# A CONTROL AND SYSTEMS THEORY APPROACH TO THE HIGH GRADIENT CAVITY DETUNING COMPENSATION

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## *Abstract*

The compensation of dynamic detuning is of primary importance in order to operate TESLA type cavities at the high accelerating gradient foreseen for the ILC (31.5 MV/m). This paper firstly resumes recent successful experiences of open loop compensation of the Lorentz force detuning, repetitive and synchronous to the RF pulse, using fast piezoelectric actuators with different fast tuning systems. Possible strategies and results for the closed loop compensation of the stochastic microphonic detuning are also presented. Lastly, a deep characterization of the system under control is given, exploiting the system transfer functions acquired through both installed piezo actuators/sensors and phase locked measurements. This allows the analytical modeling of the behaviour of cavity detuning and of its active compensation with piezoelectric actuators.

## INTRODUCTION

TESLA type superconducting (SC) resonators are extremely sensitive to detuning ($\Delta\omega$) induced by mechanical deformations, mainly due to the extremely high quality factor (Q) of the 1.3 GHz resonance mode, in the range of $10^6$ ($10^7$ for continuous wave, CW), and to the reduced longitudinal stiffness, about 3 kN/mm.

Among the few electro-mechanical static tuning solutions that have been realized in the frame of TESLA technology collaboration, special focus will be here given to the current cavity tuner for XFEL, referred as Saclay-I, and to the most attractive solution among coaxial tuners, the Blade Tuner (BT) [1]. Both these devices have been, more recently, evolved as “fast tuners” introducing piezoelectric actuators in order to actively compensate the dynamic contributions to cavity detuning, a primary request when aiming to high gradient pulsed operations or narrow bandwidth CW applications.

## FEED-FORWARD LFD COMPENSATION FOR PULSED OPERATION

The resonant EM field generates, through the Lorentz forces, a pressure distribution on the cavity inner walls that is responsible of the so called Lorentz force detuning (LFD). When the cavity is operated in pulsed mode, this disturbance excites several resonator mechanical modes leading to a dynamic detuning during the RF pulse that makes power consumption and stability performances of the LLRF control critical.

The dynamic LFD finally leads to a cavity oscillation pattern that is repetitive and coherently synchronous to the RF pulse and that has been extensively characterized [2]. Therefore, here neglecting the small deviations from pulse to pulse due to microphonics (MP), an open-loop control can be optimal for its active compensation aiming to introduce a calibrated time-varying detuning, in the form of a linear frequency drift, that cancels the effect of the LFD on the controlled variable $\Delta\omega$ during the RF pulse (0.5 ms filling time, 0.8 ms flat-top for FLASH).

Theoretically a set of different actuators acting in parallel would be needed in order to couple to every mode excited by the disturbances. Despite to this, direct experiences widely proved that successful results can be achieved with a single actuator acting, in contrast with the LFD, locally on the cavity edge and mainly on its length. This results in a different but still effective coupling at least to main cavity mechanical modes.

The chosen strategy has been to roughly replicate the kind of excitation provided by the RF pulse itself, so choosing a single pulse signal with about 1.3 ms rise time. Since the capacitive behaviour of the piezo actuators requires to avoid sharp transitions in the driving signal, that would lead to undesirable current peaks, a *single semi-sinusoidal pulse* with a total time width of 2.5 ms has been used. Very short pulses as well as significantly steeper rises in the driving pulse would not be far more effective at all for LFD compensation purposes, since the cavity intrinsic mechanical dynamic would dump higher harmonics included in the signal [2].

Beside amplitude, the time advance or delay between piezo pulse start and RF pulse also plays a key role. Experimental investigations of this aspect of the control of LFD have been performed for both Saclay-I and Blade Tuner using small amplitude piezo pulses. As a reference, results from the former case related to 3 cavities of FLASH ACC6 cryomodule are presented in figure 1 (un-compensated detuning is normalized to 1 for each cavity).

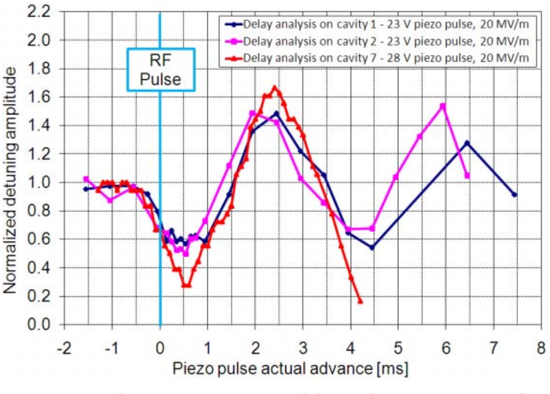

Figure 1: Saclay-I tuner assembly pulse timing analysis

Results confirm that specific time advance values exist for the best LFD compensation. Particularly the first clear minimum in the plot of figure 1, measured to be *0.65 ms* for the Saclay-I tuner assembly and *0.95 ms* for the Blade Tuner, corresponds to using the first oscillation induced by the piezo pulse for compensation. These values are related to the time needed for the piezo action to propagate, expected to be higher for the BT since its central position leads to a lower external stiffness (for the old He tank design) and an higher components inertia [1].

Using the chosen pulse shape and the shown time settings, the entire LFD has been successfully compensated for every cavity in FLASH ACC6 and ACC7 as well as for the Z86 cavity equipped with the Blade Tuner ([2] and MOPP120 at this conference). In particular, in the former case it has been possible to operate cavity #3 in module ACC6 up to a maximum gradient of 35 MV/m and the resulting full LFD compensation, here remarkably achieved for the first time at this gradient value, is presented in figure 2.

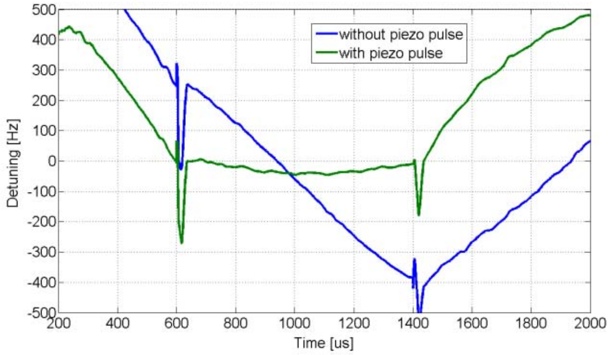

Figure 2: full open-loop LFD compensation at 35 MV/m

An absolute detuning over the flat-top of *630 Hz* has been compensated in this case with a single 80 V amplitude piezo pulse (36 mm piezo, 120 V maximum voltage). The LFD has been in this way compensated not only for each cavity individually but also, in the case of ACC6 cryomodule at CMTB (DESY), simultaneously within a closed LLRF loop thus verifying the expected RF power saving and field stability enhancement [2].

Figure 1 actually reveals that also the 2nd oscillation induced by piezo pulse can be used for LFD compensation, this corresponds in this case to the second minimum at *4.5 ms* advance. This configuration has been experimentally verified and can be considered as a valid alternative solution. Figure 3 shows the compensated LFD in cavity #4 in ACC6; the static value is controlled by the piezo pulse delay in a range of about 200 Hz.

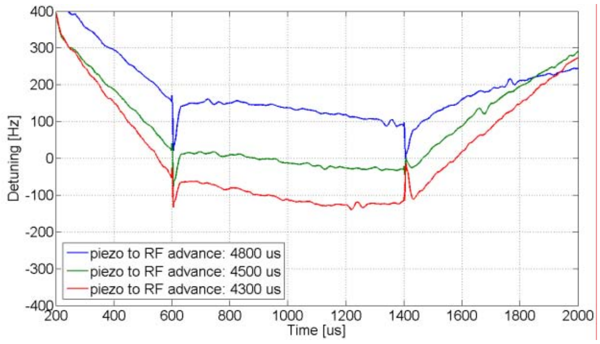

Figure 3: LFD compensation using the second oscillation

Important benefits emerge in this configuration[2]:

- no static detuning, to be compensated by the stepper motor, is added by piezo pulse.
- static and dynamic detuning controls are decoupled to two different parameters: the piezo pulse delay and amplitude respectively.
- small static detuning variation can be easily compensated without moving the stepper motor.

## COMPENSATION OF STOCHASTIC DYNAMIC DETUNING

A stochastic contribution to cavity dynamic detuning is always present, its importance being different between pulsed and CW operations moreover since it is overcome by the LFD in the former case. As a consequence, two different approaches are under studying for each of these applications.

During pulsed operations, as for XFEL and ILC, microphonics (MP) emerge as a stochastic oscillation of cavity detuning from pulse to pulse around the repetitive LFD pattern. The proposed strategy aims to implement, using the same FPGA electronic equipment already in use for LLRF controls, a complete and multi-cavity digital control system that also integrates the developed open-loop LFD compensation. This control system, schematically presented in figure 4, will make use of a real-time cavity detuning computation, parametric piezo pulse generators and a control logic to make it adaptive to slowly drifting changes in the system.

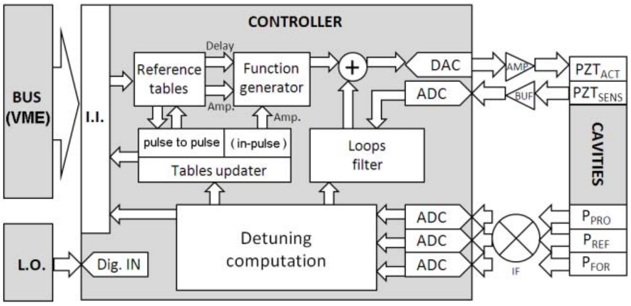

Figure 4: detuning controller for pulsed operations

Exploiting the presence of a second piezo stack (always installed) used as a sensor, a classic feedback control loop can be feasible to further improve the stability of tuning and fields during RF pulse and even actively compensate for free cavity oscillations from pulse to pulse that can be critical when moving to higher repetition rates. After the trial implementation and test of the main controller code [4], the activity is currently under development.

Microphonics role is even more important in high $Q_{ext}$ applications, where bandwidth is typically comparable to MP induced frequency oscillations (few Hz to few tens of Hz, rms), and especially for CW regimes, where the LFD is purely static. It has been observed that, for both tuner assemblies, the major contribution, beside sub-Hz range, comes from the lower mechanical modes of the cavity around 20-30 Hz (confirmed by both previous results with Saclay-I tuner [3] and by recent measurements with the Blade Tuner at the HoBiCaT cryostat at BESSY).

In this CW operational scenario, a feed-back control loop making use of the cavity phase-error as the control signal could address the tune stability requests. The presence of mechanical resonances anyway requires a sophisticated digital loop controller; results in this frame have already been achieved both on DSP based systems as well as FPGA [2]. Currently used solution make use of a PI controller to compensate for DC and sub-Hz contributions in addition to an adaptive feed-forward on selected harmonic frequencies [3]. It is noteworthy that any control strategy in this scenario would benefit the use of the Blade Tuner since lower frequencies involved correspond to bending modes of the cavity system, to which the coaxial piezo tuner is strongly coupled by design [1] (see also MOPP146).

## ANALYTICAL MODELING OF CAVITY DYNAMIC DETUNING

A possible analytical modelling of the TESLA cavity dynamic detuning and its active compensation is here proposed, mainly making use of data acquired during Blade Tuner cold tests at BESSY (see MOPP120). In particular, static and dynamic tuning range of piezo actuators have been measured, the latter through a detailed transfer function (TF) between piezo driving voltage and calibrated PLL error signal in the range 5-500 Hz (32k points over 9 h, see figure 5). This reference TF obtained with both piezo operated in parallel has then been analytically interpolated achieving a fine fit* of the system response with a $32^{nd}$ order state-space model (see figure 5 and [2]). A correct interpolation has been obtained in particular for main contributions in the spectrum as the lower (about 28 Hz) bending mode and the longitudinal compressive modes (180 Hz, 290 Hz). This fitting procedure results in an analytical model of the entire system under control that allows to accurately simulate any kind of control strategy exploiting piezo actuators.

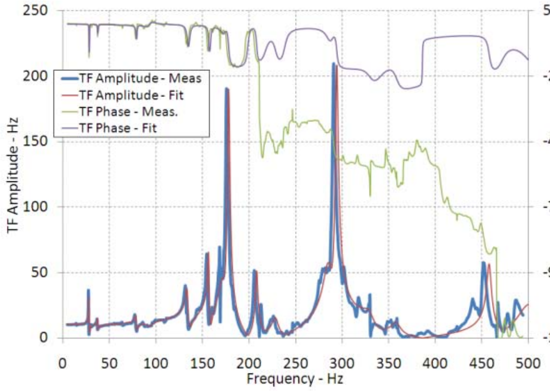

Figure 5: reference TF and its best analytical fit

The system response to a piezo pulse, in term of cavity detuning, can be precisely computed assuming that the superposition of RF and piezo effects applies for the behaviour of the detuning variable. For example, the computed response to the same half-sinusoidal piezo pulse used for LFD compensation, in the case of both piezo operated at their maximum voltage of 200 V is shown in figure 6 (no RF pulse). The computation has been performed taking into account both the measured group delay (from TF phase drift) and the measured piezo non-linearity (see paper MOPP120).

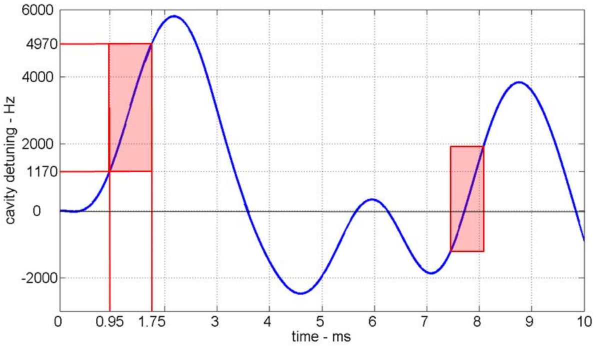

Figure 6: simulated response of the cavity

This analysis actually provides significant results:

- The best piezo pulse timing found during test, *0.95 ms* advance, is actually coherent with the ideal configuration (maximum slope and linearity).
- The maximum LFD compensation performances of the Blade Tuner assembly installed can be computed: up to *3.8 kHz* with both piezo, up to about *1.9 kHz* with one piezo only (during a 800 µs flat-top only).
- A successive cavity oscillation leading to a useful LFD compensating slope, as previously seen for the Saclay-I assembly, can be identified corresponding to higher time advance values (7-8 ms).

Once the analytical model would be completed (through RF-to-$\Delta\omega$ and piezo-to-piezo TF measurements) it would allow the design of a more sophisticated dynamic and static detuning control system, exploiting both adaptive feed-forward and feed-back loops.

## ACKNOWLEDGEMENTS

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* System Identification feature of MATLAB, The MathWorks inc., has been used. FIT=82=[1 - NORM(Y – $Y_{FIT}$)/NORM(Y -MEAN(Y))]*100