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DEVELOPING KALMAN FILTER BASED DETUNING CONTROL WITH A DIGITAL SRF CW CAVITY SIMULATOR

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Abstract

Continuous wave operated superconducting cavities experiencing small net beam loading and thus operate potentially at narrow bandwidth require precise detuning control to reach the high stability requirements for RF fields within facilities such as FELF or ERL based photon sources. Microphonics compensation down to sub-hertz detuning regime not only improves stability but reduces the risk of raising the Lorentz force detuning driven ponderomotive instabilities. Usually, the complex and second order nature of the mechanical to RF detuning transfer functions of the cavity and cavity-tuner system require more advanced control schemes. In this paper, we will show the application of a Kalman filter (KF) based detuning estimator algorithm, first introduced during IPAC2017 [1] to the SRF cavity simulator developed at Helmholtz Zentrum Berlin [2].

CAVITY BASICS

Superconducting radio-frequency cavities represent a rather complex system. Even when well designed, optimized and debugged every part of that system can perform differently from expected due to the changeable environment. The uncertainties in system behavior should be compensated by the LLRF control system. We propose the element of the control system representing a kind of estimator based on the KF. The idea to use this mathematical approach for adaptive cavities control allows for definition of the estimate for not fully described systems work under uncertain circumstances. The intellectual property core allowing the cavity estimate for distinctive mechanical modes was developed and proven.

The variation of external conditions, especially the effect of mechanical vibrations cause the swing of the central frequency of the resonant cavity. At the same time the higher the quality factor the narrower the resonance frequency bandwidth. For instance, the technical characteristics of the cavities designed for bERLinPro [3] are collected in Table 1.

The resonant cavities keep the accelerating field at a required accelerating phase and loaded quality at each stage of the beam propagation (acceleration/deceleration). The Eq. (1) for the field power consists of the component dependable on the cavities coupling and intrinsic characteristics and simultaneously on the frequency detuning. In such a way the microphonic noise will produce the angular frequency deviation and therefore affects the field power.

One of the ways to ensure the cavity is stable and free from microphonics is to use the low level RF systems [4]. These systems are built into the control loop and allow to correct any unwanted influences such as microphonics by the input power sources manipulation.

Table 1: Some bERLinPro Cavities Characteristics

Name	Structure	Frequency f_0, GHz	Loaded quality Q_L	Half BW $f_{1/2}=f_0/2Q_L$, Hz
Gun	1.4 cell	1.3	$3\cdot10^6 \div 1\cdot10^7$	216.6 ÷ 65
Booster	3 x 2-cell	1.3	$1\cdot10^5$	6500
Linac	3 x 7-cell	1.3	$5\cdot10^7$	13

$$P_f = \frac{V_{cav}^2}{\frac{R}{Q}Q_L}\frac{1}{4}\left[\left(1+\frac{\frac{R}{Q}Q_L I_{b0}}{V_{cav}}\cos\varphi_{acc}\right)^2 + \left(\frac{\Delta f}{f_{1/2}}+\frac{\frac{R}{Q}Q_L I_{b0}}{V_{cav}}\sin\varphi_{acc}\right)^2\right] \quad (1)$$

KALMAN FILTER APPLICATION FOR MICROPHONICS CONTROL

Nowadays several control techniques are used to perform LLRF control tasks; classical PID regulators, adaptive LMS filters and main vibration tones cancelling technique are all examples of successfully implemented control algorithms. Our institute has developed an additional control technique for more precise resonant cavity status estimates based on KF. The first application of the KF to debug and accelerate algorithm developed in mTCA 4.0 equipment came from the SRF Cavity simulator for control algorithms debugging developed as well by our team.

The structure of cavity and the cooling system defines the sources of microphonic noises. They are mostly excited by the Lorentz force during transient states in the cavity and by the mechanical vibrations of the helium vessel. Both of these influences can be described by the following second order equations:

$$\frac{d}{dt}\begin{pmatrix}\Delta\omega_k(t)\\ \Delta\dot{\omega}_k(t)\end{pmatrix} = \left[\begin{pmatrix}0 & 1\\ -\omega_m^2 & 2\frac{\omega_k}{Q}\omega_m\end{pmatrix}\cdot\begin{pmatrix}\Delta\omega_k(t)\\ \Delta\dot{\omega}_k(t)\end{pmatrix} + \begin{pmatrix}0\\ \pm k_k 2\pi\cdot{\omega^2}_k\end{pmatrix}\cdot E_{acc}^2(t)\right] \quad (2)$$

Where $\Delta\omega_k(t)$ is the detuning, ω_m is the eigenmode angular frequency, Q is the quality factor of the mode and k_k is the coupling factor. The distinction of Lorentz force description from the piezo drive actuator counteracting the mentioned force and any other microphonics is in the last component of the equation. It describes the piezo reaction, therefore it uses the piezo actuator stiffness coefficient instead of the coupling and piezo driving voltage instead of squared acceleration field. The total detuning experienced by the cavity is the sum of the individual.

The state of the SRF cavity in mTCA4.0 feedback loop depends on the intrinsic characteristics of RF system rep-

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resented by cavity, pickup antennas, feeding cabling system, then mechanical sources more related to the cryogenic surround, changing environment and mTCA equipment like ADCs, calculation rounding, and overflow processing. This system has a predictable but changeable nature. The initial frequency response analysis taken in the PLL loop could vary with time and any attempt to write the realistic universal physical low for the system of such complexity could fail because they do not take into account the whole sum of environmental variables. Therefore the KF algorithm was chosen as a start point for observer-estimator-predictor physical model. The Kalman method [5, 6, 7] represents a mathematical method which can predict a system's state with defined probability when the measured system's values contain unpredicted or random error, uncertainty or variation. For superconducting cavities, first order systems to describe the field envelope are routinely used in LLRF control. Second order models are applied to emulate the cavity detuning response to external forces like Lorentz forces by the contained field or piezo tuner action. We will use the latter implemented with the KF observer-estimator-predictor algorithm to develop a new detuning compensation approach.

The KF method is based on an iterative calculation of three sequential equations: Kalman gain (KG), estimate (EST) and error in the estimate (E_{EST}).

KG is defined by two errors: error in the measurement (E_{MEA}) and error in the estimate. It determines how much one can trust a new measurement data sample to update the new estimate. The new obtained error in the estimate decreases every cycle time to the correct value with a velocity defined by KG.

The transition from cavity behavioral model to KF mathematical description is done according to the rules of state-space model derivation from a differential equation describing system behavior. An overview of the sequential iterative estimate calculation by KF algorithm can be found in [1].

FEATURES OF KF IMPLEMENTATION IN MTCA 4.0 BY FPGA

Detuning calculation was done by the help of I and Q components of forward and transmitted signal.

$$\Delta f = \frac{f_0 \cdot \tan(\tan^{-1}(Q_{TR}, I_{TR}) - \tan^{-1}(Q_{FW}, I_{FW}))}{2 \cdot Q_l} \quad (3)$$

The final matrix calculation was derived by the trigonometrical conversions.

$$\tan(\alpha - \beta) = \frac{\tan\alpha - \tan\beta}{1 + \tan\alpha \cdot \tan\beta} = \begin{bmatrix} Q_{FW} & -Q_{TR} \\ I_{FW} & Q_{FW} \end{bmatrix} * \begin{bmatrix} I_{TR} & I_{TR} \\ I_{FW} & Q_{TR} \end{bmatrix} \quad (4)$$

Where $\tan\alpha = \frac{Q_{FW}}{I_{FW}}$ and $\tan\beta = \frac{Q_{TR}}{I_{TR}}$

The final matrix calculation was derived from the trigonometrical conversions. The certain efforts were done to optimize the matrix algebra for FPGA implementation. Three basic operations were defined to cope with 4 modes. Each mechanical mode is described by a 2 by 2 matrix. The XC6VLX130T FPGA capacity on SIS8300L2 made by Struck could be used for any number of modes but then they should be processed sequentially or in some sort of mixed parallel-sequential pipelined mode. The extensive matrix multiplication, especially the sequence of products, force the development of the firmware using floating point calculations. The addition/subtraction, multiplication, and division operations were defined as basic. The first two were designed for an 8 by 8 component matrix while the division for the 8 by 1 matrix divided by the scalar number. Matrix multiplication is decomposed into pipelined multiplication of one 2 by 8 string of matrix A and same size column of matrix B.

Table 2: Device Utilization Summary by KF

Slice Logic Utilization	Used	Available	Utilization
Slice Registers	54,388	160,000	33%
Slice LUTs	55,856	80,000	69%
used as logic	50,389	80,000	62%
used as Memory	1,844	27,840	6%
Occupied Slices	17,910	20,000	89%
LUT Flip Flop pairs	64,353		
with an unused Flip Flop	15,937	64,353	24%
with an unused LUT	8,497	64,353	13%
fully used LUT-FF pairs	39,919	64,353	62%
RAMB36E1/FIFO36E1 s	222	264	84%
RAMB18E1/FIFO18E1 s	29	528	5%
DSP48E1s	228	480	47%

The result of a 2 by 2 matrix multiplication is the set of 8 terms. The sum of these terms gives one of four output results. Matrix addition is performed in a more straightforward way by summing the corresponding components of 2 matrices. Additional optimization was done to reduce the number of slice LUTs. The significant number of this resource was consumed by the addition operation. It requires the final normalization stage of mantissa and exponent. Additionally, ISE Foundation doesn't optimally recognize logic to be implemented in registers. A number of the maximal size matrixes were transferred to 2 port BRAM memory with the possibility to read or write one single precision floating point element or 8 x 2 elements representing two lines of a matrix in order to cope with the second issue. The recent configuration resource use is given in Table 2. The resources include the firmware developed by DESY. The KF firmware directly utilize the data about the non I/Q modulation generated by the field detection algorithm [8], calculates initial characterization matrixes and updates the estimate, the covariance and the Kalman gain in the iterative loop.

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KF TEST

The setup consists of two following parts:

- The mTCA NATIVE-9 crate with downconverter board DWC8VM1 and ADC board SIS8300L2 on Fig. 1.
- The Cavity simulator setup representing a mixture of generators, PXIe FPGA board performing cavity model and set of mixers/downconverters on Fig. 2.

Figure 1: mTCA setup under test.

The firmware was developed in several stages. First of all the sequential processing of 20 mechanical modes was shown, a year ago, using the Simulink model described in [9]. The limitation of that option was the use of information about individual detuning of each mode which was recognized as nonrealistic during the first firmware test in the real environment. Usually, the control equipment is provided by three antennas and the detuning is given by I and Q components as a sum of individual detunings. Therefore the characterization matrixes A, B, and C were once more derived from the 2nd order equation describing harmonic oscillations in the cavity. The number of modes was given as well by the Cavity Simulator and related to the limitations of FPGA logic capacity in the NI PXIe module and equals 4. Future this number will become a real limit for the Vitrex-6 FPGA on the SIS8300L2 board. The option to implement the control algorithms on the separate dedicated FPGA/DSP board is considered but not yet implemented.

Figure 2: Cavity simulator setup.

The first KF investigations reveals some deviation of the ideal precalculated response by Matlab from the real filter implemented in the mTCA's firmware, as shown in Fig. 3.

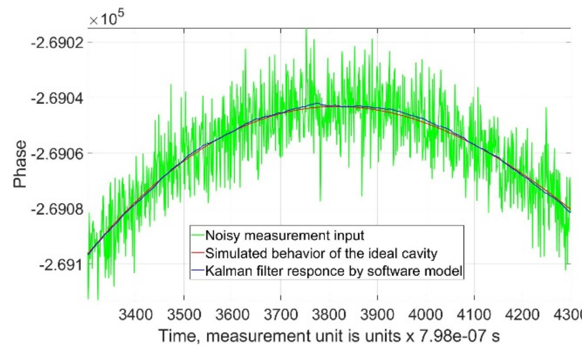

Figure 3: Noisy input, simulated and real KF comparison.

The second remarkable feature of the filter is that the initial measurement error settings have influence on the proximity of the "real" produced curve, as shown in Fig. 4. This value varies in the relatively narrow limits. Therefore it is better to do the filter tuning during some time to get the better response.

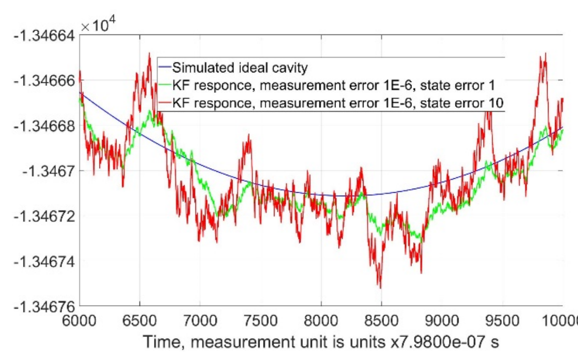

Figure 4: KF response under different measurement error.

CONCLUSION

The final testing was not yet finished because of technical reasons: the real cavity setup for bERLinPro is not available for extensive tests yet.

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REFERENCES

[1] A. Ushakov *et al.*, "Detuning compensation in SC cavities using Kalman Filters", in *Proc. 8th Int. Particle Accelerator Conf. (IPAC'17)*, Copenhagen, Denmark, May 2017, pp. 3938-3940.

[2] P. Echevarria *et al.,* "SRF Cavity Simulator for LLRF algorithms debugging", presented at the *9th Int. Particle Accelerator Conf. (IPAC'18)*, Vancouver, Canada, Apr.-May 2018, paper WEPAK013.

[3] A. Neumann *et al.,* "Update on SRF cavity design, production and testing for bERLinPro", in *Proc. 17th Int. Conference on RF Superconductivity (SRF'15)*, Whistler, Canada, September 2015, pp. 1127-1131.

[4] A. Neumann *et al.*, "Analysis and active compensation of microphonics in continuous wave narrow-bandwidth superconducting cavities", *Phy. Rev. ST Accel. Beams*, vol. 13, Iss. 8, p. 082001, Aug. 2010.

[5] R. E. Kalman, "A new approach to linear filtering and prediction problems", *Transactions of the ASME–Journal of Basic Engineering*, 82 (Series D), pp. 35-45, 1960.

[6] R. Faragher, "Understanding the basis of the Kalman Filter via a simple and intuitive derivation", *IEEE Signal Processing Magazine*, September, 2012, pp. 128-132.

[7] G. Welch and G. Bishop, "An introduction to Kalman filter", UNC-Chapel Hill, USA, July 2006, paper TR 95-041.

[8] J. Branlard *et al.*, "LLRF system design and performance for XFEL cryomodules continuous wave operation", in *Proc. 16th Int. Conference on RF Superconductivity (SRF'13)*, Paris, France, February 2014, pp. 1129-1131.

[9] G. Devanz, M. Luong, and A. Mosnier, "Numerical simulation of dynamic lorentz detuning of SC cavities", in *Proc. 8th European Particle Accelerator Conference (EPAC'02)*, Paris, France, June 2002, pp. 2220-2222.