FIRST DEMONSTRATION OF MICROPHONIC CONTROL OF A SUPERCONDUCTING CAVITY WITH A FAST PIEZOELECTRIC TUNER

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Abstract

Superconducting cavities exhibit a high susceptibility to mechanical vibrations due to their narrow bandwidth of operation. The resulting modulation of the resonance frequency (typical amplitudes are, in the absence of mechanical dampers, a few tens of Hz at a modulation frequency of up to a few hundred Hz) can exceed the cavity bandwidth leading to a perturbation of the amplitude and phase of the accelerating field, which can be controlled only at the expense of rf power. It is therefore highly desirable to control the resonance frequency of the cavity with a fast controller. A fast mechanical tuner based on piezoelectric or magnetostrictive actuator appears very attractive, since its tuning is done simply by a micrometric deformation of the resonator geometry. In the past these tuners have been limited by mechanical resonances in the transfer function to a modulation bandwidth of about 1 Hz. With modern control theory and high speed DSPs and FPGAs it is now possible to design complex controllers which allow high gain up to several hundred Hz. In this paper we present first results of fast microphonics piezoelectric control for a superconducting quarter wave resonator. Microphonics at 42 Hz (inner conductor) are controlled despite a large mechanical resonance a 662 Hz in the actuator transfer function.

1 INTRODUCTION

The control of the resonance frequency of superconducting cavities is highly desirable particularly if frequency excursions induced by microphonics (or Lorentz force detuning in pulsed operation) exceed the bandwidth of the cavity. This is usually the case in accelerators with small beam loading such as heavy ion linacs, low current high energy electron linacs and energy recovery linacs.

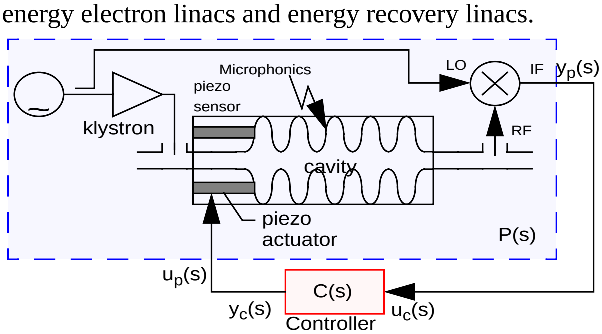

Fig.1: Schematic for feedback control of microphonics

Typical microphonic noise levels as measured in operational superconducting accelerators are of the order of several Hz to several tens of Hz with a frequency spectrum ranging up to a few hundred Hz. The observed spectrum is a result of a convolution of the spectrum of excitation and the coupling to the mechanical resonances of the cavities.
Since microphonics are induced by mechanical vibrations a natural solution to the problems appears to be a fast mechanical actuator which is driven in such a way that the detuning caused by microphonics is perfectly compensated. Due to the partially statistical nature of the microphonic noise a negative feedback loop is necessary as shown in Figure 1.
The cavity resonance frequency is detected with a phase detector comparing the wave incident to the cavity (from the directional coupler for forward power) with the transmitted signal (field probe signal). Corrections for beam loading may be necessary and can be accomplished with digital signal processing. The fast mechanical frequency tuner can be realized with a piezoelectric or magnetostrictive actuator which are integrated with the motor driven mechanical tuner. The actuators typically allow for a length change of the cavity of a few micrometers resulting in frequency changes of some tens to some hundreds of Hz. Presently several labs are pursuing the control of microphonics and Lorentz force detuning with a piezoelectric actuator [1-5].

2 MICROPHONICS CONTROL ISSUES

Fast piezoelectric tuners are installed in several superconducting linacs but are usually used to control slow drifts (< 1 Hz) of the resonance frequency of the cavity. Attempts have been made to increase the bandwidth of the feedback loop to several hundred Hertz. The failure of these attempts can be explained by the mechanical resonances of the cavity which introduce several second order poles in the transferfunction between piezo actuator input and the cavity resonance frequency measured with a phase detector.

In practice the mechanical transfer functions of multicell cavities such as employed at the TESLA Test facility or at SNS are quite complicated because of the large number of resonances up to several kHz. For quarter wave cavities the resonances of the center conductor and the bottom plate are only few up to a several kHz and are well understood. While microphonics are usually coupled strongly to the low frequencies resonances of the center conductor, the piezo actuator couples to the higher frequency resonances of the bottom plate and only weakly to the center conductor. Therefore the QWR provides the ideal testbed for control of microphonics. In summary the issues related to the control of microphonics are:

- mechanical resonances in the transfer function of piezo tuner + delay from propagation of acoustic waves
- vibrations from the environment (microphonics) and piezo tuner couple differently to mechanical resonances
- different mechanical modes couple differently to the resonance frequency of the cavity. No linear superposition of detuning from individual mechanical modes possible i.e system is nonlinear.

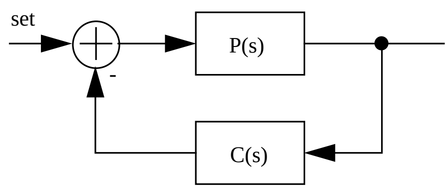

Fig.2: Feedback configuration with plant P(s) and Controller C(s)

- mechanical modes excited with large amplitude can potentially modulate the energy gain in multicell cavities significantly.

3 CONTROL OF MICROPHONICS

The goal is to find an acceptable controller C(s) for a given transferfunction P(s) of the piezo actuator in the control configuration shown in Figure 2.
The controller must fulfill several requirements

- Feedback loop must be stable i.e. the open loop transferfunction D(s)=P(s)C(s) must change the phase less than 180 deg. up to unity gain frequency.
- For fast reponse the phase margin should be at least 30-60 deg.
- Good error supression i.e. high gain of D(s) at frequencies which need to be controlled (up to several hundered Hz). The gain of D(s) should roll-off fast at higher frequencies to guarantee stability.
- Robust against small changes of the transfer function of the piezo actuator.

After choosing the desired open-loop frequency response D(s) the controller can be designed as

$$C(s) = \frac{D(s)}{P(s)}$$

A typical desired open loop transfer function would be a gain of 100 (= 40 dB) for frequencies from DC up to a few hundred Hz, then a steep roll-off (for example 3rd order low-pass with 60 dB/dec), a reduction of roll-off to 20 dB when unity gain is reached (this can be implemented with 2nd order high pass) followed by a fast roll-off above (2nd order low-pass) at a few kHz to prevent higher frequency resonances to cause instabilities.
With D(s) of 8-th order as described and assuming 10 mechanical resonances up to several kHz, the controller requires fairly high order polynomials (28-th order in the example) to be implemented. With the recent progress in digital signal processing hardware (DSPs and FPGAs) it is nowadays possible to implement such high order controllers with low latencies. For example a 20-th order transferfunction processed by a C67 DSP results in a latency of only 20 microseconds. Implementation on a VIRTEX II FPGA is expected to reduce latencies to below 1 microsecond and that very high order transferf unctions can be realized.

4 QWR AND PIEZO TUNER

The resonator [6,7] is a 80 MHz PIAVE type bulk niobium Quarter Wave Resonator (QWR) with mechanical damper. This type of QWRs has been operated in the linac at gradients of up to 6 MV/m. The operating bandwidth is only a few Hz and phaselock can be achieved without a fast frequency tuner. The resonator is ideally suited for the development of controllers for fast mechanical tuners for control of microphonics because it is a mechanically simple and well understood system.
For the experiment of controlling microphonics with a piezotuner the cavity was mounted in the cryostat after 8 months of storage while exposed to air without any rinsing done before installation. The tuning plate, a 1 mm thick copper disc with a 1 micrometer layer of sputtered niobium on the rf surface, has been mounted at the open end of the QWR.

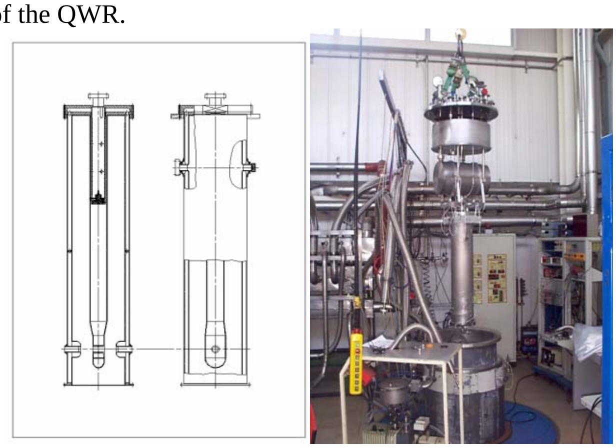

Fig.3: PIAVE type quarter wave resonator

The piezo, a EPCOS 8x8x30 mm crystal without internal preloading, was mounted in the center of the bottom plate along the resonator axis. The piezodriver was a 60 W, 400 mA, -10 to 15 V, model ENV 400 power supply from Piezojena. The measured tuning range generated by the piezo was 25Hz/100V at 4.2 K, corresponding to about 8 micrometer change in length of the piezo. The center conductor has the lowest resonance frequency at about 42 Hz while the tuning plate with the piezo had a lower mechanical mode at 672 Hz (calculated and measured). The resonator low power electrical Q measured during the test was 1.6e9.

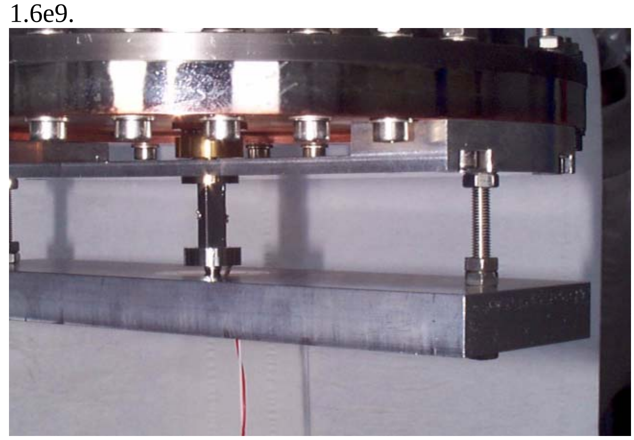

Fig.4: Piezo tuner installed at bottom plate

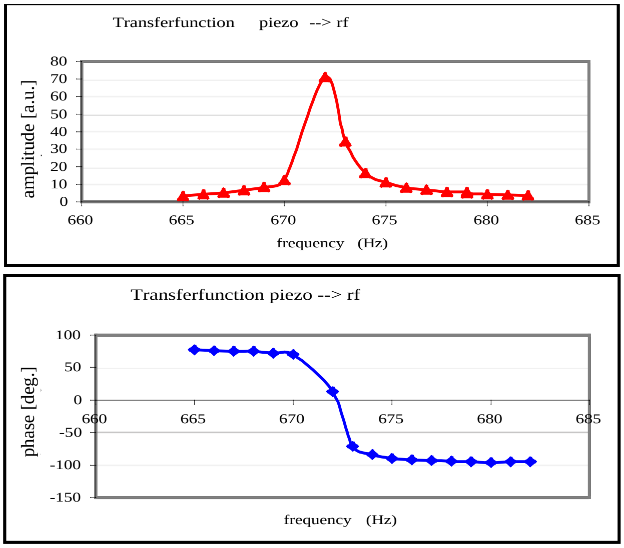

Fig.5: Transfer function of piezo tuner around 672 Hz

5 DIGITAL CONTROLLER

The digital controller made use of a C67 based DSP board (Model M67 from GBm) with an Omnibus module (A4D4) carrying 4 ADCs and 4 DACs with a maximum clock speed of 200 kHz. The DSP has been programmed in C++ to perform Matrix multiplications to realize transferfunction in state space form:

$$\hat{x}_{k+1} = A\hat{x}_k + B\hat{u}_k$$

$$\hat{y}_{k+1} = C\hat{x}_{k+1} + D\hat{u}_k$$

With the A matrix of size 20x20 transferfunction of to 20-th order could be realized. The computation time was of the order of 20 microseconds (including ADC and DAC conversion times) which is fully sufficient for feedback up to a few kHz.

Initially only a notch filter at 672 Hz and a low pass around 1 kHz have been implemented.

6 PERFORMANCE OF FEEDBACK

The feedback test has been performed at low fields to guarantee a linear response of the rf control system. During the test the cavity was locked at a gradient of about 1 MV/m. The resonator has been weakly locked in phase to allow a large residual phase error at 42 Hz. The forward power was 10 W, largely overcoupled resulting in a 3 dB bandwidth of about 50 Hz.The residual phase error in the rf control system, caused by resonator vibration due to environmental noise was reduced by one order of magnitude when activating the piezo control system. The resulting error suppression is shown in Figure 6.

7 CONCLUSION

Active suppression of microphonics in a superconducting quarter wave resonator has been demonstrated successfully. Besides reducing the microphonics by an order of magnitude, the standard controller could be turned off and the piezotuner was able to maintain the cavity in phase-lock.

Although the piezotuner did not couple to the dominating resonance of the center conductor which has been excited quite strongly by microphonics, a mechanical resonance of the bottom plate has been compensated with the digital controller. In the future it is expected that modern digital controllers allow for feedback control of microphonics in multicell cavities despite the complex mechanical mode structure.

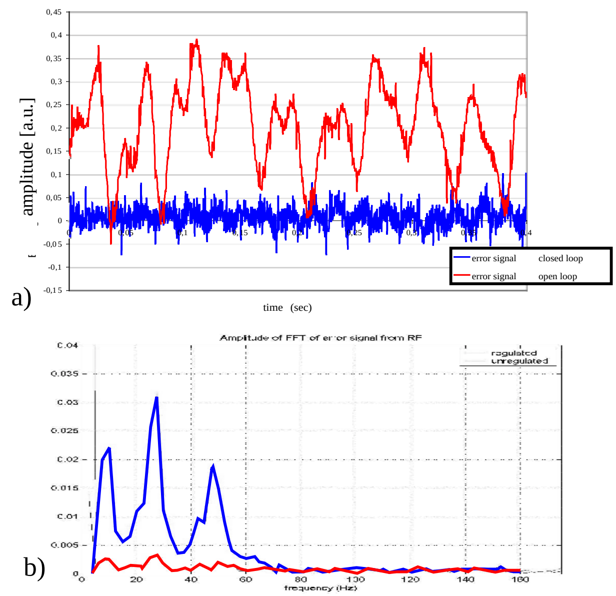

Fig.6: Active suppression of microphonic noise with feedback applied to fast piezo tuner. a) Time domain measurement. b) Frequency domain measurement

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