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 radio frequency (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 for 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.
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1. Introduction

Control of the resonant frequency of superconducting radio frequency (SRF) cavities is required in view of the narrow bandwidth of operation. Detuning of SRF cavities is caused mainly by the Lorentz force (radiation pressure

induced by the high RF field) and microphonics (mechanical vibrations). In continuous-wave (cw) accelerators, microphonics are the major concern. It is natural to think of using fast mechanical actuators to compensate for microphonics, 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 Ref. [1] is too complex to apply to multi-cell elliptical cavities, which are 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.

In Section 2, we formulate the microphonics control problem from a control theory viewpoint and explore various standard control approaches. The measured spectrum of cw systems in a reasonably quiet environment, as is the case with properly designed accelerators, only exhibits limited narrowband sources of noise. Hence we conclude that adaptive forward cancellation (AFC) is the most appropriate for the task because it handles sinusoidal disturbances. AFC 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. In Section 3, we review the main elements of the theory of AFC, and in Section 4 we present our experimental demonstration of the successful use of AFC in microphonics control of elliptical cavities.

2. Problem formulation and preliminary work

The starting point in microphonics control 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 at steady state by

$$\tan \psi = 2Q_{\mathrm{L}}\left(\frac{\Delta\omega}{\omega}\right) \tag{1}$$

where ω is the RF generator frequency, ω_0 is the cavity eigenfrequency, and Q_{L} is the loaded Q factor, defined by

$$Q_{\mathrm{L}} = 2\pi \frac{\text{Stored energy}}{\text{Total power dissipation/cycle}}. \tag{2}$$

To attenuate the detuning $\Delta\omega$, we design a feedback controller to reduce the angle ψ. Towards that end, we develop a model of the system with ψ as the output and the actuator input voltage u as a control input. 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.

The transfer function $G(s)$ can be determined experimentally by applying a sinusoidal input at u and measuring the steady-state phase angle ψ. By sweeping the frequency of the sinusoidal input over the frequency band of interest, we can determine the frequency response from the input $u - d$ to the output ψ, usually with the help of a lock-in amplifier that produces the Bode plots of the transfer function.

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. They are

(1) proportional (P)
(2) proportional-integral (PI)

(3) proportional-integral-derivative (PID)
(4) high-gain band-limited
(5) servocompensator design
(6) adaptive feedforward cancellation (AFC)

The first four techniques are classical ones for disturbance rejection of a wide class of disturbance inputs. They do not require the disturbance input to have a special form, other than being a bounded signal. The last two techniques work when the disturbance input can be represented as the sum of sinusoidal signals of known frequencies but unknown amplitudes and phases. The six techniques were investigated in the internal reports [4,5] 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. In the low-frequency range the controller essentially inverts the system's transfer function, which is allowable in our case because the transfer function is stable and minimum phase. The drawback of this design is the relatively high order of the controller, which may not be justified in view of the fact that such a controller guards against a wide class of disturbance inputs that may not be present in the current problem. It is worthwhile to note that this technique is used by Simrock et al. [1] for 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 a 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 are 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. Refs. [6,7], and adaptive feedforward cancellation, e.g. Refs. [8,9], are more appropriate because they are designed to work with this particular class of signals. The servocompensator approach includes an internal model of the disturbance signal as part of the controller in such a way that the loop gain at the frequencies of the disturbance is infinite; hence rejecting the disturbance asymptotically. AFC uses an adaptive algorithm to learn the magnitudes and phases of the sinusoidal disturbances and synthesizes the control to cancel them. Both approaches performed satisfactorily in the simulation study [5], 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 are easily obtained from the measured Bode plots. We will see in the next section that we can tolerate up to $90°$ error in determining the phase and that errors in determining the magnitude will affect the speed of convergence of the adaptive algorithm but will not alter its stability. Although Ref. [8] showed equivalence between the AFC and a special design of the internal model for the servocompensator approach, we must still 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. The method is explained in more detail in the next section.

3. 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, i.e.,

$$d = \sum_{i=1}^{n} A_i \sin(\omega_i t + \beta_i) \stackrel{\text{def}}{=} \sum_{i=1}^{n} [a_i \sin(\omega_i t) + b_i \cos(\omega_i t)] \tag{3}$$

where ω_i, for $i = 1, \ldots, n$, are known but a_i and b_i are unknown. The goal is to design the control input so as to attenuate the output y in the presence of the disturbance d. Had we known the amplitudes and phases of the sinusoidal signals, we could have cancelled the disturbance by the control

$$u = \sum_{i=1}^{n} [a_i \sin(\omega_i t) + b_i \cos(\omega_i t)]. \tag{4}$$

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

$$u = \sum_{i=1}^{n} [\hat{a}_i \sin(\omega_i t) + \hat{b}_i \cos(\omega_i t)] \tag{5}$$

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

$$\dot{\hat{a}}_i(t) = -\gamma_i y(t) \sin(\omega_i t + \theta_i) \tag{6}$$

$$\dot{\hat{b}}_i(t) = -\gamma_i y(t) \cos(\omega_i t + \theta_i) \tag{7}$$

where $\gamma_i > 0$ are positive adaptation gains. Define

$$z = \begin{bmatrix} \hat{a}_1 - a_1 \\ \hat{b}_1 - b_1 \\ \hat{a}_2 - a_2 \\ \hat{b}_2 - b_2 \\ \vdots \\ \hat{a}_n - a_n \\ \hat{b}_n - b_n \end{bmatrix}, \quad w = \begin{bmatrix} \sin \omega_1 t \\ \cos \omega_1 t \\ \sin \omega_2 t \\ \cos \omega_2 t \\ \vdots \\ \sin \omega_n t \\ \cos \omega_n t \end{bmatrix},$$

$$\Gamma = \text{diag}[\gamma_1, \gamma_1, \gamma_2, \gamma_2, \ldots, \gamma_n, \gamma_n] \tag{8}$$

$$E_i = \begin{bmatrix} \cos \theta_i & \sin \theta_i \\ -\sin \theta_i & \cos \theta_i \end{bmatrix},$$
$$E = \text{blockdiag}[E_1, E_2, \ldots, E_n] \tag{9}$$

and let $\{A, B, C\}$ be a minimal realization of the transfer function $G(s)$. Then, the overall system can be represented by the following state space equations

$$\dot{z}(t) = -\Gamma E w(t) C x(t) \tag{10}$$

$$\dot{x}(t) = Ax(t) + Bz^{\text{T}}(t)w(t). \tag{11}$$

Since $G(s)$ is stable, all the eigenvalues of A have negative real parts. By choosing the adaptation gains γ_i small enough that $z(t)$ is much slower than $w(t)$ and $x(t)$, we can apply the averaging theory [10, Theorem 4.4.3] to conclude that $z(t)$ can be approximated by the solution of the (time-invariant) average system

$$\dot{z}(t) = Fz(t) \tag{12}$$

where

$$F = -\Gamma E \lim_{T \to \infty} \frac{1}{T} \int_{t_0}^{t_0+T}$$
$$\times \left\{ w(\tau) C \int_0^{\tau} e^{A(\tau-\sigma)} B w^{\text{T}}(\sigma) \, d\sigma \right\} d\tau. \tag{13}$$

Lengthy, but straightforward, calculations show that

$$F = \text{blockdiag}[F_1, F_2, \ldots, F_n] \tag{14}$$

where

$$F_i = -\frac{\gamma_i}{2} |G(j\omega_i)| \begin{bmatrix} \cos(\theta_i - \phi_i) & \sin(\theta_i - \phi_i) \\ -\sin(\theta_i - \phi_i) & \cos(\theta_i - \phi_i) \end{bmatrix} \tag{15}$$

and $\phi_i = \angle G(j\omega_i)$. Choosing θ_i to satisfy

$$|\theta_i - \angle G(j\omega_i)| < 90° \tag{16}$$

ensures that the eigenvalues of F_i have negative real parts at $-(\gamma_i/2)|G(j\omega_i)| \cos(\theta_i - \phi_i)$. The best choice would be

$$\theta_i = \angle G(j\omega_i) \tag{17}$$

which yields multiple real eigenvalues at $-(\gamma_i/2)|G(j\omega_i)|$. In this case, Eq. (16) shows that we can tolerate up to $90°$ error in determining the phase of the transfer function at ω_i. The eigenvalues of F corresponding to different diagonal blocks would vary with the magnitude of the frequency response $|G(j\omega_i)|$. The range of these variations can be limited by choosing $\gamma_i = c_i/|G(j\omega_i)|$ for some positive numbers c_i of the same order of magnitude. It is clear that errors in

determining $|G(j\omega_i)|$ will not be crucial, as they affect the location of the eigenvalues of F but do not change the fact that their real parts will be always negative.

With the choice Eq. (17), all the eigenvalues of F have negative real parts. Hence, it follows from [10, Theorem 4.4.3] that

$$\lim_{t \to \infty} z(t) = 0, \quad \lim_{t \to \infty} x(t) = 0 \quad (18)$$

which shows that $\lim_{t \to \infty} y(t) = 0$. We conclude 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, e.g., Ref. [11, Chapter 9], to show that, after finite time, $z(t)$ and $y(t)$ will be of the order of the measurement noise.

The notation used in this section is retained in the experimental section, with the exception that the output y is taken to be the phase angle ψ. The state x does not appear in the experimental section as the state model is used only for analysis.

4. Experimental demonstration

The experimental setup is shown in Fig. 1. The estimated noise signal is added to the system by
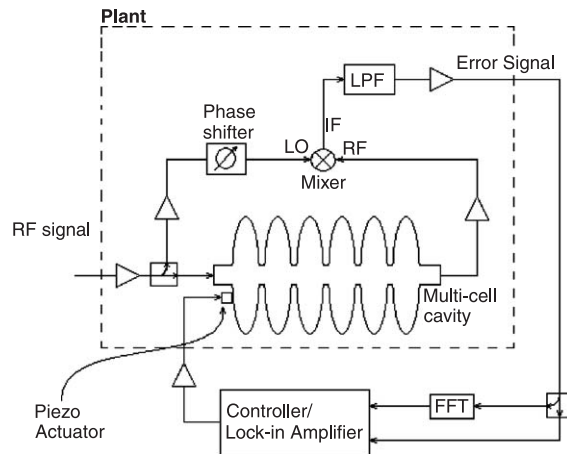

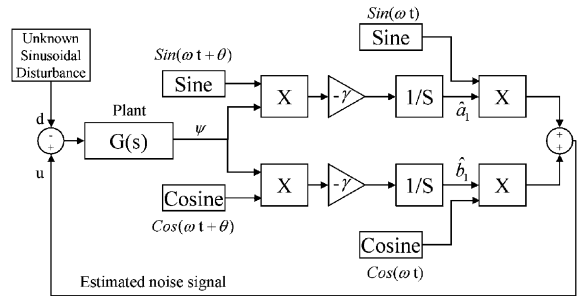Fig. 1. Physical setup of the cavities with the control unit or lock-in amplifier.

Fig. 2. Implementation of the AFC on Simulink.

directly shaking an SRF 6-cell elliptical cavity, cooled to 2 K, using a piezo-electric 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 Fig. 2 for the case of a single-frequency disturbance. It is an implementation of Eqs. (5), (6) and (7).

In Fig. 2, ω is the angular frequency of the disturbance signal that is calculated from a Fast Fourier Transform (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 measured 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.

4.1. Experimental setup

A prototype 805 MHz cryomodule has been tested to demonstrate the required performance for the Rare Isotope Accelerator [12–14]. An external PC is used for modelling the controller in MATLAB/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.

Fig. 3 shows the Bode plot obtained by an SRS digital lock-in amplifier model SR850, using the setup shown in Fig. 1. Although the actual Bode
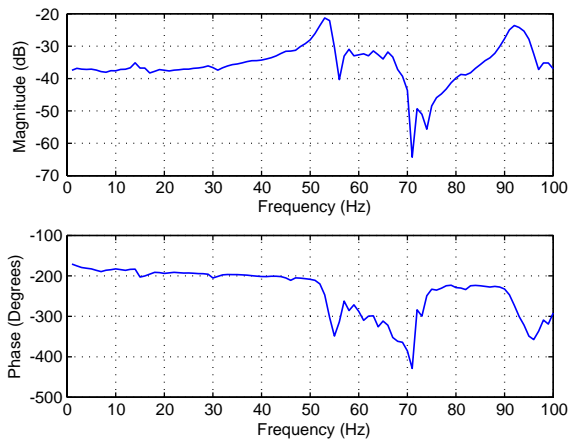
Fig. 3. Bode diagram of the system generated by a lock-in amplifier.

Fig. 4. Active damping of helium oscillations at 2 K.
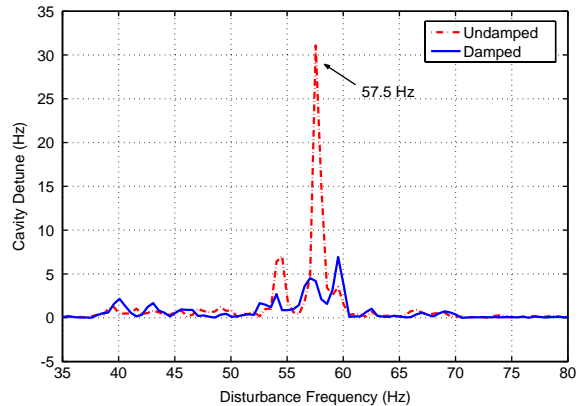
Fig. 5. Active damping of external vibration at 2 K.

plot was measured from 1–1000 Hz with a phase rolling down to about −3500°, Fig. 3 only illustrates the range of interest where disturbances have been observed. 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 to be 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 the LeCroy Waverunner LT342 digital oscilloscope, from which the largest frequency components are picked for damping to acceptable levels.

4.2. Experimental results

We observed two types of microphonics vibration: internal (helium oscillations) and external (motors, pumps, etc.). The results of applying AFC to both types are shown in Figs. 4 and 5. Liquid helium is introduced rapidly to fill a helium reservoir on top of the cryomodule to cool the cavities down. Once the helium reservoir is full, thermo-acoustic oscillations appear at 6.5 Hz due to trapped gas volumes in the liquid helium space along with a small peak at its second harmonic at 13 Hz. Fig. 4 shows an FFT of the detuning for the undamped and damped responses. After applying a cancellation signal at 6.5 Hz, the effect of the
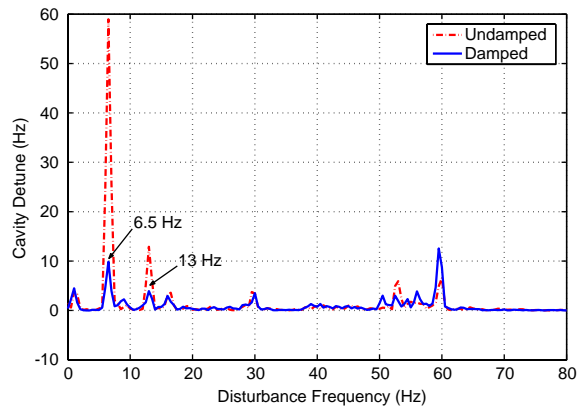
oscillation was damped at that frequency; however the internal energy causing this oscillation was still present, and its effect was observed to have shifted up to the oscillation's second harmonic at 13 Hz increasing the peak at that frequency, where another cancellation signal was applied. The first peak at 6.5 Hz was reduced by a factor of 6 from 59 to 10 Hz, while the second peak at 13 Hz was reduced to 4 Hz. It is worthwhile mentioning that these oscillations will not be present under the operating conditions as they disappear once the helium level is low enough to allow the release of the trapped gas volumes. However, testing the active damping for different kinds of disturbances was done to check the performance of the controlling algorithm.

Fig. 5 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. It was successfully damped by a factor of 7.4 from 31 to 4.2 Hz.

5. Conclusion

We have demonstrated the successful use of piezo-electric actuators and the 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, along the lines of Ref. [9].

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