ADAPTIVE LORENTZ FORCE DETUNING COMPENSATION IN THE ILC S1-G CRYOMODULE AT KEK

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Abstract

The recent tests of the S1-Global [1] cryomodule at KEK provided a unique opportunity to compare the performance of four different styles of 1.3 GHz SRF cavities and tuners under similar operating conditions. An adaptive Lorentz Force Detuning (LFD) compensation system deployed at KEK successfully reduced LFD from between 100 to 700 Hz at the maximum gradient to better than 20 Hz for all four of the cavity types tested.

INTRODUCTION

As a part of ILC Global Design Effort, the S1-Global Cryomodule was built and installed at KEK by groups from KEK, in Japan, DESY and INFN in Europe and FNAL and SLAC in the USA.

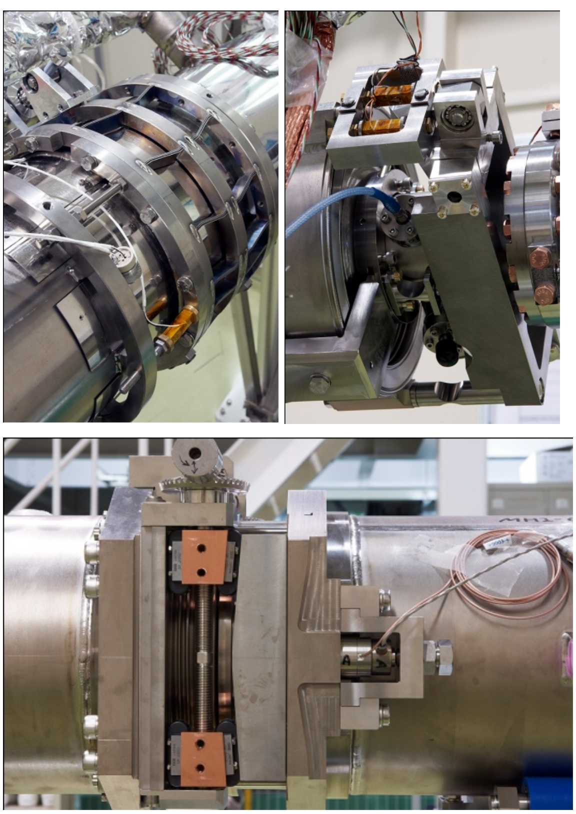

Figure 1: S1-G Cavity Tuners; a) INFN Blade Tuner/FNAL Cavity, b) Saclay Tuner/DESY cavity, and c) KEK Slide Jack Tuner/KEK cavity.

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One aim of the S-1G project was to compare the static and dynamic detuning performance of different candidate designs for the 1.3GHz 9-cells SRF elliptical cavities ILC cavities. S1-G contained a total of eight cavities, two each of four distinct designs as outlined in Table 1. The four cavity designs differ significantly in the mechanical response to the Lorentz force and to the piezo actuator and each of the four different tuners was designed to provide appropriate static and dynamic tuning ranges for their respective cavities.

Two independent methods were successfully employed to compensate for Lorentz force detuning in the S1-G cavities.

The first method employed the standard approach of exciting the piezo actuator with a half cycle of sine wave prior to the arrival of the RF pulse. The duration, delay and amplitude of the half sine wave are optimized manually by trial and error. The results of those tests are described in detail elsewhere [2,3].

The second method used an adaptive feed-forward algorithm based on least-squares to automatically determine an optimal waveform for each individual cavity. The results of these measurements are described below.

ADAPTIVE LFD COMPENSATION

A LFD control system built at FNAL was delivered and commissioned at KEK during the S1-G LFD studies. The system implemented an adaptive feed-forward algorithm that has been described in detail elsewhere [4].

The 10 MHz IF signals from S1-G the cavities were recorded using 100 MHz ADC and digitally converted to baseband. The baseband signals were then corrected for contamination and used to estimate the cavity detuning during the course of each RF pulse.

Prior to compensation, the mechanical response of each individual cavity was characterized by driving the piezo with a sequence of impulses from 10 ms prior to the arrival of the RF pulse to 10 ms after while recording the resulting detuning. The results of this procedure effectively measure the piezo to detuning impulse response over a 20 ms window centred on the RF pulse.

Table 1. Details of 4 different type of cavity/tuner systems installed in S1-Global cryomodule

	Units	Slim Blade	DESY/Saclay	Slide-Jack (Central)	Slide-Jack (Lateral)
Cavity package		FNAL/ INFN	DESY	KEK-a	KEK-b
Cavity type		TESLA	TESLA	TESLA -like	TESLA -like
Cavity Stiffness	N/um	3	3	3	3
Slow Tuner mechanics		Coaxial Blades/ Stepper Motor& Harmonic drive	Lateral Scissor/Stepper motor &Harmonic Drive	Slide-Jack at centre of He vessel	Slide-Jack at the end of He vessel
Motor location		Inside insulating Vacuum	Inside insulating Vacuum	Outside cryo-module	Outside cryo-module
Piezo tuner location		Inside insulating Vacuum	Inside insulating Vacuum	Inside insulating Vacuum	Inside insulating Vacuum
Number of piezo		2	2 (1 actuator +1 auxiliary)	1	1
Piezo Manufacturer		Noliac	Noliac	Piezo Mechanic	Piezo Mechanic
Piezo type, size	mm^3	10x10x40	10x10x40	d25 x 40	d25 x 40
Max. piezo voltage,	V	200	200	1000	1000
Piezo stroke at 300K	um	40	40	40	40
Piezo-to-Cavity tuning sensitivity,	Hz/V	14	4	0.6	0.7
Cavity/tuner Dominant Mechanical Resonance	Hz	200	245-260	220-540	220-325

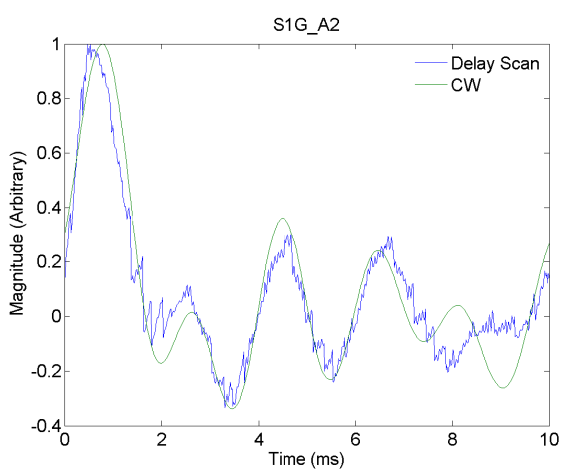

Figure 2: A comparison of the Piezo-to-Detuning impulse response measured during pulsed and CW operation.

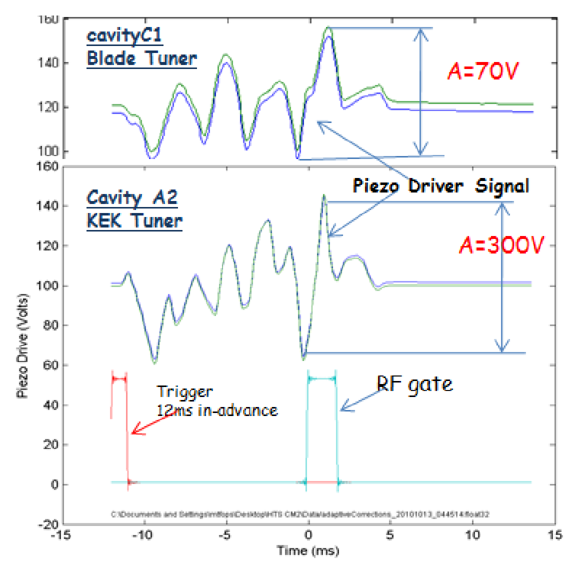

Figure 3: Piezo waveforms for two of the S1-G cavities.

Figure 2 shows a comparison of the impulse response measured in this fashion to a measurement of the same transfer function while the cavity was driven by CW power. Figure 2 shows a comparison of the pulsed and CW measurements for A2-KEK cavity with Central Slide-Jack tuner. The two independent measurements of the impulse response agreed well for all four of the cavity types tested.

The recorded response was then used to calculate the piezo waveform required for LFD compensation. Following each RF pulse, the piezo waveform and piezo DC bias were updated to compensate for any residual detuning or drift. Figure 3 shows examples of the piezo drive waveforms for two different types of S1-G cavities. The differences in the two waveforms reflect differences in the mechanical responses of the two cavities.

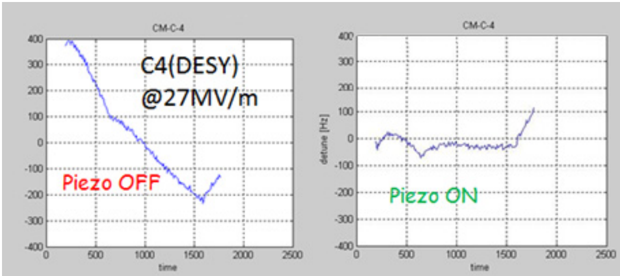

Figure 4: Lorentz force detuning before and after compensation for one of the S1-G cavities. (C4-DESY cavity at E_{acc}=27MV/m).

Figure 4 shows an example of the the Lorentz force detuning for C4-DESY cavity before and after compensation during fill +flattop part of RF pulse. Prior to compensation the cavity detunes by approximately 400Hz during fill and 300 Hz during the flattop. ILC style cavities are designed to operate with bandwidths near 200 Hz. Significant excess RF power would be required to maintain the accelerating gradient in such a cavity with this level of detuning.

Following compensation, the peak detuning during the RF pulse is less than 50 Hz, much less than the bandwidth of the cavity. Very little excess RF power is now required to maintain the gradient.

COMPENSATION OF DIFFERENT CAVITY/TUNERS

Table 2 lists the gradients and detuning before and after compensation for 5 cavities. The maximum gradient for each cavity together with the LFD before and after compensation are listed in Table 2.

Table 2: LFD Compensation Results for S1-G Cavities

Cavity	Type	E_{acc}, [MV/m]	LFD Before, [Hz]	LFD After, [Hz]
C1	FNAL/ Blade	24	240	1
C3	DESY/ Saclay	18	210	4
C4	DESY/ Saclay	27	470	3
A2	KEK-center	34	250	5
A3	KEK-end	30	100	12

To compare the performance of the four different styles of cavities, the residual detuning during the flattop was averaged over multiple RF pulses as illustrated by the black line in Figure 5. The average and standard deviation over all time samples in the flattop was then calculated.

The average detuning calculated in this way indicates how well static detuning effects are compensated. Each of the cavities is statically mistuned by less than 30 Hz as shown in Figure 6.

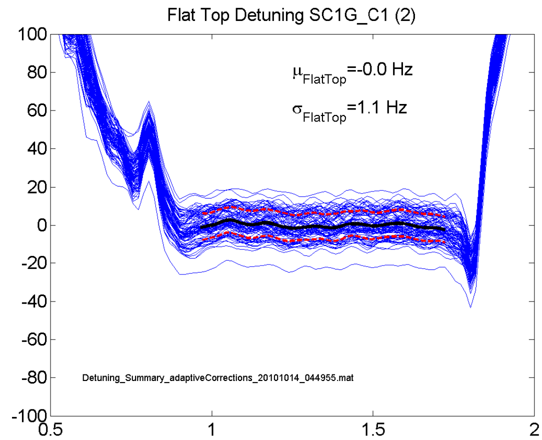

Figure 5: Residual detuning measurements for the S1-G cavity comparisons. Before compensation LFD (at E_{acc}=24) for cavity C1-FNAL/Blade tuner style was 240 Hz.

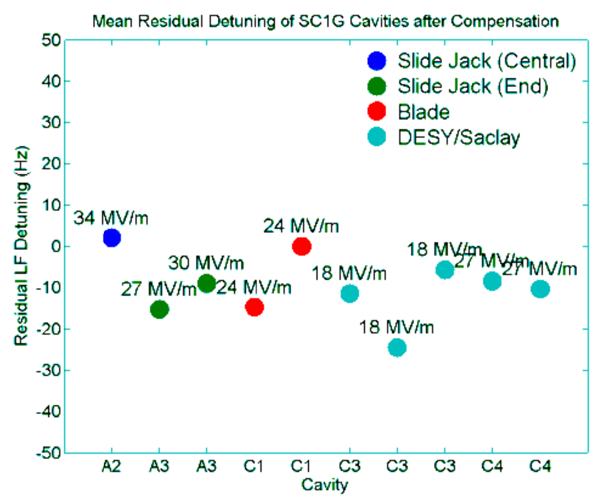

Figure 6: Mean residual detuning of six S1G cavities after adaptive LS LFD compensation.

The standard deviation indicates how well dynamic detuning has been compensated. As shown in Figure 7, the residual dynamic detuning in all cavities is less than 15 Hz. With the exception of the cavity A3 using End Slide-Jack Tuners it is much less. The cavities employing these tuners were designed to be very stiff and require a piezo drive pulse with a rapid rise time. The piezo drive amplifier used to drive the actuators on these cavities during these tests may not have had sufficient bandwidth to properly compensate for the rapid changes in tune induced by the Lorentz force.

Similar levels of residual detuning were also obtained using the standard half-sine piezo drive pulse [1]. On the face of it the similar detuning levels following compensation obtained using the two different approaches and the similar levels obtained for each of the four distinct cavity types might seem surprising. The four cavity types four distinctly different design philosophies and the mechanical response and detuning levels prior to compensation differ significantly.

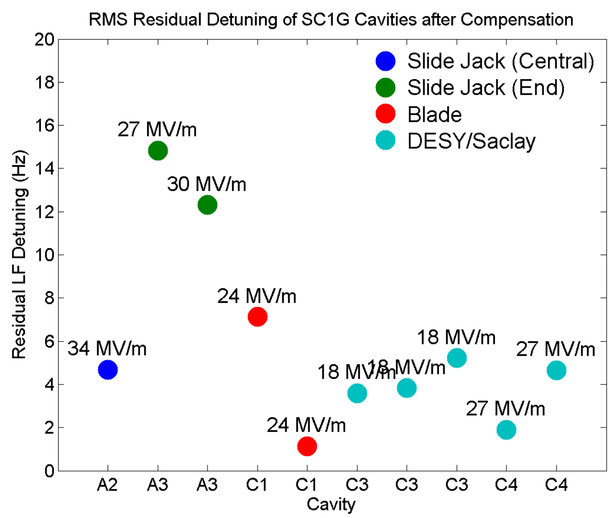

Figure 7: RMS residual detuning of six S1G cavities after adaptive LS LFD compensation.

The 1ms RF pulse excites a broad mechanical response in each of the four cavity types. Reducing the detuning for such a short RF pulse requires only an impulse from the piezo. Furthermore, while stiffer cavities detune less due to the Lorentz force than more compliant cavities, they are also less responsive to the piezo and vice versa.

While more complex wave form produced by the adaptive procedure may provide only slightly better detuning levels when compared to the half-sine approach, it allows each individual cavity to be fully characterized and compensated automatically even as cavity operating conditions such as the gradient are changed. While this may not be important during limited operation of a single cryomodule, this could prove to be a significant advantage during long term operation of many cyromodules. In addition, the more complex waveform produced by the adaptive procedure may allow lower piezo drive voltages to be used and may reduce levels of residual vibration during subsequent RF pulses.

CONCLUSION

An adaptive Adaptive LFD compensation system was successfully used to compensate for Lorentz force detuning in each of the four different cavity types installed in S1-G. The four cavity/tuner combinations tested represent four distinctly different design philosophies.

Optimal piezo drive waveform provides a rigorous basis for back-to-back cavity performance comparisons.

Residual LFD could be limited to better than 15 Hz in all four cavity types tested.

LFD control limits for ILC will likely depend more on controller and quality of the input signals than the mechanical details of cavity/tuner.

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