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IDENTIFICATION OF THE MECHANICAL DYNAMICS OF THE SUPERCONDUCTING RADIO-FREQUENCY CAVITIES FOR THE EUROPEAN XFEL CW UPGRADE

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Abstract

The European X-Ray Free-Electron Laser (EuXFEL) is to-date the largest X-ray research facility around the world which spans over 3.4 km. EuXFEL is currently being operated in a pulsed mode with a repetition rate of 10 Hz. One upgrade scenario consists of operating the EuXFEL also in a Continuous-Wave (CW) mode of operation to improve the quality of experiments. This upgrade brings new challenges and requires new algorithms to deal with controlling a stable accelerating field inside the Superconducting Radio-frequency (SRF) accelerating cavities and keeping them on resonance in this new mode of operation. The purpose of this research work is to identify the mechanical dynamics of the cavities which will facilitate the development of the resonance controller for the CW upgrade. To this extent, experiments were conducted at a test bench. For the first time, in this work, two different types of spectrally rich excitation signals: multi-sine and stepped-sine are used to excite the mechanical dynamics of the cavities using the piezo actuator. After the analysis of experimental data, mechanical modes are successfully identified and will be used to design the controller.

INTRODUCTION

The European X-Ray Free-Electron Laser (EuXFEL) is used to generate ultrashort X-ray flashes with a very high brilliance in the femtosecond range for various scientific and industrial research purposes. Currently, EuXFEL is being operated in a pulsed mode with a repetition rate of 10 Hz and a duty factor of 1.4% and can produce a maximum of 27000 electron bunches per second with a temporal separation of 220 ns. The possibility a Continuous-Wave (CW)-upgrade for EuXFEL is currently being investigated as CW allows a high average beam current and a flexible bunch pattern of the beam, which will be of great importance for the quality of experiments at the EuXFEL. To investigate the possibility a CW-upgrade, experiments are being conducted on a facility called Cryo-Module Test Bench (CMTB) at DESY, containing 8 TESLA-type SRF cavities, same as in EuXFEL. To upgrade EuXFEL to CW mode of operation, the Superconducting Radio-frequency (SRF) cavities must be operated at a very high-quality factor, in the order of 10^7, due to power limitations. But this very high-quality factor would result in an extremely narrow half-bandwidth, of less than 20Hz [1], when operating cavities at 1.3 GHz. This will make the cavities more sensitive to external mechanical disturbances or microphonics, which would cause detuning effects. Detuning is the difference between the operating frequency of the SRF cavity and the resonance frequency of the cavity. So to keep the SRF cavity at resonance with the required field stability and as well as to limit the required power, a control solution must be developed to suppress the effect of these microphonics using fast piezoelectric tuners. Various filter-based model-less algorithms have been investigated for microphonics suppression as in [2], but these solutions show limitations when combined with RF field control and are only able to suppress narrow bandwidth microphonics. To overcome this problem, a model-based control strategy can be used for microphonics suppression. However, before developing a model-based control strategy, the mechanical dynamics of the cavity (from piezo actuation to the detuning) in the form of a model (transfer function or state-space) must be identified with reasonable accuracy. So far extensive research has been done to investigate the mechanical dynamics of the cavity as in [3–6]. The commonly used excitation signal are either the stepped sine or chirp. However, a comparison between different excitation signals was never done, with the exception of [7], where stepped-sine and step signal are compared for identifying the cavity's mechanical modes. Still, in [7], spectrally rich signals like stepped-sine, chirp, multi-sine, etc. are not compared.. For the first time, in this work, two different spectrally rich excitation signals: multi-sine and stepped-sine are used to investigate the mechanical dynamics of the cavity. The reason for using multi-sine is that on one hand it is very time efficient compared to stepped-sine and on the other hand it is a much more reliable signal compared to a simple step signal when it comes to system identification. We could have used chirp as well along with stepped-sine and multi-sine but due to technical limitations of our measurement setup we are only able to collect one second of measurements at a time. So if we cover the desired frequency region using one second of a chirp signal, we might not get the steady-state measurement for the desired frequency region.

If we can identify the mechanical dynamics of the cavity using multi-sine with reasonable accuracy then it would significantly reduce the time during the online implementation routine and will be preferred over stepped-sine especially when re-characterization of the system is required often.

EXPERIMENT

Choice of excitation signal plays a key role when it comes to identify a dynamical system whether for control purpose

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or estimation purpose. Some of the key factors which influence the choice of excitation signal are time limitation and the required accuracy of the model in the desired frequency range. In this work, we need to identify a model which captures the mechanical modes of SRF cavities with reasonable accuracy (i.e. 70% or higher in time domain), especially in the frequency range of 1 to 250 Hz as the most damaging mechanical modes are within the 250 Hz bandwidth. This is the frequency range where the mechanical dynamics of a cavity is affected by the disturbances mostly.

To identify the mechanical dynamics of the cavity, experiments are conducted at CMTB. In these experiments, the mechanical dynamics of the SRF cavity are excited using the fast piezo actuators.

To identify a system with various modes such as mechanical dynamics of the SRF cavitys, the excitation signal should be spectrally rich, like a chirp, multi-sine, stepped-sine, etc. Here, two different excitation signals: multi-sine and stepped-sine are applied and compared and their viability is investigated.

Multi-sine

Multi-sine consists of a sum of multiple sinusoids. The amplitude, frequency, and phase of each sinusoid can be chosen freely. By using multi-sine as an excitation signal multiple desired discrete frequencies of the system can be excited simultaneously, as a result, we can significantly reduce the measurement time. Mathematically a multi-sine can be defined as

$$u(t) = \sum_{n=1}^{N} A_n \sin(2\pi f_n t + \phi_n)\,, \tag{1}$$

where A_n, f_n and ϕ_n are the amplitude, frequency and phase of the n^{th} sinusoid respectively. N is the total number of sinusoids considered in the signal. Altough the amplitudes and phases of sinusoids can be freely chosen but in practice the phases are optimized to attain minimum crest factor thus best Signal-to-noise ratio (SNR). A well known choice of phases are the Schröder phases defined as,

$$\phi_n = \frac{-n(n-1)\pi}{N} \tag{2}$$

Eq. (2) also ensures an equal A_n for all frequency components.

Implementation of multi-sine as excitation signal is motivated because of its lower measurement time which would significantly increase the efficiency while moving towards an online identification routine on EuXFEL.

Stepped-sine

In contrast to multi-sine, stepped-sine only allows to excite a system with a single frequency at a time, and then this frequency is updated to the next desired frequency. Therefore, several frequencies have to be excited separately to cover the desired frequency range. Mathematically, it can be represented as,

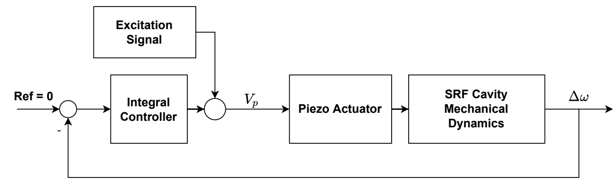

Figure 1: Experimental setup scheme.

$$u(t) = A \sin(2\pi f_n t + \phi)\,, \tag{3}$$

where A, f_n, and ϕ are the amplitude, frequency, and phase of the signal and they can be chosen freely for a particular sinusoid. Here amplitude A remain constant throughout the signal $u(t)$ but frequency f_n keep being updated after a fixed time interval (1 s in this case), so f_n can be defined as,

$$f_n = f_{n-1} + \Delta f \tag{4}$$

where f_n is the current frequency of the signal, f_{n-1} was the frequency of the signal in the previous time interval and Δf is the frequency update. The choice of the frequency update (i.e. the step size between each consecutive excited frequency) can be influenced by multiple factors like time limitation for the measurements, the memory of the measurement hardware, required identification accuracy, and the bandwidth of modes of the system under-consideration.

Implementation

Both multi-sine and stepped-sine are applied in a closed-loop as illustrated in Fig. 1. Closed-loop identification method is used because the integrator controller is required to keep the cavity on an average detuning of 0 Hz.

It can be seen that the excitation signal is super-imposed on the control feedback and then piezo voltage V_p and detuning $\Delta\omega$ are used for system identification. Since $\Delta\omega$ is not directly measurable, so the model of the cavity RF dynamics (5) is used,

$$\begin{aligned}\begin{bmatrix}\dot{V}_{P,I}(t)\\ \dot{V}_{P,Q}(t)\end{bmatrix} &= \begin{bmatrix}-\omega_{1/2} & -\Delta\omega(t)\\ \Delta\omega(t) & -\omega_{1/2}\end{bmatrix}\begin{bmatrix}V_{P,I}(t)\\ V_{P,Q}(t)\end{bmatrix}\\ &\quad + 2\omega_{1/2}\begin{bmatrix}V_{F,I}(t)\\ V_{F,Q}(t)\end{bmatrix} - \omega_{1/2}\begin{bmatrix}V_{B,I}(t)\\ V_{B,Q}(t)\end{bmatrix},\end{aligned} \tag{5}$$

where $V_{P,I}(t)$ and $V_{P,Q}(t)$ are the in-phase and the quadrature components of the probe signal respectively. The forward and beam signals are defined similarly. $\Delta\omega$ is the angular detuning and $\omega_{1/2}$ is the half bandwidth of the cavity. Since the beam is not included in the identification experiments $V_B(t)$ will be omitted.

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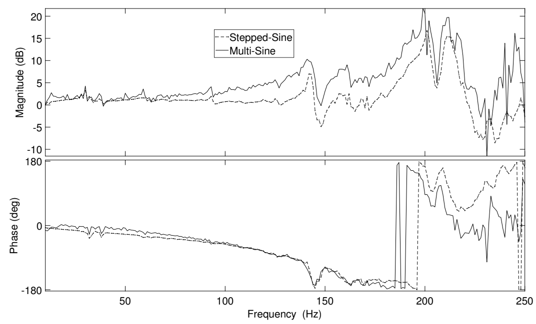

Figure 2: Comparion of transfer functions from piezo voltage to detuning for multi-sine and stepped-sine.

Multi-sine Implementation The multi-sine signal in this work for system identification has a frequency range from 1 to 250 Hz, and the desired frequency range is covered with the frequency resolution of 1 Hz. The Sampling frequency of the collected input data is 16 kHz. As the base frequency of multi-sine is 1 Hz so one period of multi-sine is of 1 sec. The first five seconds of the measured data are removed. Such a decision was done to achieve a periodic steady-state regime. The remaining collected data is divided into 10 different data sets and each data set consists of one multi-sine period. The reason for 10 different data sets is to minimize the effects of measurement noise during system identification.

Stepped-sine Implementation Stepped-Sine also covers the frequency range from 1 to 250 Hz with the frequency update of 1 Hz, and sampling frequency of 16 kHz. For stepped-sine as well we drop the first 5 seconds of measurements for each measured frequency to neglect the transients. Like in multi-sine, the remaining data is divided into 10 different data sets and each data set consists of 250 s of measurement i.e. one second of measurement for each frequency. The reason for 10 different data sets is same as for multi-sine, i.e. to minimize the effects of measurement noise during system identification.

RESULTS

Frequency Response Function

The mean frequency response for 10 different data sets of the multi-sine and stepped-sine are compared in Fig. 2. Both approaches give compatible results identifying the main mechanical eigenmodes of the system so there is a good qualitative agreement. Moreover, mechanical eigenmodes identified in this work are in good agreement with the previous work in [8]. We assume the difference in amplitude between both the approaches used in this work is due to the windowing techniques applied in the Fast Fourier Transform (FFT) calculations.

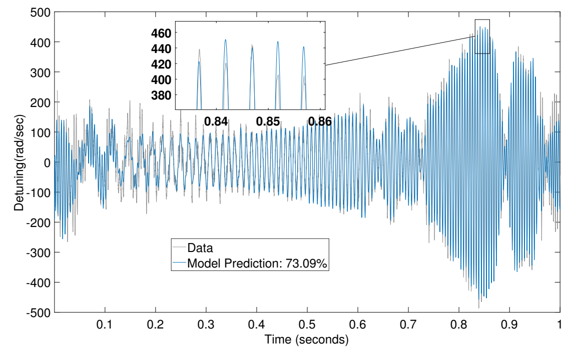

Figure 3: Time-domain validation of model identified using multi-sine data set.

Model Identification & Validation

As stepped-sine data was not continuous so we use only multi-sine data for identifying a model from piezo voltage to detuning. The System Identification Toolbox of Matlab was used to identify a 20-order model with 20 poles and 19 zeros using the black-box approach [9]. The mean prediction accuracy of 73.89% for 9 different data sets is achieved. Normalized root mean square (NRMSE) is used as a metric for validation. Validation for one of the data set is shown in Fig. 3.

CONCLUSION

For the first time, two different spectrally rich excitation signals, multi-sine and stepped-sine, are used to identify the mechanical dynamics of the SRF cavities. The use of multi-sine as an excitation signal is motivated by its time efficiency compared to stepped-sine and higher identification accuracy compared to step signal. It turns out that multi-sine is 250 times more time-efficient compared to stepped-sine and both the approaches are in good qualitative agreement in identifying mechanical eigenmodes. The model identified using multi-sine data showed mean accuracy of 73.89% when validated in the time domain for 9 different data sets and will be used for control design to suppress microphonics. But to use this model for control purposes, we need to do model order reduction, otherwise, it might not be possible to implement model-based control techniques on such a high order model.

For future work, we could increase the amplitude of piezo actuation for the multi-sine approach to increase the SNR so we can better capture the dynamics of the frequency region where we have higher disturbances. Moreover, since the mechanical modes of the cavity have narrow bandwidth, tests with higher frequency resolution (i.e. smaller frequency update) will be performed in the future to better capture these resonance peaks. The future availability of a measurement setup able to capture multiple seconds of continuous data will open the possibility to use additional excitation signal types, like continuous stepped-sine and chirp.

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