ANALYSIS OF MICROPHONIC DISTURBANCES AND SIMULATION* FOR FEEDBACK COMPENSATION

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Abstract

For FEL projects based on a superconducting linac operating in CW mode, the RF power optimization finally comes up against the microphonics disturbances, which result in an unpredictable detuning of the cavities. A new piezoelectric tuner was developed and mounted on a TTF 9-cell cavity with an appropriate instrumentation. This system enables a full characterization of the disturbances and the tuner behavior. First measurements were made in a horizontal cryomodule at 4.2 K. They set a basis for simulations to assess the possibility of a feedback compensation, which is usually credited as impracticable. The outcome of such a compensation is also shown in terms of acceleration voltage amplitude and phase residual errors.

INTRODUCTION

In low beam loading linacs as FEL drivers, the radiofrequency (RF) source power scales proportional to the square of cavity detuning. With a high external Q, which means a narrow bandwidth, any disturbance resulting in a cavity detuning leads to strong accelerating gradient errors in amplitude and phase and a high extra-power requirement due to the action of the low level RF system. Since FEL drivers would operate in a continuous wave (CW) or nearly-CW mode, the main disturbance is produced by the microphonics, related to the environment acoustic or mechanical vibrations and the excitation of the cavity system mechanical eigenmodes (MEM). However the disturbance can be cancelled using either a feedback or a feedforward technique with a fast piezoelectric tuner (FPT). Two recent experiments have demonstrated their application to a single cell 80 MHz QWR [1] and a 6-cell 805 MHz elliptical cavity [2].

The EuroFEL* study has dedicated a work package to the analysis and compensation of microphonics in different environments and conditions as representative as possible of a nominal FEL driver operation, with different FPT's and compensation algorithms. One part of the program is carried out in CryHoLab, a horizontal cryo-module, on a 9-cell 1300 MHz cavity, a reference cavity in EuroFEL [3], equipped with a new high dynamic FPT designed for Lorentz forces compensation [4].

EXPERIMENTAL ANALYSIS

The loaded Q of the cavity in test is 1.3 10^6, typically one order of magnitude lower to the values envisaged in FEL projects [3]. However, it has neither influence on the transfer function (TF) of the system nor on the microphonics characteristics. On the contrary, a larger bandwidth allows a higher dynamic for the detuning measurement based on the classical phase detection, resulting in more accurate TF identification. The experimental setup is shown in figure 1.

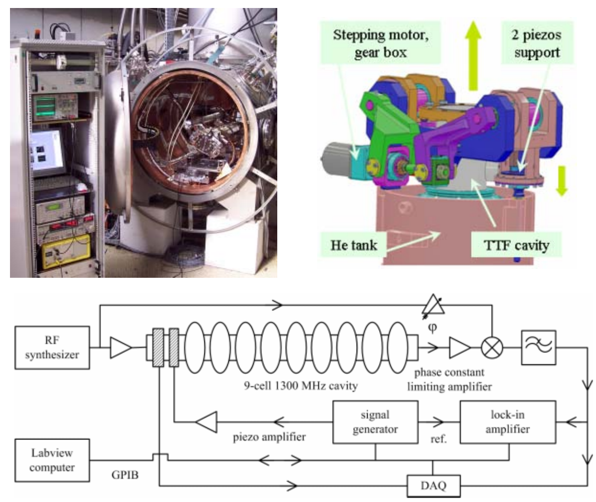

Figure 1: Experimental setup - Instrumentation (bottom), 9-cell cavity in CryHoLab (left top) with FPT (right top)

The identification of TF's, FPT to FPT or FPT to detuning is obtained as a Bode diagram from the harmonic response in a discrete frequency sweep using a lock-in amplifier which provides an excellent noise rejection. Since the quality factor of each mechanical mode (Q_m) is unknown a priori, each frequency step should last long enough, typically 5 s in order to reach a steady state before the measurements of amplitude and phase are taken.

Preliminary Investigation at Room Temperature

A comparison of FPT to FPT and FPT to detuning transfer functions is shown in Fig. 2.

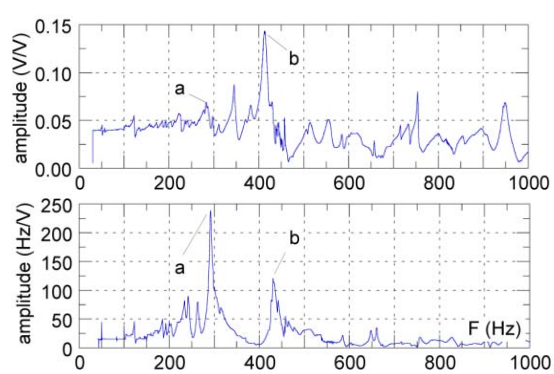

Figure 2: Transfer functions at room temperature, FPT to FPT (top), FPT to cavity detuning (bottom)

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The relative amplitude between the two dominant modes labelled as 'a' and 'b' appears different in the two TF's, which indicates that the detuning of the cavity does not depend only on the longitudinal length variation but rather on a complex mechanical coupling between the FPT and the MEM's on the one hand and between the MEM's and the cavity detuning on the other hand. Another way to assess the higher frequency modes and their associated Q_m's consists in exciting periodically one FPT with pulses and reading the signal of the second FPT on a real-time spectrum analyser (RTSA). Strong MEM's with high Q are displayed as long hot trails on the RTSA (Fig. 3a), which shows such resonant modes around 2.5 kHz. Nevertheless, their detuning contribution is expected to be weak from a theoretical analysis: mechanical and RF simulations. Microphonics have also been analysed with the RTSA on one FPT signal; the resonance 'b' appeared as a continuous hot line (Fig. 3b). The excitation of lower MEM's was also visible.

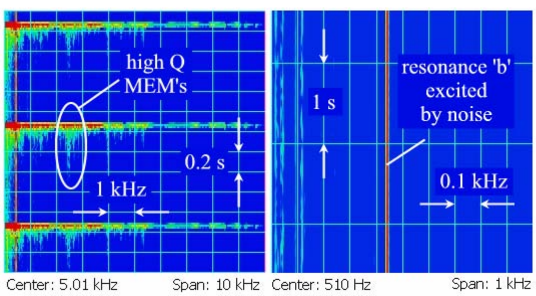

Figure 3: High frequency MEM's (a: left) and microphonics (b: right) at room temperature

Measurements at 4.2 K

Figure 4 shows FPT to FPT TF measured with 1 Hz of resolution. It is quite similar to that obtained at room temperature (Fig. 3). However, a more detailed examination would point out frequency and amplitude shifts as well as Q variations, all attributable to the change of mechanical boundary conditions and a different nominal setting of the tuner.

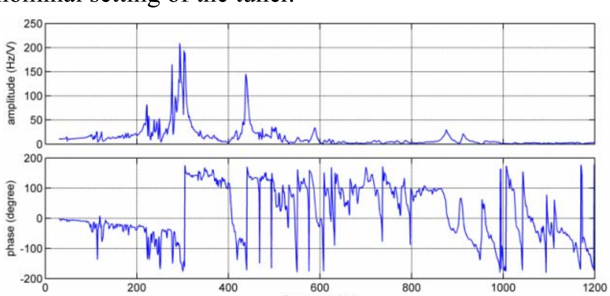

Figure 4: FPT to cavity detuning transfer function

For the microphonics analysis, the detuning signal is digitized with a sampling rate of 10 kS/s, covering a frequency analysis up to 5 kHz, and a resolution of 16 bits. A Matlab code was elaborated for the time and spectral domain analysis: 2D, 3D spectrograms, local spectrum at a given time, or amplitude change in time domain of a given frequency channel could be displayed.

Three different regimes of disturbances are identified due to: binary state helium regulation valve, vacuum pumps motors harmonics exciting the neighbouring MEM's, or excitation of MEM's by other environmental noises. The first regime corresponds to a low frequency (typically 1.4 Hz) oscillation with variable peak detuning (up to 100 Hz) and decaying in typically 5 s. This kind of disturbance is specific to CryHoLab and should not exist in a cryogenic plant at operating at 2 K. The spectrogram in Fig. 5 illustrates a case of the second regime dominated by the 50 and 100 Hz harmonics. The variation of the amplitude in the time domain (20 Hz pk-pk) must relate to some vacuum pumps internal regulation processes. When the pumps are switched off, disturbances around 50 Hz and 100 Hz are strongly reduced, leaving only a few resonances below 300 Hz (Fig. 6). The major disturbance at 115 Hz may correspond to the first longitudinal MEM which is known from the mechanical and RF simulations to provide a strong detuning to the cavity. The absence of detuning contributions above 300 Hz indicates that the environmental noises are rather bandwidth limited or the detuning effect of the MEM's at higher frequency is very low; surely both. This third regime presents typically an rms detuning of 1.5 Hz with peak to peak amplitude of 7 Hz.

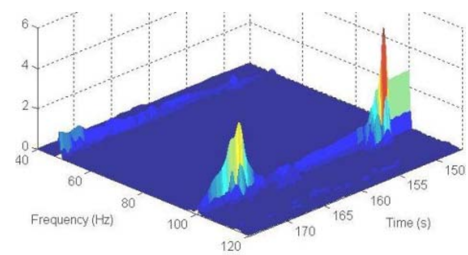

Figure 5: Spectrogram of vacuum pumps motors harmonics driven microphonics (amplitude: a. u.)

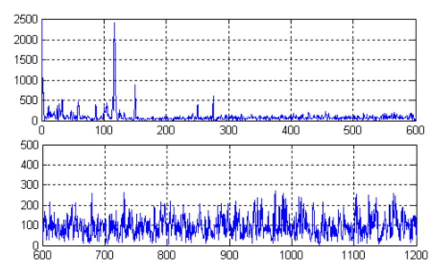

Figure 6: Spectrum of microphonics due to MEM's by other environmental noise (amplitude: a. u.)

MODELING AND SIMULATIONS

Because of the complexity of the TF evidenced by Fig. 4, any feedback compensation is bound to fail without an accurate modeling of the system composed by the tuner, cavity and cryomodule (TCCS). Meanwhile, this TF should involve more than 30 resonances even in a low frequency span limited to 1.2 kHz, ruling out any attempt to derive a canonical form: H = N/D, where N and D would be very high order polynomials. Indeed, the stability analysis of such a system is extremely sensitive to the numerical precision of the computers.

Analytical Model for FPT to Detuning TF

Fortunately, a basic consideration of the physical process behind the TF provides a simple and practical model. It states that the harmonic response at a given frequency appears as a linear combination of the contributions of an infinite number of MEM's. Practically, only a finite number can be considered. Consequently, the system model writes simply:

$$H(s) = H^1(s) + \sum_{i=1}^{N} H_i^2(s),\ \ H^1(s) = \frac{K_0}{\tau s + 1},$$

$$H_i^2(s) = \frac{\omega_i^2 K_i}{s^2 + 2\xi_i \omega_i s + \omega_i^2},\ \ \xi_i = \frac{\delta\omega_i}{\omega_i},\ \ K_i = \pm 2\xi_i \Delta f_i,$$

where the first order TF H^1 modeled the contribution of high frequency MEM's with eigenfrequencies higher than ω_N and is used to adjust the static response, ξ_i relates to Q_{mi} as $Q_{mi} = 0.5/\xi_i$. For the FPT in this study, K_0 is a negative small value about 1 Hz/V. The time constant τ corresponds typically to a cut-off frequency of 1 kHz. The other parameters: $\delta\omega_i$ the half bandwidth, ω_i the eigenfrequency, Δf_i the detuning amplitude are the model parameters. For well isolated resonances, they can be directly derived from the measured TF. More generally, their identification proceeds in two steps: a local fitting followed by a global optimization over the whole frequency span of interest. Actually, the sign of K_i is an additional, very important free parameter for the fitting procedure. A negative sign means that the transient of the associated MEM excited by a sudden shortening of the cavity length would produced a negative detuning, and vice-versa. Only a combination of positive and negative K_i's can reproduce in all details the measured TF. A constant delay should also be added to H in order to take into account the propagation of the acoustic wave from the tuner to the cavity. Its value is estimated to 400 µs from the phase slope at low frequency in Fig. 4. The fitting result over a short span is presented for illustration in Fig. 7.

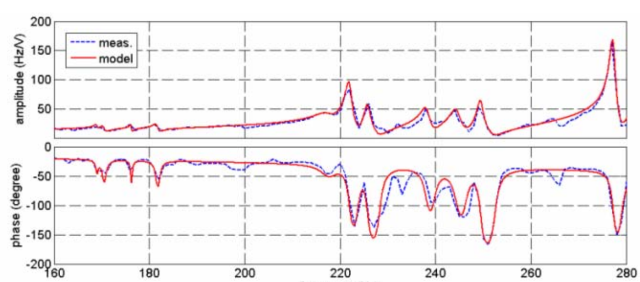

Figure 7: Model fitting result for FPT to detuning TF

Feedback Compensation Simulation

From the previous section, the disturbance regime of major concern involves mainly two frequencies corresponding to the pump motors harmonics at 50 and 100 Hz. A classical idea for complex system feedback would consist in providing gains only at the frequencies where disturbances are observed. The figure 8 shows the TF of the corrector alone, made up of a cascade of lowpass, bandpass type II Chebyshev filters, chosen for their zero phase shift far from the pass-band, and phase lead network, as well as the open loop TF including in the cascade a model of the TCCS.

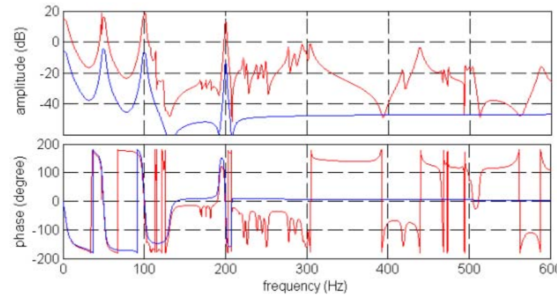

Figure 8: Corrector TF (blue) and open loop TF (red)

To assess the effect of microphonics on the accelerating voltage and RF power requirements, the operation of a cavity including the LLRF system is simulated with a set of parameters taken from [3]: V_{cav} 27 MV/m, q_b 1 nC, Q_L 4.6 10^7, T_b 2.42 µs, feedback gains 100. An operation without disturbances needs 11.4 kW of RF power. The simulation used the measured disturbances as an input. The cavity phase errors with/without the compensation are compared in Fig. 9. In the first case, the extra power is limited to about 0.5 kW while it has exceeded 2 kW in the second case. The relative cavity field errors are respectively 10^{-3} and 2 10^{-4}.

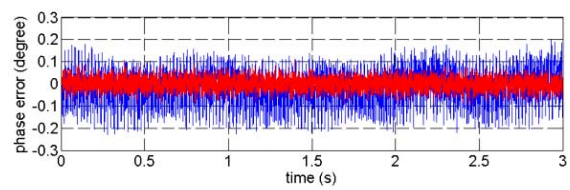

Figure 9: Cavity phase error due to microphonics, with (red), and without (blue) a FPT compensation

DISCUSSION

Provided an accurate measurement and modeling of the tuner to cavity detuning, the simulations indicate that a feedback scheme could be used for the microphonics compensation even on a rather complex 9-cell cavity. An experimental validation of this approach is planned in the EuroFEL study.

REFERENCES

[1] S. Simrock et al., “First Demonstration of Microphonic Control of a Superconducting Cavity with a Fast Piezoelectric Tuner”, PAC'03, Portland, 2003, p. 470.
[2] T. Kandil et al., “Adaptive Feedforward Cancellation of Sinusoidal Disturbances in Superconducting RF Cavities”, LINAC 2004, Lübeck, 2004, p. 447.
[3] J. Sekutowicz, “Parameter set for CW and nearly-CW Operation of a XFEL Driving Superconducting Linac”, EuroFEL report 2005-DS5-003.
[4] G. Devanz et al., “Compensation of Lorentz Force Detuning of a TTF 9-cell Cavity with a New Integrated Piezo Tuner”, this conference.