ADAPTIVE COMPENSATION FOR LORENTZ FORCE DETUNING IN SUPERCONDUCTING RF CAVITIES

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Abstract

The Lorentz force can dynamically detune pulsed Superconducting RF cavities. Considerable additional RF power can be required to maintain the accelerating gradient if no effort is made to compensate for this detuning. An adaptive feed-forward Lorentz Force Detuning (LFD) compensation algorithm developed at Fermilab is described. Systems based on this approach have been used to successfully reduce LFD from several hundred Hz to several 10s of Hz or better.

INTRODUCTION

Superconducting RF cavities are in common use at accelerators around the world and cryomodules incorporating high-gradient (>30 MV/m) pulsed Tesla style 9-cell cavities are currently being constructed for the SCRF Test Area in NML [1] at Fermilab as a part of the ILC Global Design Effort.

The walls of SCRF cavities are deliberately kept thin (<= several mm) to allow the cavities to be kept cool but the thin walls make the cavities susceptible to mechanical deformations induced by:

- The force of the accelerating electromagnetic field on the cavity walls (the Lorentz force);
- Fluctuations in the pressure of the surrounding helium bath;
- Mechanical vibrations induced by external mechanical noise sources (e.g. pumps, cranes, etc.).

These mechanical deformations can change the resonant frequency of the cavity. For high-gradient, pulsed cavities operating in super-fluid helium, the Lorentz force is the dominant source of cavity detuning. If no efforts are made to compensate for LFD, cavities can dynamically detune by several bandwidths. Maintaining the accelerating gradient under these conditions would require considerable excess RF power.

The use of piezo actuators to compensate for LFD was pioneered at DESY but has since been adopted widely [2]. Actuators connected to the beam flange are driven by a short unipolar drive signal prior to the arrival of the RF pulse. The timing, amplitude, width and bias level of the piezo drive signal are chosen such that the detuning of the cavity by the resulting acoustic impulse cancels the detuning of the cavity induced by the Lorentz force. This technique can successfully reduce the detuning of the cavity during the RF pulse from several hundreds of Hz to several tens of Hz.

While the standard approach can provide acceptable compensation for LFD, the mechanical response of individual cavities to the Lorentz force and to the piezo actuator can differ. Changes in cavity operating conditions, for example the changes in the gradient or bath pressure can require corresponding changes in the compensating waveform. At present, the compensation parameters for each cavity are selected manually. Operating multiple cavities for extended periods will require control systems that can automatically determine the best parameters for each cavity and adapt to changing operating conditions. Because the cavity detuning does not respond linearly to the changes in some parameters of the standard unipolar pulse, the adaptive capability that can be incorporated in LFD systems based on this approach may be limited. Furthermore while a single unipolar pulse can compensate cavities driven by short RF pulses, it may not be suitable for cavities where the length of the RF pulse is comparable to or greater than the period of the dominant mechanical resonance.

MEASURING CAVITY DETUNING

The electromagnetic and mechanical behaviour of the cavity can be described well by the following equation [3] relating the complex envelopes of the forward, F, and probe, P , signals to the detuning, δ.

$$\frac{dP}{dt} = -\left(\omega_{1/2} - i\delta\right)P + 2\omega_{1/2}F;$$

The half-bandwidth, $\omega_{1/2}$, and detuning, δ, during the pulse can be extracted from the cavity probe and forward RF waveforms by rearranging the terms of the equation for the complex envelope of the cavity field:

$$\omega_{1/2} = \frac{Re(P^*\frac{dP}{dt})}{Re(2P^*F - P^*P)};$$

$$\delta = \frac{Im(P^*\frac{dP}{dt} - 2\omega_{1/2}P^*F)}{P^*P}.$$

Accurately determining the half-bandwidth and the detuning requires accurate measurements of the complex cavity forward and probe RF waveforms. On the flattop, a ten percent error in the amplitude of the forward signal could lead to an error in the detuning equal to 20% of the cavity half bandwidth.

In general, the relative gains and phases of the baseband signals are not known and the phases may drift with

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temperature or with time. In addition, although the probe signal is generally measured accurately, the forward and reflected signals can cross- contaminate each other if they are monitored using a common coupler.

In particular the forward power often shows a significant tail after the drive to the klystron is cut off and the magnitude and phase of the forward signal during the fill and flattop can change as the resonance frequency of the cavity is varied using either the fast or slow tuner. The forward tail often decays over time at the same rate as the probe and reflected signals. This suggests that the dominant component of the tail may be cross-contamination by the reflected power. Variations of up to 15% in the magnitude of the forward signal during the fill and flattop as the cavity resonance frequency is varies have been seen in the Fermilab Horizontal Test Stand [4].

CORRECTING THE BASEBAND WAVEFORMS

Prior to calculating the detuning, the procedure outlined in Table 1 is used to correct the baseband signals. The procedure is based on the assumption that the forward tail is due entirely to contamination by the reflected power. This procedure has been tested using simulated data generated under that assumption and found to give accurate estimates of the relative gains and phases of the three baseband signals and of the forward-reflected cross-contamination coefficients.

Although the procedure uses only the decay region of the signals to estimate contamination levels, the procedure typically reduces tuning induced variations in the magnitude of forward signal from cavities in the Fermilab HTS from as much as 15% to a few percent during the fill and flattop.

Table 1: Relative Calibration and Correction of the Cavity Baseband Waveforms.

$G_{Reflected} = \frac{\langle P^*P\rangle_{Decay}}{\langle P^*R\rangle_{Decay}}$ $R_{Corrected} = G_{Reflected}R_{Raw}$	The magnitude and phase of the reflected power during the decay region compared to the probe signal in the same region to determine a relative complex gain. The reflected power over the entire pulse is then scaled by that gain.
$C_{Forward} = \frac{\langle F^*F\rangle_{Decay}}{\langle F^*R\rangle_{Decay}}$ $F_{Corrected} = F_{Raw} - C_{Forward}R_{Corrected}$	The contamination of the forward power is estimated by comparing the forward power in the decay region to the reflected power in that region. The contamination is then subtracted to obtain the corrected forward signal.
$Re\left(P^*\frac{dP}{dt}\right) = -\omega_{1/2}P^*P + \alpha Re(P^*F) + \beta Re(iP^*F)$ $F_{Normalized} = \left(\frac{\alpha + i\beta}{2\omega_{1/2}}\right)F_{Corrected}$	Appropriate combinations of the probe, forward and the time derivative of the probe signal are fit to estimate the cavity half-bandwidth and a complex gain factor for the forward signal relative to the probe. The forward power is then scaled by that gain factor.

DETUNING RESPONSE TO THE PIEZO

Because many mechanical modes can be excited, cavities often exhibit a complex detuning response to Lorentz force or the piezo actuator impulses. While these impulse responses can be most easily measured during CW operation, switching from pulsed operations may not always be convenient.

As an alternative, the cavity can be excited with a small piezo impulse some ms prior to the arrival of the RF pulse. If the relative delay between the piezo impulse and the RF pulse is systematically reduced over a number of successive pulses and the detuning of each pulse is measured, the detuning response of the cavity during a time window centered on the RF pulse can be determined. The response can be characterized by a 2-dimensional array relating the amplitude of the piezo impulse at any time relative the arrival of the RF pulse to the detuning of the cavity at any point in time during the RF pulse. This can be combined with measurements of the detuning due to changes in the DC bias on the piezo to obtain a matrix completely characterizing the small signal response of the detuning to the piezo.

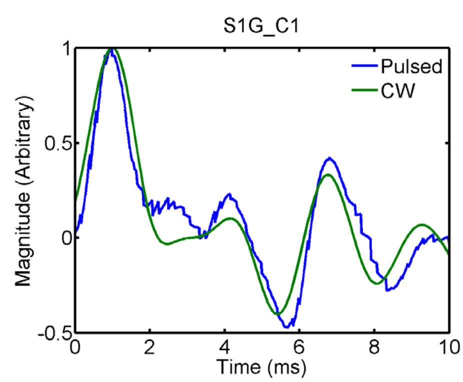

Figure 1: A comparison of the Piezo-Detuning Impulse Response measured during CW and pulsed operation.

The response matrix can be compared directly to CW measurements of the piezo impulse response by shifting each response curve in time so that the piezo impulses are aligned in time. Figure 1 shows such a comparison for a blade tuner equipped cavity. The response measured in pulsed mode agreed well with the CW measurements for all four cavity types tested.

ADAPTIVE COMPENSATION

The response matrix can be inverted to give the piezo waveform required to produce a given detuning profile during the course of the RF pulse. If this inverse response matrix is multiplied by the negative of the measured Lorentz force detuning, the detuning due to resulting piezo drive waveform should cancel with the Lorentz force and the cavity should remain in tune during the pulse.

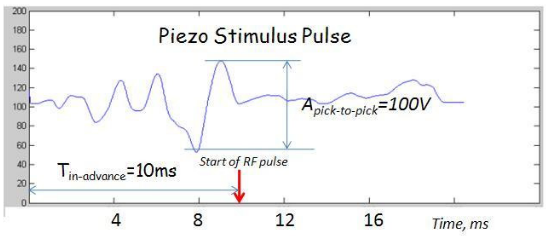

Figure 2: Compensation piezo waveform for a Blade-Tuner equipped nine-cell elliptical cavity

Figure **2** shows piezo waveform determined in this way. The waveform is complex but it can be determined automatically from the response measurements using simple matrix algebra.

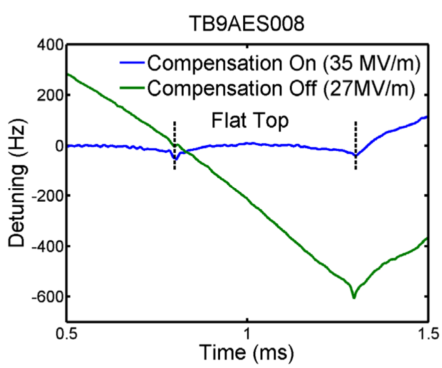

Figure 3: Lorentz force compensation in a Blade-Tuner equipped nine-cell elliptical cavity.

This procedure can be applied iteratively to provide adaptive feed-forward detuning control. The response matrix characterizes the mechanical behaviour and should not depend on cavity operating conditions. The piezo drive waveform can be incremented to cancel any residual detuning following each RF pulse. Figure 3 shows the residual detuning after compensation for a 1.3 GHz nine-cell elliptical cavity. Detuning is reduced from 600 Hz (close to 3 times the cavity half bandwidth) during the flattop at a gradient of 27 MV/m to less than 50 Hz at 35 MV/m.

During tests in the Fermilab HTS, a system based on this approach was able to successfully track and compensate for changes in the Lorentz Force detuning of a 1.3 GHz nine-cell elliptical cavity as the cavity gradient was ramped from 12 MV/m to 34 MV/m and back.

APPLICATIONS

The single-cavity system installed in the HTS has been routinely used over the past year to stabilize cavities during heat loss measurements and other routine operations. The same system was successfully used to compensate for LFD during tests for the proposed Project X that employed an 8 ms long RF pulse [5]. The hardware and software design and implementation of the HTS system have been described elsewhere and will not be repeated here [5].

A second system, based on the HTS design, was successfully constructed and deployed during pulsed tests of the 325 MHz SSR1 cavity developed for the proposed Project X accelerator [6]. A third single-cavity system was deployed to KEK during LFD measurements using the S1-G cryomodule [7]. That system was successfully used to compensate LFD in each of the four distinct cavity/tuner types tested to 16 Hz or better. An eight-cavity system for Cryomodule 1 in the SCRF Test Facility at Fermilab is nearing completion.

CONCLUSION

An adaptive procedure has been developed at Fermilab to compensate for Lorentz force detuning in SRF cavities. The procedure can automatically characterize the response of individual cavities to the Lorentz force and to the compensation actuator. The measured response is used to automatically calculate an appropriate compensation waveform and adapt that waveform to changing cavity operating conditions. The procedure has been successfully used to compensate a variety of cavity/tuner types at Fermilab and elsewhere.

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