ADAPTIVE FEED FORWARD FOR THE DIGITAL RF CONTROL SYSTEM AT THE TESLA TEST FACILITY

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1 ABSTRACT

The rf control system of the TESLA Test Facility regulates the vector sum of multiple superconducting cavities which are operated in pulsed mode at accelerating gradients exceeding 15 MV/m. In addition to the feed back control loop which suppresses stochastic errors, feedforward [1] is applied to reduce repetitive perturbations induced by beam loading and dynamic lorentz force detuning. In the case of TESLA repetitive errors are dominating. The feedforward algorithm first identifies the time varying state space model of the closed loop system by measurement of a step response. Next the pulse to pulse average of the measured perturbations is applied to the inverse state space model to obtain the correct feedforward table. The feed forward tables can be updated continuously to follow slow changes in the perturbation parameters. On-line system identification is transparent to routine beam operation due to the small step size used.

2 INTRODUCTION

The requirements for amplitude and phase stability of the vector-sum of 16 cavities are driven by the maximum tolerable energy spread for the TESLA Test Facility. The goal is an rms energy spread of $\sigma_E/E = 2 \cdot 10^{-3}$. The requirements for gradient and phase stability are therefore of the order of $2 \cdot 10^{-3}$ and $0.5°$ respectively [1].

The amplitude and phase errors to be controlled are of the order of 5% for the amplitude and 20 degrees for the phase a result of Lorentz force detuning and microphonics. These errors must be suppressed by a factor of at least 40 which implies that the loop gain must be adequate to meet this goal. Fortunately, the dominant source of errors is repetitive (Lorentz force and beam loading) and can be reduced by use of feedforward significantly.

3 DESIGN OF THE TTF RF CONTROL SYSTEM

The digital rf control system at the TTF [2] has been designed for maximum flexibility of the control algorithm. The main features are:

- digital IQ detection of the cavity field of each individual cavity. The fields are sampled at a rate of 1 MHz.
- calibration of the individual measured cavity field vectors by multiplication with an appropriate rotation matrix
- calculation of the vector-sum and subtraction from a (time varying) setpoint to form the error signal.
- application of the feedback control algorithm which is presently implemented as proportional controller in form of a time varying gain matrix
- a time varying feedforward is added to eliminate repetitive disturbances

All time varying signals are implemented as tables consisting of 2048 pairs of real (*r*) and imaginary (*i*) values covering a pulse length of 2048 μs. The goal of the adaptive feedforward is to determine the optimum feedforward table which minimizes the residual amplitude and phase error and to continually update the feedforward tables to track slowly varying repetitive perturbations.

4 SOURCES OF PERTURBATIONS

The major perturbations of the pulsed accelerating fields in the superconducting cavities are induced by microphonics, dynamic Lorentz force detuning, beamloading, and power fluctuations of the klystron. While microphonics and power fluctuations of the klystron are of random nature and cannot be predicted in advance of the rf pulse, the effects of lorentz force detuning and beam loading can be measured before they influence the cavity field. While typical microphonic noise amplitudes are of the order of ±5 Hz, the lorentz force detuning reaches ±200 Hz at a gradient of

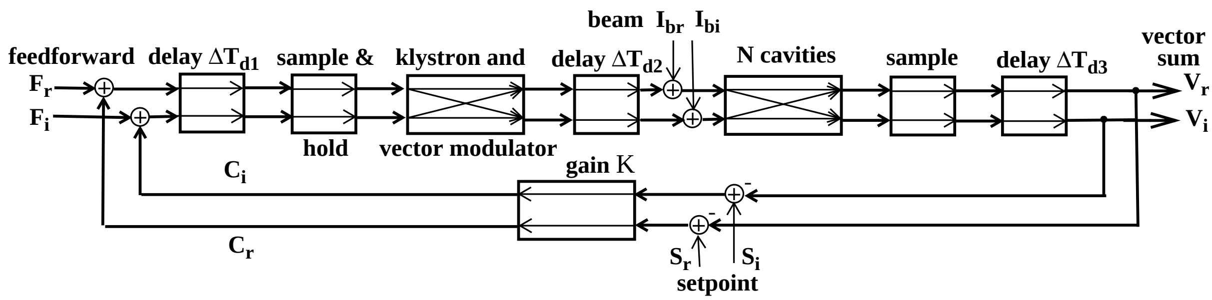

Figure 1: Schematic block diagram of the closed loop system of the TTF RF control

25 MV/m. Both errors have to be compared to the cavity bandwidth of 200 Hz (HWHM). The steady state beam loading at 8 mA beam current is equal to the accelerating gradient. The klystron power and phase fluctuates as a function of (slow) line voltage variations with a typical magnitude of 1% for power and 4 degrees in phase.

5 SYSTEM IDENTIFICATION

5.1 RF SYSTEM MODEL

The closed loop system consists of the vector-modulator, the klystron, the cavities, the feedback controller, and various delays which are dominated by computational delay as shown in figure 1.

The dynamics of the closed loop system are dominated by the low frequency poles of the rf cavity which can be described by the state space equation:

$$\begin{bmatrix} \dot{v}_r(t) \\ \dot{v}_i(t) \end{bmatrix} = \begin{bmatrix} -\omega_{1/2} & -\Delta\omega(t) \\ \Delta\omega(t) & -\omega_{1/2} \end{bmatrix} \cdot \begin{bmatrix} v_r(t) \\ v_i(t) \end{bmatrix} + \frac{R\omega_{rf}}{2Q} \cdot \begin{bmatrix} \frac{1}{m} I_{gr}(t) + I_{br}(t) \\ \frac{1}{m} I_{gi}(t) + I_{bi}(t) \end{bmatrix} \quad (1)$$

where v_r, v_i, I_{br}, I_{bi}, I_{gr}, I_{gi} are the real and imaginary parts of the cavity voltage, beam current, and generator current respectively. The remaining parameters are the cavity detuning $\Delta\omega$, the cavity bandwidth $\omega_{1/2}$, the cavity shunt impedance $R=(r/Q)*Q_L$, and the rf frequency ω_{rf}. The Lorentz force will detune the cavity dynamically resulting in a time varying detuning $\Delta\omega(t)$.

The closed loop model of the time discrete system with delay can be obtained using standard techniques as described in various textbooks on control theory [3]. It is given by equation 2, where V describes the cavity vector-sum voltage, F is the feedforward signal, S the cavity voltage setpoint, N the number of cavities, ΔT_s the sampling period, K the feedback gain, $g_a,...,g_d$ the gain of klystron and vector modulator, $k_{dm}=\Delta T_{d3}/\Delta T_s$, and $k_{dg}=(\Delta T_{d1}+\Delta T_{d2})/\Delta T_s$. The indices r and i denote real and imaginary part of the relevant quantity.

The parameters of the closed loop state space model described by equation 2 can be determined from a step response at the desired operating point. For this purpose a step function is applied as feedforward signal. The system response to the single step is measured and the model parameters are calculated. Based on the model it is now possible to calculate the change of feedforward table ΔF which is required to achieve a given state response ΔV, see equation 3.

5.2 SYSTEM REPONSE MATRIX

Another approach to describe the closed loop system with respect to feedforward input is the system response matrix [3]. This approach employs a set of step functions instead of the single step that can be used for system identification. The result is a feedforward system-response matrix which allows to identify a time varying system even if a parameterized model is not available. The inversion of the response matrix allows calculation of the feedforward δf which is necessary to achieve a given state response ΔV:

$$\begin{bmatrix} \delta f_{r1} \\ \dots \\ \delta f_{rn} \\ \delta f_{i1} \\ \dots \\ \delta f_{in} \end{bmatrix} = \mathrm{R}^{-1} \cdot \begin{bmatrix} \Delta V_{r1} \\ \dots \\ \Delta V_{rn} \\ \Delta V_{i1} \\ \dots \\ \Delta V_{in} \end{bmatrix} \quad (4)$$

where:

$$\Delta F_{*k} = \sum_{j=1}^{k} \delta f_{*j} . \quad (5)$$

The method is computationally more intensive than the system identification with a single step described before.

6 PRINCIPLE OF ADAPTIVE FEEDFORWARD

As mentioned before the feedforward system will eliminate only repetitive errors. In practise however stochastic errors will be superimposed and require averaging methods for sufficiently precise measurement of the predictable perturbations. Repetitive perturbations as well as the plant model may however vary slowly as function of time and may require a continuous update of feedforward table and model. It is therefore desirable to measure the step responses continually to maintain a current system model. The step size should be small to prevent excessive perturbations of

Equation 2:

$$\begin{bmatrix} V_r \\ V_i \end{bmatrix}_{k+k_{dm}+1} = \begin{bmatrix} 1-\omega_{1/2}\Delta T_S & -\Delta\omega\Delta T_S \\ \Delta\omega\Delta T_S & 1-\omega_{1/2}\Delta T_S \end{bmatrix}_{k+k_{dm}} \cdot \begin{bmatrix} V_r \\ V_i \end{bmatrix}_{k+k_{dm}} + \frac{R\omega_{rf}\Delta T_S}{2Q} N \cdot \begin{bmatrix} I_{br} \\ I_{bi} \end{bmatrix}_k + \frac{R\omega_{rf}\Delta T_S}{2Q} \begin{bmatrix} \frac{\sqrt{N}}{m} g_a(t) & \frac{\sqrt{N}}{m} g_b(t) \\ \frac{\sqrt{N}}{m} g_c(t) & \frac{\sqrt{N}}{m} g_d(t) \end{bmatrix}_{k-k_{dg}} \cdot \left(\begin{bmatrix} F_r \\ F_i \end{bmatrix} + \mathrm{K} \begin{bmatrix} S_r - V_r \\ S_i - V_i \end{bmatrix} \right)_{k-k_{dg}}$$

Equation 3:

$$\begin{bmatrix} \Delta F_r \\ \Delta F_i \end{bmatrix}_{k-k_{dg}} = \left(\mathrm{K} \begin{bmatrix} \Delta V_r \\ \Delta V_i \end{bmatrix} \right)_{k-k_{dg}} + \frac{2Q}{R\omega_{rf}\Delta T_S} \cdot \begin{bmatrix} \frac{\sqrt{N}}{m} g_a(t) & \frac{\sqrt{N}}{m} g_b(t) \\ \frac{\sqrt{N}}{m} g_c(t) & \frac{\sqrt{N}}{m} g_d(t) \end{bmatrix}_{k-k_{dg}}^{-1} \cdot \left(\begin{bmatrix} \Delta V_r \\ \Delta V_i \end{bmatrix}_{k+k_{dm}+1} - \begin{bmatrix} 1-\omega_{1/2}\Delta T_S & -\Delta\omega\Delta T_S \\ \Delta\omega\Delta T_S & 1-\omega_{1/2}\Delta T_S \end{bmatrix}_{k+k_{dm}} \cdot \begin{bmatrix} \Delta V_r \\ \Delta V_i \end{bmatrix}_{k+k_{dm}} \right)$$

the state but sufficiently large to allow for an acceptable signal to noise ratio. A flow diagram of the adaptive feedforward algorithm as implemented at the TTF is shown in figure 2.

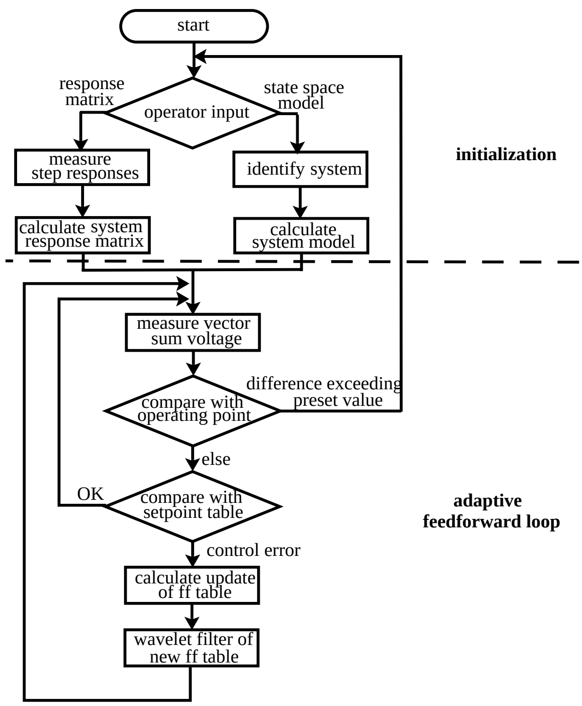

Figure 2: Flow diagram of the adaptive feedforward

7 PERFORMANCE OF THE ADAPTIVE FEEDFORWARD

The adaptive feedforward scheme for the digital rf control system at the TESLA Test Facility has been implemented in a very early stage of the project. A comparison of the residual amplitude and phase errors without and with adaptive feedforward show a significant improvement (approximately a factor of 10) in system performance which is reflected in the low energy spread of the beam. The rf field stability is considerably better than required as can be seen in figure 3.

8 CONCLUSION

Initial tests have demonstrated that by application of the adaptive feedforward control in addition to the feed back control the required field stability is exceeded by a substantial factor. The adaptive feedforward control proved to be an effective way of compensating the repetitive part of the perturbations. The delay in the system and its nonlinearity can be handled by the adaptive feedforward via linearization at a chosen operating point.

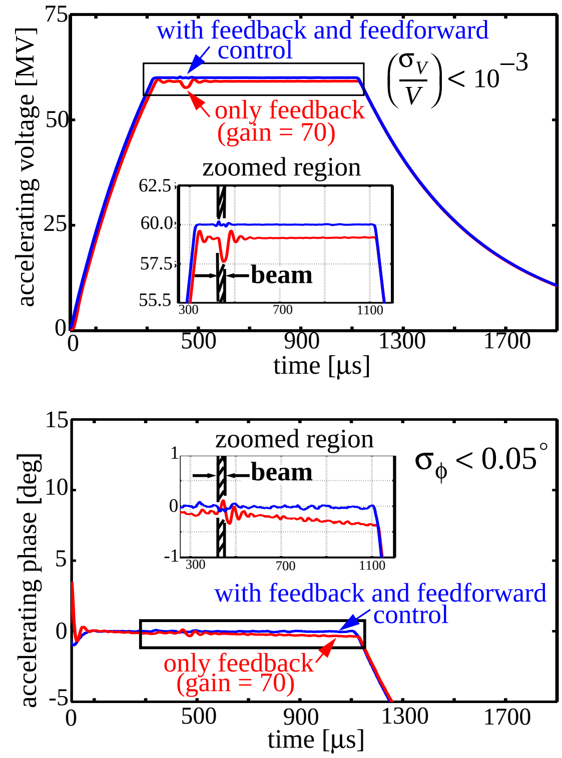

Figure 3: RF control system performance without and with adaptive feedforward.

9 ACKNOWLEDGEMENTS

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