tuner control system has been developed to achieve a cavity tuning phase error of ±0.7° (peak-to-peak). The system also provides a Graphical User Interface (GUI) based on Control System Studio (CSS) within the Experimental Physics and Industrial Control System (EPICS) framework for remote operation. The spoke012 SRF cavities exhibit high Q-factors, requiring operation with narrow bandwidths. Electromechanical coupled resonance (ponderomotive instability) results in amplitude and phase instability of the field in superconducting cavities [2]. The resonance frequency appears within 200–250 Hz at ±3 dB bandwidths of spoke012 cavities. Fast feedback control of piezoelectric mechanical tuners has been used with some success to compensate for cavity frequency detuning and stabilize the field in SRF cavities [3]. This paper presents results of detuning compensation for the 325 MHz spoke012 SRF cavity in Injector I of the C-ADS project at IHEP under proton beam test.

2. Mechanical Structure of the Tuner

Cavity tuners are mechanical devices designed to adjust cavity frequency. As shown in Fig. 2 [Figure 2: see original paper] (a) and (b), a mechanical tuner employing a stepping motor as a slow tuner and piezo actuators as a fast tuner is used to compensate for cavity detuning.

The mechanical stepping motor tuner operates at room temperature for a large adjustable frequency range of approximately ±200 kHz, while the piezo tuner works in a 2 K environment for small but rapid frequency adjustments. The main parameters of the 325 MHz tuner are listed in Table 1 [4].

The step angle of the stepping motor (PKE596AC-HS50) is 0.009° per step, which has been further subdivided 80 times through motor driver adjustment. The reduction ratio of the gears is 1:3, and the screw pitch of the tuner is 2 mm. The theoretical relationship between pulse number and cavity frequency shift is given by:

$$\Delta f = \frac{21.3 \times f \times p \times n}{1,000,000,009,136,050}$$

where Δf represents cavity frequency shift and n represents pulse numbers.

According to this formula, the theoretical resolution of the main stepping motor is 0.33 nm per pulse. However, the actual resolution is significantly lower than the theoretical value due to installation errors and other factors [4]. Fig. 3 [Figure 3: see original paper] shows the relationship between stepping motor pulse number and cavity frequency at $E_{acc} = 1$ MV/m. The return difference caused by gear backlash is indicated within the red circle, with a maximum backlash value of approximately 337 Hz—close to the full cavity bandwidth (~400 Hz).

Fig. 4 [Figure 4: see original paper] (a) and (b) illustrate the excitation voltage of one piezo actuator versus cavity frequency variation at room temperature and 2 K, respectively. The cavity frequency changed by approximately 6 kHz using one piezo actuator at room temperature as the excitation voltage varied from 0 to 900 V (with a 500 V offset). However, the adjustable range of one piezo actuator decreased to 1.63 kHz at 2 K temperature. Hysteresis phenomena are evident in both motor and piezo tuners during round-trip operation. Large frequency detuning combined with narrow cavity bandwidths presents a significant challenge for tuner control system precision.

4. Resonance Stabilization Using Feedback Control

4.1 Main Factors Influencing Cavity Frequency

Cavity frequency is disturbed by numerous factors, including Lorentz force, liquid helium pressure, beam loading, and microphonics. The primary detuning factors vary from cavity to cavity in operational machines. The main RF parameters of the spoke012 cavity are listed in Table 2 .

For low-velocity proton accelerators, beam loading is often negligible. The cryomodule operates in a 2 K environment where liquid helium pressure fluctuations are minimal. Any cavity possesses an infinite number of mechanical eigenmodes that can be excited by microphonics and Lorentz force, causing frequency shifts. Furthermore, coupling between electromagnetic and mechanical modes can lead to resonance instabilities. Consequently, ponderomotive instability and microphonics represent major challenges for cavity tuning and RF field stabilization in superconducting cavities.

The mechanical eigenmodes of vibration for one spoke012 cavity, measured with turbo and scroll pumps, are shown in Fig. 8 [Figure 8: see original paper]. The main resonance frequency appears at approximately 250 Hz, with a complex transfer function due to numerous low-frequency modes.

The coupling between the RF field and mechanical modes, along with the field amplitude and external vibration/microphonics driving terms, determines the frequency shift. In steady-state, the total frequency shift is governed by the static Lorentz coefficient of the cavity [7].

Eq. (2) describes how the cavity field is affected by frequency amplitude and microphonics. Eq. (3) illustrates that the total Lorentz function for a cavity equals the sum of functions for individual mechanical modes. The Lorentz coefficient of cavity #7 has been measured and is shown in Fig. 10 [Figure 10: see original paper]. The Lorentz coefficient ($k = -10$) is sufficiently high that the frequency shift caused by Lorentz force exceeds several half-bandwidths at 8 MV/m.

According to the adiabatic theorem, the frequency shift caused by mechanical modes is given by:

$$\mu\omega\Delta\mu ...2222().kVnt\mu\mu\mu\mu\mu\mu\mu\omega\omega\omega\tau\Delta+\Delta+\Omega=-\Omega+\mu\tau\mu\mu\Omega\mu k\mu\mu V()nt200.Vk\mu\mu\mu\mu\omega\omega\Delta=\Delta=-\sum\sum k\mu\mu$$

where μ represents the decay time of mechanical modes.

Fig. 9 [Figure 9: see original paper] shows the frequency spectrum of the pickup signal from the cavity when driven by a fixed-frequency source in the presence of ponderomotive effects. Considering ponderomotive effects and microphonics, the frequency control loop must provide precise rejection of electromechanical coupled resonance.

4.2 Feedback Control of Piezo Tuner

With amplitude and phase control loops closed, we compared cavity field stability with the feedback controller on and off. The test results are shown in Fig. 11 [Figure 11: see original paper] and Fig. 12 [Figure 12: see original paper].

With the PI feedback controller active, field amplitude stability improved from ±0.9% to ±0.3% (peak-to-peak), and phase stability improved from ±3° to ±0.7°. Meanwhile, the maximum accelerating field increased from 5.5 MV/m to 10 MV/m. The combination of fast feedback compensation successfully locked the cavity resonance to a fixed frequency, though long-term drift remains inevitable.

An additional test verified interactions between two piezo actuator tuners, demonstrating that they do not produce multiple resonances at 6 MV/m during 4-hour proton beam tests.

5. Summary

This tuner control system has been successfully implemented for the first time, achieving a phase error of ±0.7°. It has been applied to CM1 of C-ADS Injector I under proton beam conditions (6 MeV, 1 ms pulse operation). Feedback control has proven effective for reducing cavity detuning in a noisy vibrational environment. However, cavity characteristics should be analyzed to better understand the coupled electromechanical system and apply feedforward algorithms to design an optimal resonance controller.

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Note: Figure translations are in progress. See original paper for figures.

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