ADAPTIVE FEEDFORWARD CANCELLATION OF SINUSOIDAL DISTURBANCES IN SUPERCONDUCTING RF CAVITIES *

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Abstract: A control method, known as adaptive feedforward cancellation (AFC) is applied to damp sinusoidal disturbances due to microphonics in superconducting RF (SRF) cavities. AFC provides a method for damping internal, and external sinusoidal disturbances with known frequencies. It is preferred over other schemes because it uses rudimentary information about the frequency response at the disturbance frequencies, without the necessity of knowing an analytic model (transfer function) of the system. It estimates the magnitude and phase of the sinusoidal disturbance inputs and generates a control signal to cancel their effect. AFC, along with a frequency estimation process, is shown to be very successful in the cancellation of sinusoidal signals from different sources. The results of this research may significantly reduce the power requirements and increase the stability for lightly loaded continuous-wave SRF systems.

INTRODUCTION

The control of the resonance frequency of SRF cavities is highly desirable in view of the narrow bandwidth of operation. Detuning of SRF cavities is caused mainly by the Lorentz force (radiation pressure induced by high RF field) and microphonics (mechanical vibrations). In continuous-wave (cw) accelerators, microphonics is the major concern. It is natural to think of using fast mechanical actuators to compensate for, i.e., attenuate, the effect of mechanical vibrations on detuning. This concept was applied successfully by Simrock et al [1] to a simple quarter wave resonator (QWR) with a fast piezoelectric tuner. However, the high-gain feedback approach used in [1] is too complex to apply to multi-cell elliptical cavities, which is the subject of this work. In fact, in a previous work by Simrock [2] for elliptical cavities it is stated that “the large phase shift over this frequency range makes it clear that feedback for microphonics control using the RF signal will not be possible with the piezo actuator.” To date, there has been no demonstration of microphonics control on multi-cell SRF cavities, and the current paper presents the first such demonstration.

We start by formulating the microphonics control problem from a control theory viewpoint and exploring various standard control approaches. We conclude that AFC is the most appropriate for the task because it handles sinusoidal disturbances, which are the main source of microphonics, it is developed for stable systems, as in the current case, and it does not require an analytic model of the system to design a feedback controller. Then, we review the main elements of the theory of AFC, and present our experimental demonstration of its successful use in microphonics control of elliptical cavities.

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PROBLEM FORMULATION AND PRELIMINARY WORK

The starting point is to develop a mathematical model that describes how the mechanical vibrations and the control actuator determine the cavity detuning. It is shown in [3, Section 3.2] that the relationship between the cavity detuning $\Delta\omega = \omega_0 - \omega$ and the phase angle ψ (between the driving current and cavity voltage) can be approximated by a parallel RLC circuit; consequently,

$$\tan\psi = 2Q_L\left(\frac{\Delta\omega}{\omega}\right) \qquad (1)$$

where ω is the RF generator frequency, ω_0 is the cavity eigenfrequency, and Q_L is the loaded Q factor, defined by

$$Q_L = 2\pi\cdot\frac{\text{Stored energy}}{\text{Total power dissipation/cycle}}$$

From (1), we see that detuning can be reduced by reducing the phase angle ψ. Towards that end, we develop a model for ψ. Two basic assumptions in developing this model are:

- Mechanical vibrations, which affect the cavity in a distributed way, can be modelled by an equivalent lumped disturbance that affects the system at the same point where the control actuator is applied. In other words, the input to the system can be represented as the sum $u-d$, where d is the disturbance input and u is the control input.
- The system with input $u-d$ and output ψ is linear and time-invariant. Hence, it can be represented by a transfer function $G(s)$ from $u-d$ to ψ.

From a control theory viewpoint, the problem reduces to designing the control u to reject or attenuate the effect of the disturbance d on the output ψ. We started our investigation by examining six different control techniques for disturbance rejection: (1) Proportional (P), (2) Proportional-Integral (PI), (3) Proportional-Integral-Derivative (PID), (4) High-gain band-limited, (5) Servocompensator design, and (6) Adaptive Feedforward Cancellation (AFC). The six techniques were investigated in the internal report [4] using simulation of an experimentally-determined model of a single-cell copper RF cavity at room temperature. The simulation studies showed that the traditional P, PI, and PID controllers would not achieve the desired level of disturbance attenuation because the controller gains are limited by stability requirements. In the high-gain band-limited control design, a controller is designed to have a high loop gain over the frequency band of interest, while rolling off the controller's frequency response rapidly at high frequency to ensure the stability of the closed-loop system. The drawback of this design is the relatively high-order of the controller. It is worthwhile to note that this technique is used by Simrock et al. [1] in microphonics control of a quarter wave resonator with a fast piezoelectric tuner. However, our investigation indicates that the complexity of the controller and the demand on the control effort in such design will be prohibitive for multi-cell cavities because the order of the controller will be very high. Even in the simple experiment of [1], the controller's order is 20, i.e., the degree of the denominator polynomial of the controller's transfer function is 20.

Microphonics is known to be caused, primarily, by mechanical vibrations that are almost periodic; in particular, the disturbance signal can be represented as the sum of a finite number of sinusoidal signals. For this type of disturbance, the techniques of servocompensators, e.g. [5], and AFC, e.g. [6], are more appropriate because they are designed to work with this particular class of signals. Both approaches performed satisfactorily in the simulation study [4], but the AFC has the advantage that the only information about the transfer function $G(s)$ that is needed is its magnitude and phase at the input frequencies, which can be easily obtained from the experimentally-determined Bode plots. Mathematical analysis of the system illustrated that we can tolerate up to 90 deg phase error, while magnitude error will only affect the speed of convergence of the adaptive algorithm and will not alter its stability. For the servocompensator approach, we have to obtain an analytic model of the system in the form of a rational transfer function to use in designing the compensator. Because of the simplicity of the AFC method, we have adopted it in the experimental part of our work.

ADAPTIVE FEEDFORWARD CANCELLATION

Consider a linear stable system represented by the transfer function $G(s)$. Let y be the output of the system and suppose the input is the sum of two signals $u-d$, where u is the control input and d is an unknown disturbance that can be modelled as the sum of sinusoidal signals of known frequencies, but unknown amplitudes and phases, that is,

$$d = \sum_{i=1}^{n} A_i \sin(\omega_i t + \theta_i) \stackrel{\text{def}}{=} \sum_{i=1}^{n} [a_i \sin(\omega_i t) + b_i \cos(\omega_i t)] \quad (2)$$

where ω_i, for $i = 1, \cdots, n$, are known but a_i and b_i are unknown. The goal is to design the control input u, so as to attenuate the output y in the presence of the disturbance d.

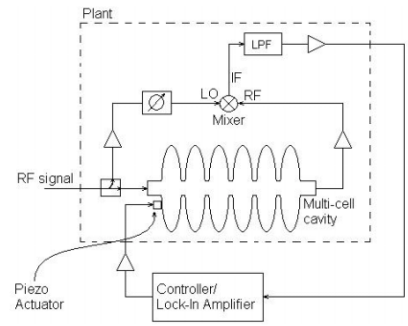

Figure 1: Physical setup of the cavities with the control unit or lock-in amplifier.

Had we known the amplitudes and phases of the sinusoidal signals, we could have cancelled the disturbance by

$$u = \sum_{i=1}^{n} [a_i \sin(\omega_i t) + b_i \cos(\omega_i t)]$$

To cope with the uncertainty in the parameters a_i and b_i, we use the control

$$u = \sum_{i=1}^{n} [\hat{a}_i \sin(\omega_i t) + \hat{b}_i \cos(\omega_i t)] \quad (3)$$

where $\hat{a}_i$ and $\hat{b}_i$ are estimates of a_i and b_i, respectively, obtained by the adaptive algorithm

$$\dot{\hat{a}}_i(t) = -\gamma_i y(t) \sin(\omega_i t + \theta_i) \quad (4)$$

$$\dot{\hat{b}}_i(t) = -\gamma_i y(t) \cos(\omega_i t + \theta_i) \quad (5)$$

where $\gamma_i > 0$ are positive adaptation gains. Since $G(s)$ is stable, by choosing the adaptation gains γ_i small enough so it follows from [7, Theorem 4.4.3] that, in the absence of measurement noise, the adaptive algorithm ensures convergence of the parameter estimates $\hat{a}_i$ and $\hat{b}_i$ to the true parameters a_i and b_i, respectively, and convergence of the output $y(t)$ to zero. In the presence of bounded measurement noise, we can invoke standard perturbation analysis to show that, after finite time, the output will be of the order of the measurement noise.

EXPERIMENTAL DEMONSTRATION

The setup is shown in Figure 1, where the estimated noise signal is added to the system by directly shaking an SRF 6-cell elliptical cavity, cooled to 2 K, using a piezoelectric actuator (PI, model P-842.60). The controller can also be replaced by a lock-in amplifier to generate the Bode plot of the system. The block diagram of the AFC algorithm is shown in Figure 2 for the case of a single-frequency disturbance. It is an implementation of Equations (4) and (5). In Figure 2, ω is the angular frequency of the disturbance signal that is calculated from an FFT of the RF error signal, θ is a phase advance introduced to ensure maximum stability of the system, and γ is the adaptation gain. Both θ and γ are determined from a numerically saved Bode plot, where θ is the phase at the frequency to be cancelled and γ is calculated from the magnitude information such that its value is large at small magnitudes and relatively small at large magnitudes.

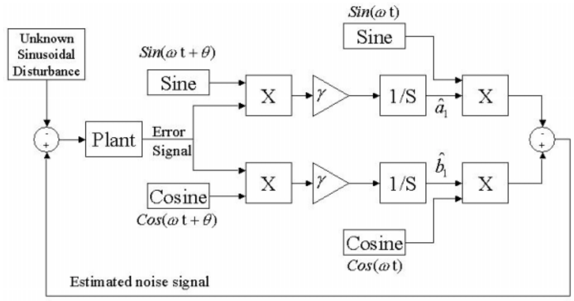

Figure 2: Implementation of the AFC on Simulink.

Experimental setup

A prototype 805 MHz cryomodule has been tested to demonstrate the required performance for the Rare Isotope Accelerator [8, 9]. An external PC is used for modelling the controller in Simulink, which is then built in dSPACE CONTROLDESK developer version that communicates with an external hardware (dSPACE RTI1104 board), with 16 I/O ports. The user's interface is through dSPACE CONTROLDESK developer version for parameters adjustments to achieve optimum control.

The Bode plot is obtained using an SRS digital lock-in amplifier model SR850, as shown in Figure 1. The lock-in amplifier sends out a sinusoidal signal to the piezo-electric actuator that is swept through the desired frequency range, step size, and sampling rate, then the output of the plant is fed back into the lock-in amplifier compared to the output signal of the lock-in amplifier to produce a Bode plot, which is saved in the form of a look-up table. The FFT of the RF error signal is generated from a LeCroy Waverunner LT342 digital oscilloscope, from which the largest frequency components are picked for damping.

Experimental Results

We observed two types of microphonics vibrations: internal (helium oscillations) and external (motors, pumps, etc.). The results of applying AFC to both types are shown in Figures 3 and 4. Figure 3 shows cavity detuning due to internal helium oscillation at 6.5 Hz. It shows an FFT of the detuning for the undamped and damped responses. After applying a cancellation signal at 6.5 Hz, the internal energy shifted to 13 Hz, where another cancellation signal was applied. The first peak at 6.5 Hz was reduced by a factor of 6 from 59 Hz to 10 Hz, while the second peak at 13 Hz was reduced from 13 Hz to 4 Hz.

Figure 4 shows the undamped and damped responses due to external vibrations from a motor that was turned on purposely for demonstration. The noise appeared at 57.5 Hz, and it was successfully damped by a factor of 7.4 from 31 Hz to 4.2 Hz.

CONCLUSIONS

We have demonstrated the successful use of piezoelectric actuators and adaptive feedforward cancellation control to damp sinusoidal disturbances due to microphonics in SRF cavities. The next step in our research is to equip the AFC algorithm with a mechanism to identify the frequencies of the disturbance inputs, and to implement it using field programmable gate arrays (FPGA).

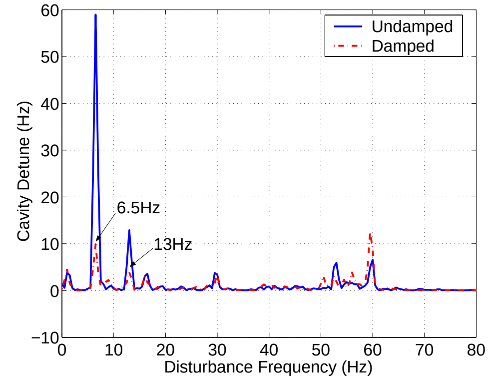

Figure 3: Active damping of helium oscillations at 2K.

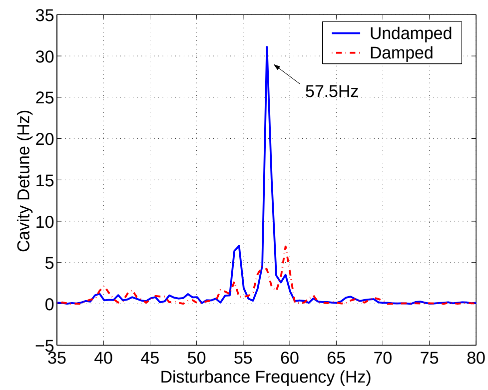

Figure 4: Active damping of external vibration at 2K.

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