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FPGA-Based Implementation of Adaptive Noise Controller for Continuous Wave Superconducting Cavity

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Editor-in-Chief: Prof. Dr. Shahram Minaei
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Dear Prof. Shahram Minaei,

I am writing to submit my research article, titled "FPGA-Based Implementation of Adaptive Noise Cancellation for Continuous Wave Superconducting Cavity," for consideration for publication in AEÜ - International Journal of Electronics and Communications. I believe that this article aligns well with the journal's scope, which covers all aspects of the analog and digital integrated circuit design electronic components, and devices for electronics, signal processing, and RF circuits.

I selected AEÜ as my preferred publication venue due to its strong reputation for promoting high-quality research in the field of electronics. My research investigates how to compensate for microphonic effects on cryomodules and proposes the optimal controller. The microphonics changes on the cryomodule restrict the performance of the PI controller at the LLRF system. Therefore, the proposed Narrowband Active Noise Controller method is implemented based on the presented Variable Step-Size Least Mean Square algorithm to compensate for the microphonics effects on the cryomodule.

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Sincerely,

Fatemeh Abdi

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FPGA-Based Implementation of Adaptive Noise Controller for Continuous Wave Superconducting Cavity

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Abstract: Low-level radio frequency (LLRF) systems have been designed to regulate the accelerator field in the cavity; these systems have been used in the free electron laser (FLASH) and European X-ray free-electron laser (E-XFEL). However, the reliable operation of these cavities is often hindered by two primary sources of noise and disturbances: Lorentz force detuning (LFD) and mechanical vibrations, commonly known as microphonics.

This article presents an innovative solution in the form of a narrowband active noise controller (NANC) designed to compensate for the narrowband mechanical noise generated by certain supporting machines, such as vacuum pumps and helium pressure vibrations. To identify the adaptive filter coefficients in the NANC method, a least mean square (LMS) algorithm is put forward. Furthermore, a variable step size (VSS) method is proposed to estimate the adaptive filter coefficients based on changes in microphonics, ultimately compensating for their effects on the cryomodule. The proposed NANC method is characterized by low computational complexity, stability, and high tracking ability. By addressing the challenges associated with noise and

disturbances in cavity operation, this research contributes to the enhanced performance and reliability of LLRF systems in particle accelerators.

Keywords: Narrowband Active Noise Controller (NANC), Least Mean Square (LMS), field-programmable gate array (FPGA), Microphonics, Accelerator, and Continuous Wave (CW).

1. Introduction

Currently, the free electron laser in Hamburg (FLASH) [1] and the European X-ray free-electron laser (E-XFEL) utilize a digital low-level radio frequency (LLRF) control system based on field-programmable gate array (FPGA) technology to stabilize the accelerator field at facilities [2]. FPGA technology is employed in the control system design to maximize computation power while minimizing latency.

In particle accelerator facilities, two distinct operational modes are used: pulsed or continuous wave (CW). The maximum number of particle bunches that a particle accelerator can create in pulsed mode is typically in the range of a few ten thousand bunches per second and the beam energy, however, can be quite high (17.5 GeV for the E-XFEL). Short pulses require MHz beam injection, and the duty cycle is relatively low because the accelerator operates in bursts with significant downtime between bunch trains.

CW accelerators operate with a steady stream of particle bunches, often at a significantly lower frequency than the pulsed accelerators, but yield a higher number of bunches per second (up to a million). Although the CW mode typically has lower energy than pulsed mode (4-8 GeV). For these reasons, research and development (R&D) programs focused on the potential upgrade of the E-XFEL for CW operations are of high interest. The steady and effectively higher bunch throughput is the main motivation for users to explore CW machines with simplified beam detection and diagnostic systems [3-4].

The application of the conventional proportional-integral (PI) control method for resonance control feedback in the cavities is restricted by the mechanical properties of the cavities. The transfer function of the actuators, when considered in conjunction with the cavity, exhibits poles in a frequency range proximate to the prevailing components of microphonic disturbances. Consequently, the use of the PI control scheme proves ineffective due to an inadequate phase margin within the crossover frequency range. To surmount these limitations, more sophisticated algorithms have been devised and implemented, such as the active noise controller (ANC) and narrowband active noise controller (NANC) methods. Both the ANC and the NANC methods are commonly employed to reduce the noise in many media and these techniques have also been applied to superconducting radio frequency cavities [5]. Mechanical vibrations (microphonics) are generated in the accelerator environment by various sources, like vacuum pumps, helium pressure vibrations, and fans. Microphonics change the mechanical dimensions of the cavities, which results in a shift in the resonant frequency. To counteract this, the accelerating structure must be tuned to the specified resonance frequency. The detuning frequency, the difference between the actual frequency and the resonance frequency, should be cancelled using an advanced controller [6-7].

According to measurements made at the cryomodule test bench (CMTB), the microphonics are frequencies below 500 Hz that change based on the characteristics, size, and placement of the cavity concerning its surroundings [8]. The ANC controller corrects for microphonics effects at CMTB. This controller, however, has a longer response time and concentrates on the detuning determined from the RF signal, while the operators must manually set the microphonics frequency and the step size of the ANC method.

In this paper, we propose an advanced NANC method to control and track microphonic disturbances. This controller utilizes the variable step size least mean square (VSS LMS) algorithm to identify and estimate the adaptive filter coefficients based on the microphonics changes. The controller produces a signal with the same amplitude and opposite phase of the microphonic disturbances. The step size parameter significantly influences the LMS algorithm's performance. Initially, a large step size is necessary to quickly adapt to the noise changes. A smaller step size ensures minimal misadjustment and stability after the error signal converges to a minimum value [9].

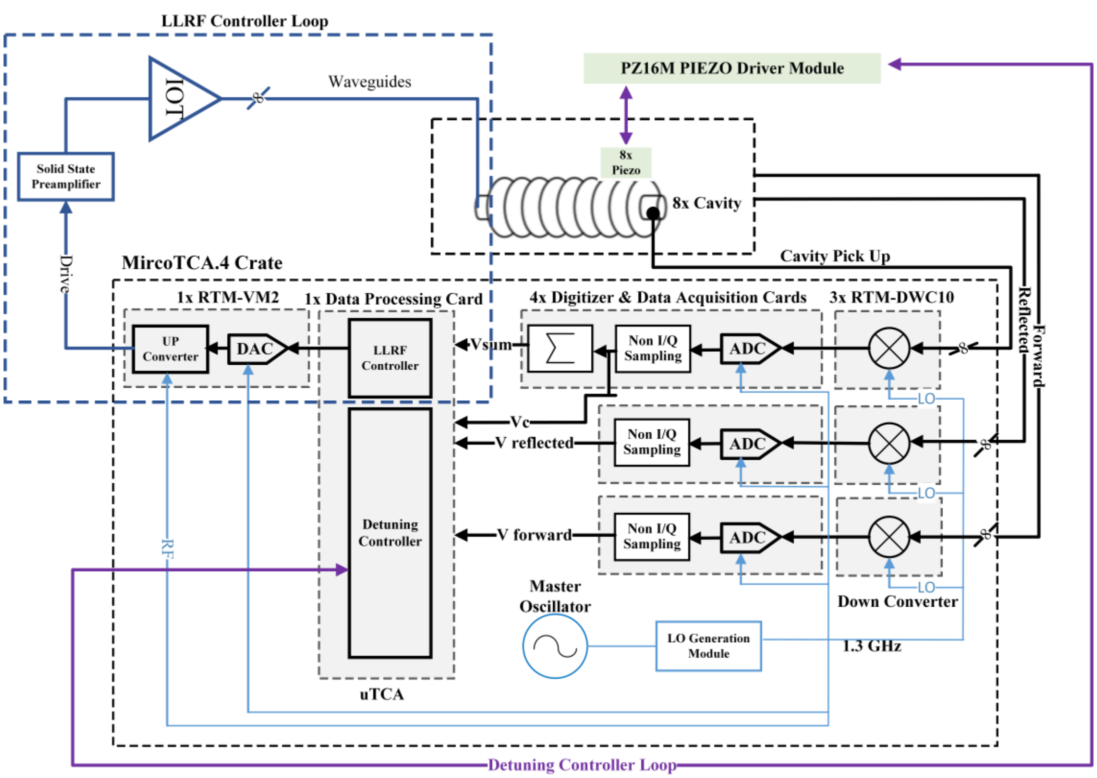

Fig. 1 General view of the LLRF control system at CMTB

2. Controller Loops

The LLRF system comprises two control loops:

1. The LLRF controller is responsible for stabilizing the accelerator field. Fig. 1 provides an overview of the LLRF control system currently in operation at CMTB. The RF signals are down-converted from 1.3 GHz to 54.17 MHz and subsequently transferred to other MicroTCA.4 cards for digitization and data acquisition. The primary LLRF controller algorithms are implemented on a dedicated data processing card. The LLRF controller's output is then transmitted to an upconverter/vector modulator card, and the resulting signals drive the preamplifier and inductive output tube (IoT) [10-11].

2. The detuning controller loop aims to stabilize the resonance frequency of the cavities. This paper primarily focuses on the implementation of the detuning controller. An approach has been proposed to identify microphonics changes and estimate adaptive filter coefficients using the VSS LMS algorithm.

3. Compensation Method of the Microphonics Detuning

Mechanical noises, generated by vacuum pumps, compressors, refrigeration equipment, helium boiling, and turbulent flows in pipes, are typically periodic [12].

An advanced narrowband active noise controller (NANC) method is proposed to compensate for the mechanical noise. It provides a reference signal that includes the fundamental frequency and all harmonics of the mechanical noise. In the NANC method, two types of reference signals are commonly used:

1. An impulse train with a period equal to the inverse of the fundamental frequency of the periodic noise [13-14].

2. Sinewaves that match the frequencies of the corresponding harmonic tones to be cancelled. A particular sinusoid signal can be eliminated by a finite impulse response (FIR) notch filter in the NANC method while having very little impact on narrowband noise, as shown in Fig. 2. The second technique, the adaptive FIR notch filter, was developed to cancel tonal interference [15] and has been adapted for use in the periodic NANC method [16].

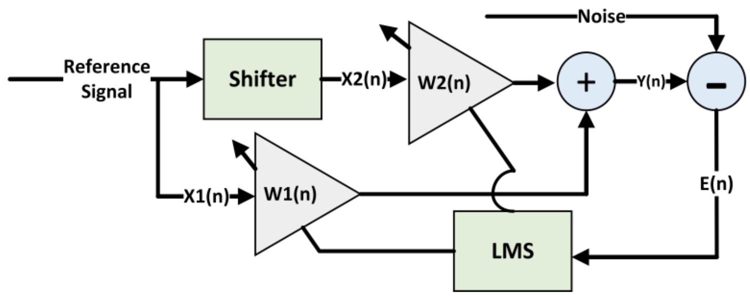

Fig. 2 Single-frequency adaptive FIR notch filter

The proposed NANC method is implemented using an adaptive FIR notch filter, offering the advantages of easy bandwidth control and precise frequency tracking of the mechanical noise. Within the adaptive notch filter, two adaptive coefficients are used: $x_1(n) = A\sin(w_0 n)$ and $x_2(n) = A\cos(w_0 n)$. These are individually weighted and then summed to produce the controller's output signal (Y(n)). The LMS algorithm is employed to update the filter coefficients ($w_1(n)$ and $w_2(n)$) and minimize the residual error (E(n)). According to Fig. 2, an error signal is the difference between the noise and the controller's output signal.

The NANC method, incorporating the VSS LMS algorithm implemented with hardware description language (HDL) language, is utilized to adapt to changes in the resonance frequency of the cavity induced by microphonics.

3.1 NANC Components

As depicted in Fig. 3, the presented method comprises four components:

1. The first component, the adaptive filter component, implements the adaptive FIR notch filter. Its purpose is to generate the controller output, which contains the same amplitude and opposite phase as the microphonics signal. The FIR notch filter is implemented to calculate the controller output signal, based on Eq.(1), and transfer it to the actuator. Input signals should be multiplied by $w_{1,i,x}(n)$ and $w_{2,i,x}(n)$, respectively.

$$y_i(n) = w_{1,i,x}(n)\sin(w_i n) + w_{2,i,x}(n)\cos(w_i n) \quad (1)$$

2. The second component, known as the weight computation FxLMS component, is designed for determining the new coefficients in the FxLMS and LMS algorithms.
   The delayed error signal $f_e(n\text{-}D)$, which is the difference between the output of the NANC algorithm $y_i(n)$ and the microphonics measured by the piezo sensor, updates the filter coefficients, $w_{1,i,x}(n+1)$ and $w_{2,i,x}(n+1)$, to minimize the residual error, according to Eq.(2-5):

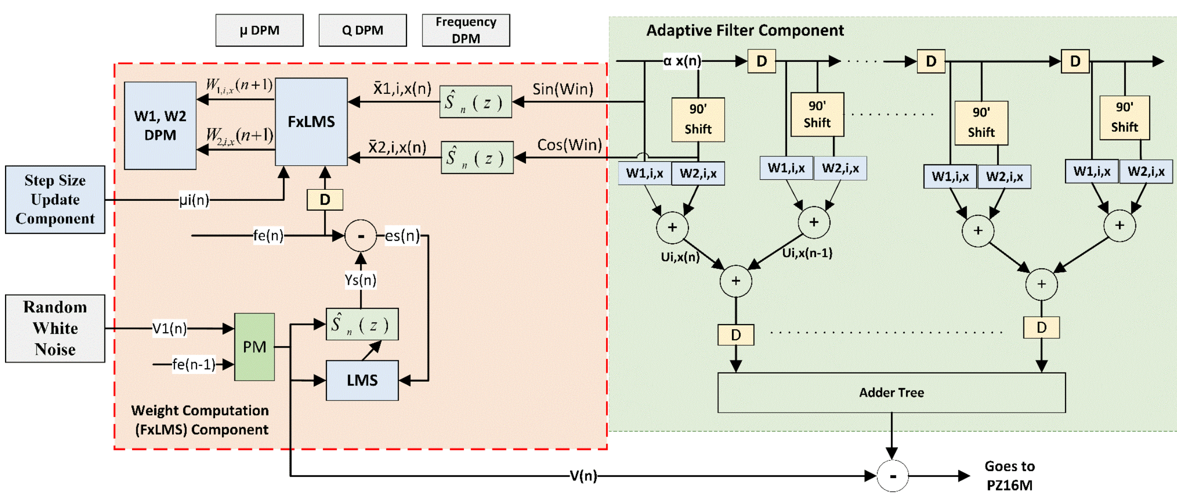

Fig. 3 NANC system with four components to identify the microphonics

$$w_{1,i,x}(n+1) = w_{1,i,x}(n) + \mu_i(n) f_e(n-D)\hat{x}_{1,i,x}(n) \quad (2)$$

$$w_{2,i,x}(n+1) = w_{2,i,x}(n) + \mu_i(n) f_e(n-D)\hat{x}_{2,i,x}(n) \tag{3}$$

$$\hat{x}_{1,i,x}(n) = \sum_{i=1}^{n_w} \hat{s}_i(n)\sin(w_i n) \tag{4}$$

$$\hat{x}_{2,i,x}(n) = \sum_{i=1}^{n_w} \hat{s}_i(n)\cos(w_i n) \tag{5}$$

3. The third component involves the suggested step size update component (shown in Fig. 4). This component calculates the new variable step size and is responsible for improving the convergence rate, computational complexity, and the bit error rate performance of the algorithm over the existing algorithms. To ensure the algorithm's stability and desired steady-state performance, the step size should be constrained to the minimum and maximum values of the step size.

   The adaptive algorithm needs the maximum value of the step size when the error signal is large and it should identify the microphonics changes. The step size should have the minimum value when the error signal convergences to zero and the system is near stable mode. The step size is updated by using the error signal's sign. This technique reduces the computational complexity of the program and makes it robust to low signal-to-noise ratio (SNR) environments [17].

   In Eq.(6), the transfer function $\hat{s}(z)$ (transfer function of the actuator) represents the secondary path modelling and is usually considered an FIR filter with $\hat{s}(n)$ coefficients. The white noise $v_1(n)$ with zero mean and variance $\sigma_{v1}{}^2$ may be scaled by a function $f_e(n-i)$ added to the secondary source ($y_s(n)$).

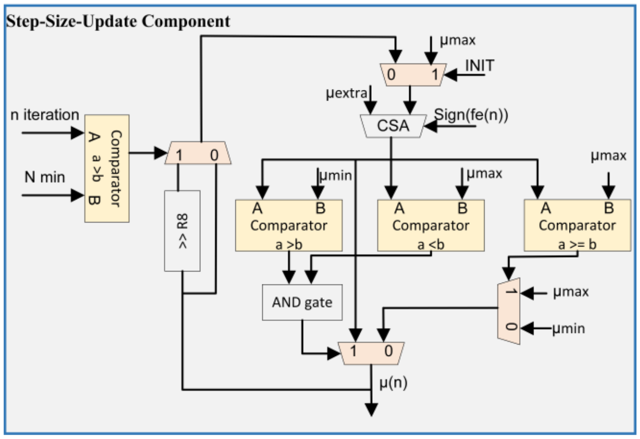

Fig. 4 Step size update component

$$y_s(n) = \sum_{i=1}^{n_w} \hat{s}_i(n) v_1(n-i) f_e(n-i) \tag{6}$$

According to Eq.(7), a $\mu_s(n)$ is a variable step size of the SPM and the coefficients of the transfer function of the actuator are updated by an LMS algorithm.

$$\hat{s}_i(n+1) = \hat{s}_i(n) + \mu_s(n) e_s(n) v_1(n-i) f_e(n-i) \tag{7}$$

The steps of updating the step size of the proposed method are described using Eq.(8-10):

$$\mu(n+1) = \begin{cases} c * \mu(n) + \mu_{Extra}\, sign\big(e(n)\big), \mu_{min} \le \mu(n) \le \mu_{max} \\ \mu_{max}\,, \mu(n) > \mu_{max} \\ \mu_{min,} \text{Otherwise} \end{cases} \tag{8}$$

$$c = \begin{cases} 2^{-r}, i > i'_{min} \\ 1, \text{Otherwise} \end{cases} \tag{9}$$

$$sign\big(e(n)\big) = \begin{cases} +1, e(n) > \zeta_{tol} \\ 0, |e(n)| < \zeta_{tol} \\ -1, e(n) < -\zeta_{tol} \end{cases} \tag{10}$$

Where sign(0) is the signum function and ζ_{tol} is a very small positive value that presents the tolerance of the error signal at a steady state. The $\mu_{Extra} > 0$ is a constant value that affects the convergence rate. The proposed method includes two different values to calculate the c parameter, a large c =1 is taken for the initial iteration. i_{min} is defined as the convergence time of the mean step size and a small c value is used in the variation process. According to Eq.(8-10), when overestimation (measured microphonics < controller output signal) occurs and the sign of e(n) is negative while the positive sign of e(n) indicates underestimation (measured microphonics > controller output signal). The step size is updated by subtracting a small positive value μ_{EXTRA}. $\mu(n+1) = c\times\mu(n) - \mu_{EXTRA}$, whenever overestimation occurs. Similarly, to oppose underestimation, the step size is updated by adding a small positive value μ_{EXTRA}, $\mu(n+1) = c\times\mu(n) + \mu_{EXTRA}$, whenever underestimation is encountered [17].

4. The final component is responsible for random white noise. It governs the injection or cessation of the white noise in the NANC method. Random white noise component: According to Eq.(7), the LMS algorithm needs the random white noise $v_1(n)$ to update the coefficients of the secondary path ($\hat{s}_i(n+1)$). The performance block is implemented in the NANC method to apply the random white noise to the algorithm.

When the error signal converges to the minimum value, the injection of the white noise will be stopped. Also, the performance block injects the white noise into the algorithm when sudden changes happen in the secondary path. Based on the operation of the performance block, the current step size value is compared to the previous step size value, if the step size has slight changes, the random white noise $v_1(n)$ will be stopped. The random white noise will be given back to the algorithm when the error signal is divergent [18].

4. Firmware Implementation of the NANC

Two adaptive algorithms are used to identify and update the primary coefficients of the FxLMS algorithm and the OSPM filter coefficients through the LMS algorithm. In Fig. 5, several FPGA modules are implemented to design the NANC method using HDL language. The measured microphonics are directed to the FIFO module (ENT_FIFO). A hamming window is applied to suppress spurious frequencies caused by discontinuity in the samples and other operations like low-pass filtering. The subsequent FPGA module is the FFT module (fft_ipCore), which converts discrete input signals from the time domain to the frequency domain.

The max_3freq module calculates the three highest amplitudes of the microphonics and their corresponding indexes. The Fout_finder modules compute the microphonics frequencies based on the indexes. The Ph_inc module is designed to calculate the phase increment and transmit them to the Sig_Gen_dds module, generating sine and cosine signals as input signals to the NANC modules that incorporate the presented NANC method, which is implemented based on the proposed VSS LMS algorithm.

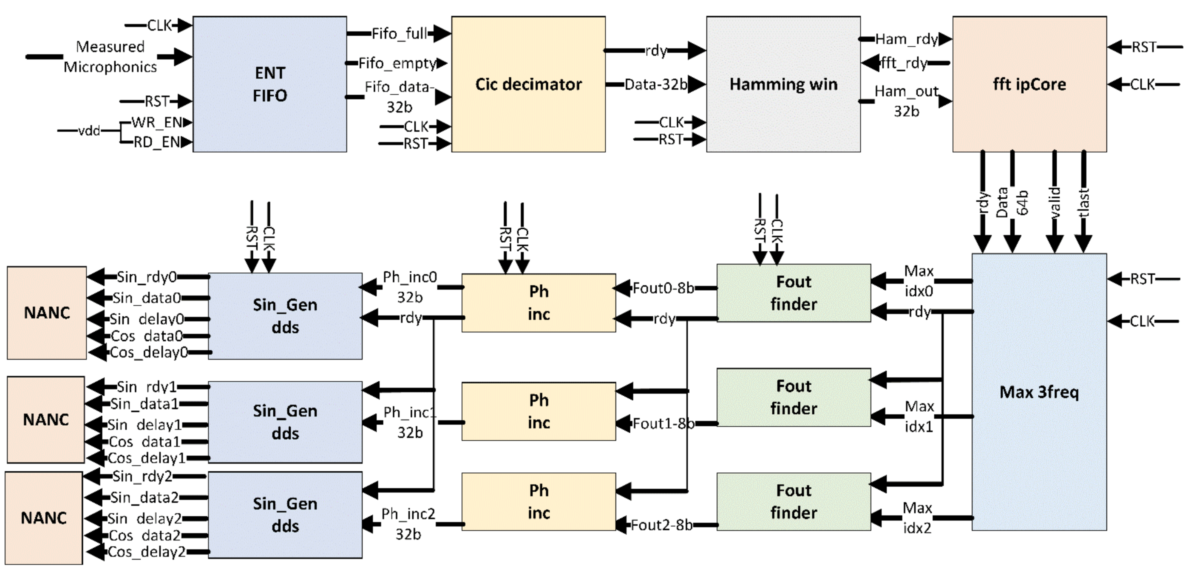

Fig. 5 Implementation of the NANC with FPGA modules

5. Firmware Implementation Results

The microphonics is measured by the piezo sensor which is connected to the PZ16M piezo driver module and a fiber connects PZ16M to the DAMC-TCK7 card. The software that reads the values from the FPGA and exposes them to Java DOOCS Data Display (JDDD) is called the piezo server at DESY. The firmware implementation utilized 18-bit fixed-point operation. Fig. 6 shows the measurement setup in the experimental test.

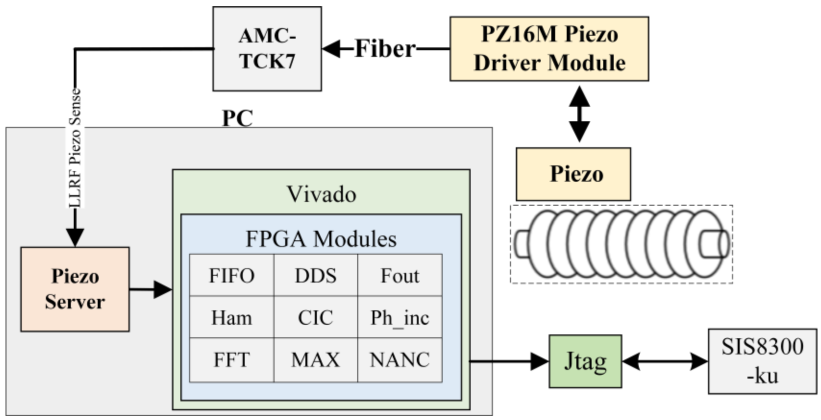

Fig. 6 Diagram of the measurement set-up

Fig. 7 displays the microphonics data measured, revealing microphonics occurred in three frequencies with the highest amplitudes at 25 Hz, 28 Hz, and 31 Hz.

Fig. 8 illustrates the output signals of the FIFO, Hamming Window, and Fout_finder modules. The FFT module generates the output (FFT_tdata) after a 1024-point process is completed when the FFT_tlast goes to '1'. The Max_3freq module identifies the three highest amplitude input signals and their corresponding indexes (Max_IDX0-2). These identified frequencies (25 Hz, 28 Hz, and 31 Hz) match the frequencies shown in Fig. 7. The Ph_inc modules calculate the phase increment and send them to the Sin_Gen_dds module to generate sin and cosine signals based on the microphonic frequencies.

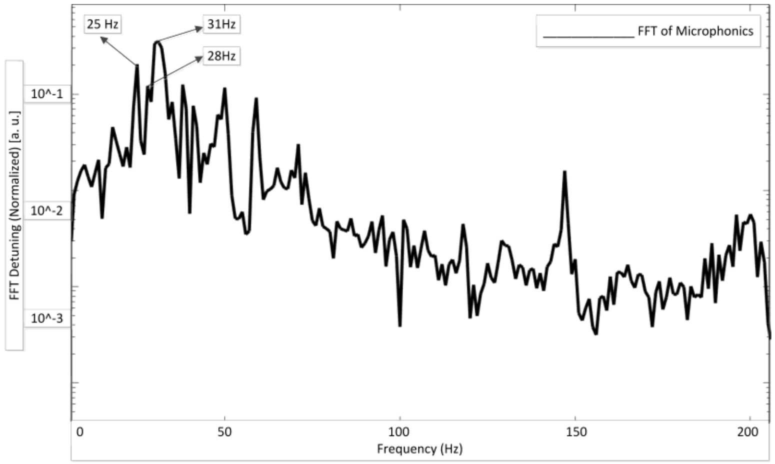

Fig. 7. Measured microphonics by piezo sensor

In Fig. 9, the error signal represents the difference between measured microphonics and the NANC output, convergence to the minimum value. This indicates that the algorithm can efficiently track the microphonics variation with high convergence and high tracking ability. The proposed NANC controller is implemented on an SIS-8300-ku [19] which features the Xilinx Kintex Ultra scale FPGA with a 100MHz clock cycle. In Table. I, the hardware complexity of the implemented architectures is detailed.

Table. I Resource utilization on Xilinx Kintex Ultrascale FPGA

Module	LUT	FF	DSP	RAM
Available	242400	484800	1920	600
Complete Project	26248	9404	49	31
NANC Module	1104	1710	12	0

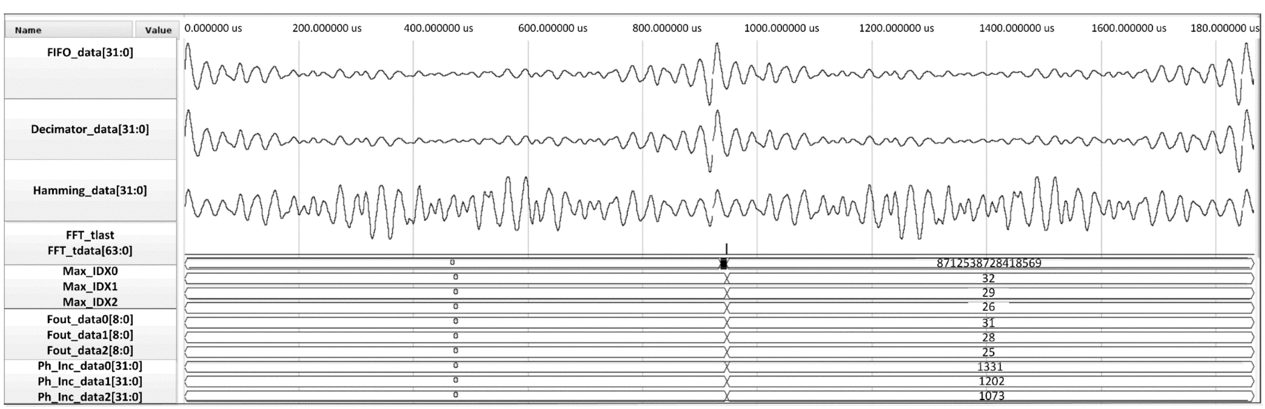

Fig. 8 Outputs of the FPGA modules in the NANC method

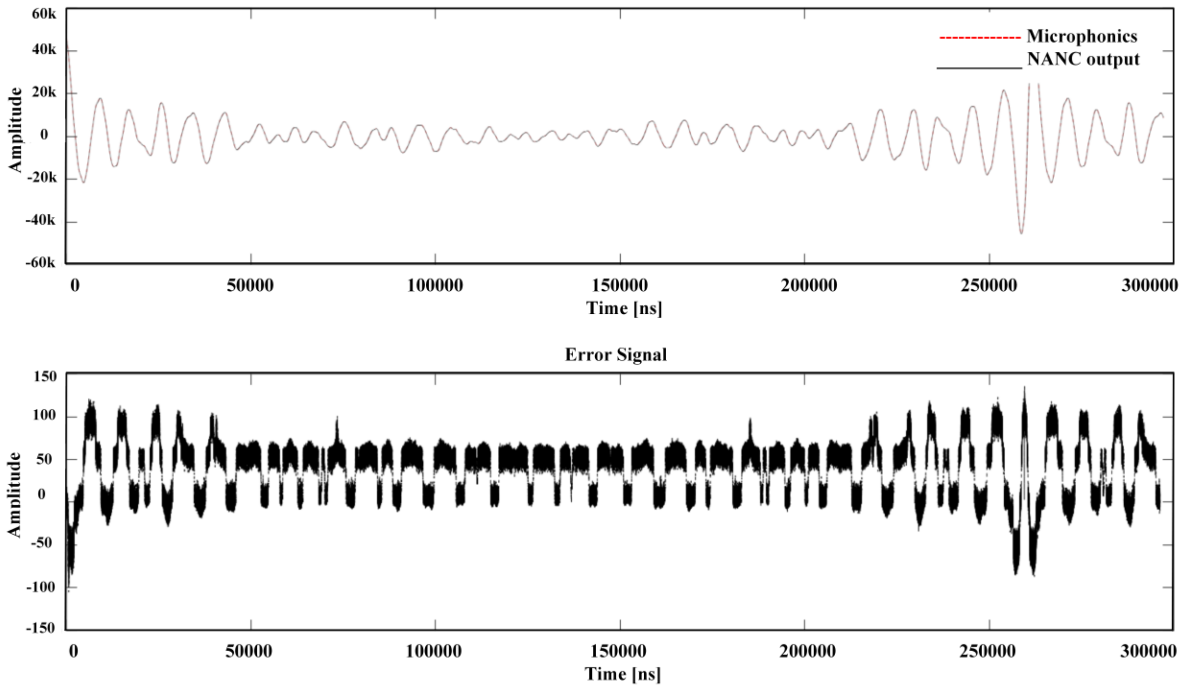

Fig. 9 Identification of microphonic changes by NANC method

6. Conclusion

The microphonics changes on the cryomodule restrict the performance of the PI controller at the LLRF system. Therefore, the proposed NANC method is implemented based on the presented VSS LMS algorithm to compensate for the microphonics effects on the cryomodule. Some advantages of the proposed method are:

1. There is no need to identify the transfer function of the cryomodule and plant

2. Low computational complexity

3. High tracking ability

The proposed method identified three frequencies of the microphonics with the highest amplitude. In principle, the adaptive filter coefficients of the NANC method are adjusted during the operation of the system by an iterative optimization method. The presented method is implemented in the

SIS-8300-ku struck board and permits to control the microphonics changes in CW mode. In the next step, a microelectromechanical systems (MEMS) sensor will be mounted on several locations of the cryomodule at CMTB to find an optimal location for measuring the microphonics. The components implementation will be integrated into the LLRF controller module to compensate for the measured microphonics changes.

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This is the project that has been realized with DMCS at Lodz and DESY at Hamburg.

Author Contributions

Conceptualization, F.A, W.C, W.J, L.B, J.B, A.B.; methodology, F.A, W.J, W.C, L.B.; software, F.A.; validation, F.A, W.J., L.B..; formal analysis, F.A.; investigation, F.A.; writing—original and draft preparation, F.A.; writing—review and editing, F.A, W.C, W.J, J.B; supervision, W.C. All authors have read and agreed to the published version of the manuscript.

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Declaration of interests

☐The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☒The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Fatemeh Abdi reports equipment, drugs, or supplies was provided by German Electron -Synchrotron.

Submission declaration and verification

We the undersigned declare that the manuscript entitled "FPGA-Based Implementation of Adaptive Noise Cancellation for Continuous Wave Superconducting Cavity" is original, has not been fully or partly published before, and is not currently being considered for publication elsewhere.

We confirm that the manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship but are not listed. We further confirm that the order of authors listed in the manuscript has been approved by the undersigned.

We understand that the Corresponding Author is the sole contact for the editorial process. The corresponding author "Fatemeh Abdi" is responsible for communicating with the other authors about the process, submissions of revisions, and final approval of proofs."

Best Regards

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