MICROPHONICS DETUNING COMPENSATION IN 3.9 GHz SUPERCONDUCTING RF CAVITIES*

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Abstract

Mechanical vibrations can detune superconducting radio frequency (SCRF) cavities unless a tuning mechanism counteracting the vibrations is present. Due to their narrow operating bandwidth and demanding mechanical structure, the 13-cell 3.9GHz SCRF cavities for the Charged Kaons at Main Injector (CKM) experiment at Fermilab are especially susceptible to this microphonic phenomena. We present early results correlating RF frequency detuning with cavity vibration measurements for CKM cavities; initial detuning compensation results with piezoelectric actuators are also presented.

INTRODUCTION

Details of the CKM experiment can be found in [1]. The current 3.9 GHz cavity design specification calls for a 65 Hz full loaded bandwidth. To minimize RF control efforts and power, an initial detuning tolerance target of 1/10 of the bandwidth, or ±6.5 Hz, was established; this corresponds to ±3.1 nm in cavity length.

Piezoelectric actuators were successfully used for compensation of Lorentz force detuning on TESLA cavities [2]. In this work, we study the feasibility of piezoelectric actuators for compensation of microphonics detuning on CKM cavities.

Microphonics detuning compensation studies were performed on a 3-cell prototype CKM cavity at 1.8 K and on a full 13-cell prototype CKM cavity at room temperature. Automatic detuning compensation was accomplished using an adaptive feed forward control method based on the Least Mean Squares (LMS) algorithm [3].

COMPENSATION AT 1.8 K

The 1.8 K test on a 3-cell CKM prototype cavity took place in a vertical Dewar located near large vacuum pumps. Microphonics detuning was severe for this setup due to the lack of vibration isolation between the test stand and the vibration sources.

The piezo actuator was used in the test setup as both a vibration sensor and compensating actuator. The piezo actuator was installed so as to couple to vibrations of the cavity end flanges relative to each other. The cavity operated under continuous RF power.

Microphonics Spectrum

Figure 1 shows a measurement of the microphonics spectrum, with the cryogenic pumps on and off.

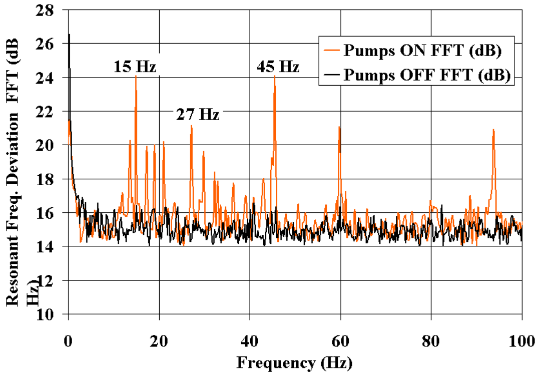

Figure 1: Microphonics spectrum with cryogenic pumps on and off.

The microphonics spectrum was not stable, but it remained more or less steady for periods of several minutes to hours.

Manual Microphonics Detuning Compensation

In one instance, at a time when the spectrum showed a single dominant frequency near 30 Hz, we attempted manual detuning compensation. We adjusted the piezo actuator drive signal frequency, amplitude, and phase until a decrease in the resonant frequency deviation amplitude was observed. Figure 2 shows the resonant frequency deviation amplitude was reduced by more than a factor of three.

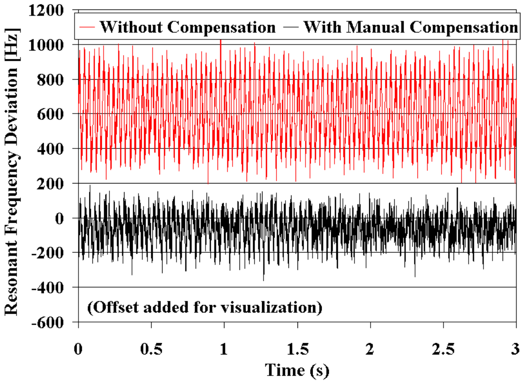

Figure 2: Manual Detuning Compensation at 1.8 K

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Though longer-term reduction was difficult because of the simple frequency matching method, the result was reproducible. It demonstrates the feasibility of using a piezo actuator to compensate microphonics detuning at 1.8 K. The next step in this development effort was to investigate automatic detuning compensation.

AUTOMATIC DETUNING COMPENSATION

Active noise or vibration cancellation is typically accomplished using adaptive feed forward control. The LMS algorithm, which was developed by Widrow and Hoff (1960), is a widely used method for this application [3]. The LMS algorithm consists of a Finite-Impulse-Response (FIR) filter whose weights are continuously adjusted to minimize the error estimation (see Figure 3).

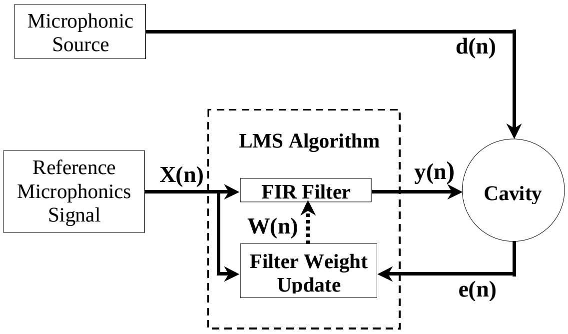

Figure 3: The LMS Algorithm. $X^T(n) = [x_o, x_1, \ldots, x_{M-1}]$ is a vector containing the M most-recent samples of the microphonic noise, $W^T(n) = [w_o, w_1, \ldots, w_{M-1}]$ is the coefficient vector of the FIR filter at time n, $y(n)$ is the LMS output, and $e(n)$ is the error signal.

There are several variations of the LMS algorithm. The type used for these studies was the normalized LMS, or NLMS algorithm. The output of this algorithm is:

$$y(n) = W^T(n-1)X(n)$$

The weight vector is adjusted at each iteration according to:

$$W(n) = W(n-1) + \frac{\mu}{\left|a + X^T(n)X(n)\right|} e(n)X(n)$$

where μ is the step size that controls the convergence rate. It must be chosen such that $0 < \mu < 2$. The normalized version of the LMS algorithm was used here in order to reduce divergences caused by gradient noise amplification. The small constant 'a' is added to the denominator to prevent the calculation from diverging for very small values of $X(n)$.

The output signal $y(n)$ drove the compensating piezo actuator and the RF phase difference signal (see Figure 4) was taken as the error signal $e(n)$. Effectively, the Cavity sums the actual microphonic noise $d(n)$ to the canceling calculated $y(n)$. For the source of $X(n)$, we took a one-second sample of the uncompensated RF phase difference signal, saved it, and replayed it continuously. The LMS algorithm will adapt even if the actual perturbations change amplitude or phase with respect to the original sample. However, it will not be able to adapt if new frequencies appear. In this case, a new sample must be taken.

Experimental setup

To demonstrate the ability of the LMS algorithm to compensate for microphonics detuning, we used a room temperature system shown in Figure 4. It consists of the following elements:

- A 13-cell CKM cavity with piezo actuators at each end. We selected piezo actuator P-206-40 from Piezosystem Jena, with a length of 90 mm and a room temperature range of 80 µm for the full 160 Volt range. The range of motion is expected to decrease by approximately a factor of 10 at the CKM operating temperature of 1.8K.
- A National Instruments PXI real-time system programmed in Labview with the normalized LMS algorithm and a function generator
- An RF circuit to excite the cavity and provide the RF phase difference signal.

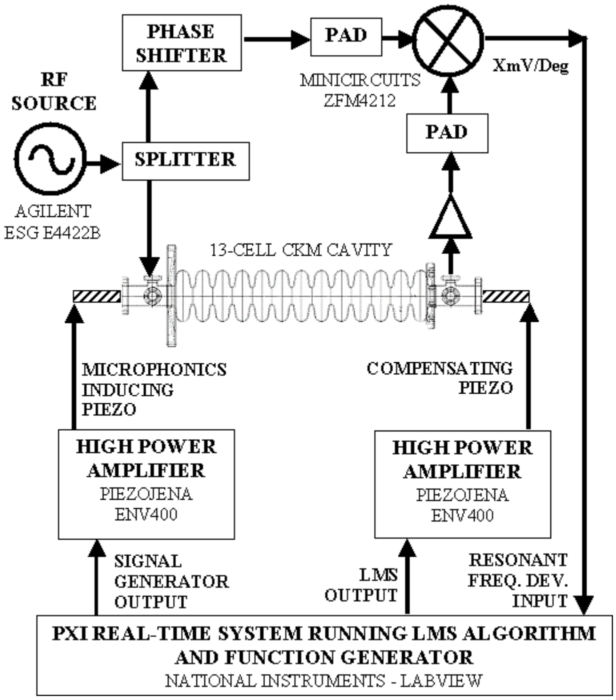

Figure 4: Room Temperature Experimental Setup

Because the cavity was operated at room temperature, we had to induce strong vibrations to observe a detuning effect in the RF phase difference. We drove one of the piezo actuators with a signal generator programmed in the PXI system. The detuning accomplished with this method (~KHz) was much larger than the expected natural detuning at 1.8 K (~Hz), but the width of the resonance was also correspondingly larger.

We determined the coupling between mechanical resonances and the RF by driving the piezo actuator with white noise limited to frequencies below 600 Hz. Figure 5 shows the FFT of the RF resonant frequency deviation. Two strong resonances are found at 230 Hz and 375 Hz.

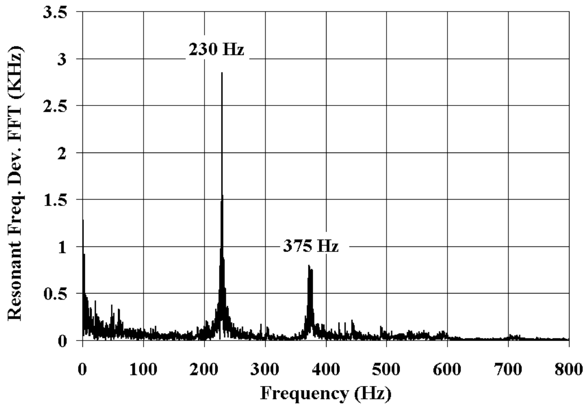

Figure 5: System Mechanical Resonances

Next, we drove the microphonics-inducing piezo actuator with a waveform consisting of sine waves at 15 Hz, 27 Hz, and 45 Hz simultaneously. These frequencies simulate the three highest amplitude frequencies of the microphonics spectrum of Figure 1. The output y(n) of the LMS algorithm drove the second piezo actuator. The algorithm ran at a rate of 2.5 KHz with 200 taps, and the factor µ was adjusted until we observed convergence on all three frequencies. Figure 6 shows the FFT of the uncompensated and compensated phase difference signal.

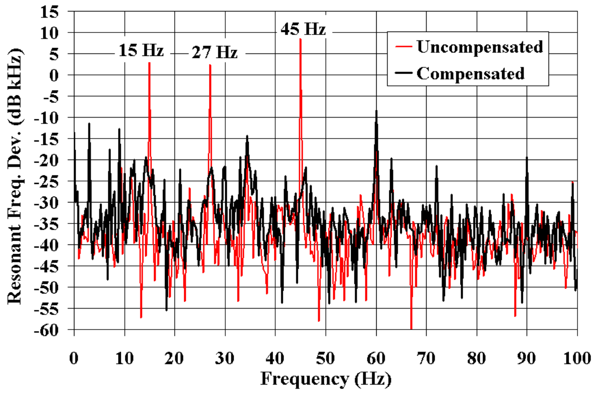

Figure 6: Automatic Compensation

Convergence was achieved in a fraction of a second, with more than 20dB attenuation for all three frequencies. Long-term compensation was also observed. The algorithm also adapted quickly (within a small fraction of a second) to changes in the amplitude and phase of the microphonics-inducing waveform. Figure 7 shows a detail of all waveforms in the time domain. The LMS algorithm used only the RF phase difference signal as input.

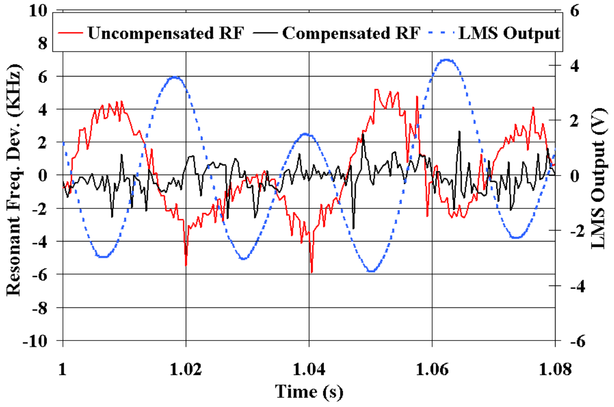

Figure 7: Automatic Compensation Detail

Detuning Compensation near a resonance

Near a mechanical resonance, vibrations couple strongly to the cavity, resulting in large detuning amplitudes. Significantly, the transfer function between the RF phase difference and the external vibration shows a change of phase as it passes through the mechanical resonance [4].

We were able to achieve convergence of our system around the 230 Hz mechanical resonance shown in Figure 2. Figure 8 shows the time domain waveforms for convergence at 240 Hz. To achieve convergence, we had to change the phase of the LMS output by 180 degrees. Comparing Figures 7 and 8, the different phase of the LMS output with respect to the RF signal can be observed. Detuning was reduced by approximately a factor of three, and it is possible that with a finer adjustment of the LMS output phase this factor could be higher.

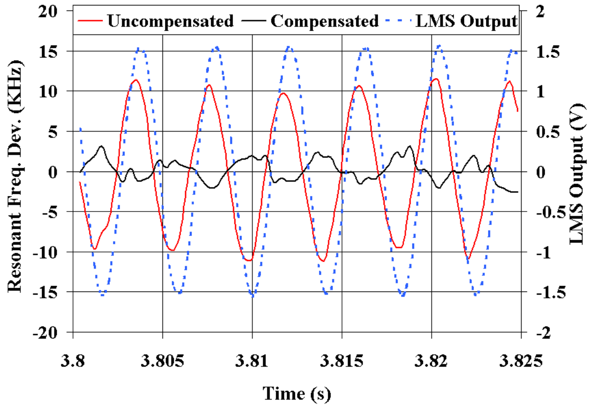

Figure 8: Detuning Compensation at 240 Hz

The phase shift introduced in the forward path by the cavity transfer function can be incorporated into the LMS algorithm by what is known as the Filtered-X LMS algorithm [5]. It makes use of the LMS algorithm to characterize the secondary path, *i.e.*, determine the uncompensated cavity response. Once the secondary path weights are determined, the LMS filter is then used for active noise compensation while the saved secondary path weights are used to filter X(n) (FIR filter) in order to compensate for phase changes of the forward path. Hence the term "Filtered-X". Initial results using this approach were very encouraging, but we encountered some unexpected problems described in the following section.

Nonlinear Behavior

The LMS algorithm, like most feed forward or feedback control algorithms, assumes a linear behavior of the system. The effects of non-linear behavior are magnified at sub-harmonics of system resonant frequencies. That is, when driving the microphonics-inducing piezo actuator at an integral fraction of the frequency of the strong resonances at 230 Hz or 375 Hz, these resonances themselves were excited. Under these conditions we could not achieve convergence. Figure 9 is an example of this response when the cavity was driven at 115 Hz.

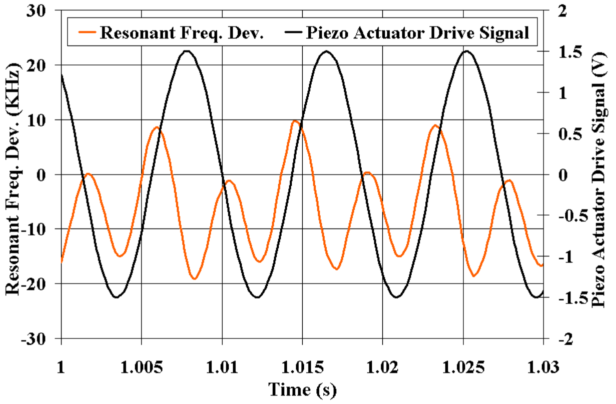

Figure 9: Nonlinear Behavior

We do not yet have an explanation for this nonlinear behavior. In particular, with our existing data, it is not possible to assert definitively the degree to which the non-linearities of piezo systems are responsible for these phenomena, as opposed to non-linearities in the rather soft niobium structure. Further studies into this phenomenon are under consideration.

CONCLUSIONS

Microphonics detuning compensation on 3.9 GHz CKM cavities using a piezo electric actuator was demonstrated at 1.8 K and at room temperature. Automatic detuning compensation was achieved with an adaptive feed forward control algorithm - the LMS algorithm - that is typically used for noise or vibration cancellation.

Unexpected nonlinear behavior of the system was evident by inducing vibrations around sub-harmonic frequencies of mechanical resonances. Further studies are needed to determine the source of these nonlinearities, which affect the performance of adaptive feed forward or feedback control methods.

Future efforts in this development are to study automatic microphonics detuning compensation at 1.8 K. In addition to adaptive feed forward control studies, we also plan to study feedback control methods. However, a faster electronic system that we have available is required for feedback control studies.

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