TIME DELAY COMPENSATION FOR THE DIGITAL RF CONTROL AT THE TESLA TEST FACILITY

H. Imsieke, A. Kholodnyi, S.N. Simrock, DESY
Notkestr. 85, D-22603 Hamburg, Germany

Abstract

Time delays or dead times between inputs and outputs are an inherent characteristic of digital feedback systems. The time delay limits the maximum allowable gain required for system stability. Modern control theory provides a scheme called Smith predictor which has the potential to improve control performance significantly. The method is based on model internal control which works well if the dynamics of the plant are slow compared to the time delay. In this paper we analyze the performance improvement that can be achieved in the TTF rf control system where the time delay is dominated by computational delay. In this system the time delay of 4 microseconds and sampling period of 1 microsecond are short compared to the cavity time constant of 700 microseconds. Attention is paid to both theoretical and practical aspects.

1 INTRODUCTION

The cavities in the TESLA Test Facility are operated in pulsed mode at gradients of up to 25 MV/m with each klystron driving multiple cavities. Significant Lorentz force detuning and control of the vector-sum are the main issues for the low level rf controls. A digital feedback system has been developed [1] to provide flexibility in the control algorithms, precise calibration of the vector-sum, and extensive diagnostics and exception handling. The main features are a sampling rate of 1 MHz for the individual cavity signals, digital in-phase and quadrature detection, calculation of the vector-sum which includes gradient calibration and the correction of phase offsets, and feedback algorithm.

The presently implemented version of the feedback employs a proportional controller and has demonstrated excellent performance [2] especially in combination with the adaptive feed forward [3]. Due to the large time delay of 4 microseconds in the feedback loop the loop becomes unstable at gains exceeding 40 dB. The need for a high gain to maximize error suppression results in a small range of usable gains. Therefore a compensation of the loop delay appears to be attractive since it could improve the robustness and possibly increase the performance of the feedback loops.

2 TIME DELAY

The time delay in the feedback loop is given by:

- 500 ns conversion time of the 14 bit, 2 MHz ADC
- 200 ns writing to the comm-port of the TMS320C40
- 1000 ns multiplication with rotation matrix for individual field calibration and calculation of the vector-sum
- 200 ns writing to next comm-port of C40
- 1000 ns for the feedback algorithm (subtract setpoint, multiply with gain table, and add feedforward)
- 200 ns to write to the DAC
- 200 ns delay in the klystron
- 800 ns cable delay

The sum of the delays is about 4 µs. The implementation of the Smith-Predictor and Kalman filter might add up to 2 µs to the total delay. Time delay increases the phase shift between input and output signals and thus limits the maximum allowable gain. The system becomes unstable if the loop gain exceeds unity gain while the phase exhibits 180 deg. The phase shift due to delay is proportional to the frequency and is 180 deg. at 125 kHz for a delay of 4 µs. The phase margin of the rf system with a loop gain of 40 dB, and the cavity pole (first order) at 200 Hz is approximately 60 degrees at the unity gain frequency of 20 kHz.

3 SMITH PREDICTOR STRUCTURE

In 1957 O.J. Smith presented a control scheme to predict the reaction of a plant P to the output of a controller C thereby providing the potential of improving the control loops with delay (Figure 1).

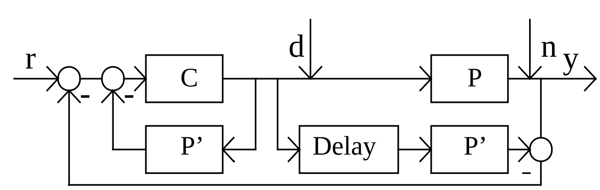

Figure 1: Smith Predictor structure

The total delay time in the feedback loop can be ascribed to the plant. P' is the model of the plant without delay time, r is the setpoint, y the output, d disturbances in and before the cavity and n measurement noise. With exact model matching and no disturbances or noise, the controller would only get signals from the model and the delay would be removed from the control loop as shown in Figure 2. The outer feedback loop in Figure 1 accounts for uncertainties of the model and disturbances.

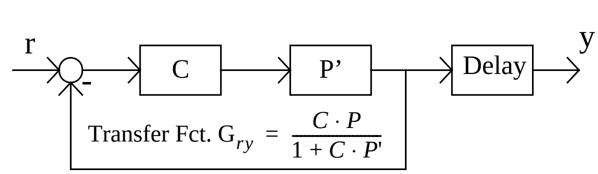

Figure 2: Desired Feedback with SP.

4 IMPLEMENTATION

The response of a single cavity to the beam current and the generator current can be described by two coupled first order differential equations for the envelope of the cavity voltage:

$$\begin{bmatrix} \dot{V}_{Re} \\ \dot{V}_{Im} \end{bmatrix} = \begin{bmatrix} -\omega_{1/2} & -\Delta\omega(t) \\ \Delta\omega(t) & -\omega_{1/2} \end{bmatrix} \begin{bmatrix} V_{Re} \\ V_{Im} \end{bmatrix} + \begin{bmatrix} R \cdot \omega_{1/2} & 0 \\ 0 & R \cdot \omega_{1/2} \end{bmatrix} \begin{bmatrix} I_{Re} \\ I_{Im} \end{bmatrix}$$

where V is the complex cavity voltage, I the complex current (generator + beam), $\omega_{1/2}$ (=π*operating frequency of 1.3 GHz/loaded quality factor ~3*10^6) the half width of resonance, $\Delta\omega$ the cavity detuning, and R the cavity shunt impedance.

A macropulse consists of cavity filling (500 µs), flat top with beam injection (800 µs), and field decay. The goal of the control system is to maintain a constant accelerating voltage during the flat top. The cavity is predetuned to minimize the power required to control the dynamic detuning which is a result of the Lorentz force. The cavity detuning should be zero in the middle of flat top. The cavity model used in the predictor should reflect the dynamics of the time varying Lorentz force detuning but has been omitted for simplicity. The field error resulting from such a simplification is comparable to the error caused by 1% quality factor or shunt impedance difference between model and plant (worst case: around 0.01%). The error caused by detuning is slowly changing and repetitive and can therefore be compensated by adaptive feedforward.

With a peak detuning of one bandwidth (realistic for 25 MV/m gradient) a step input on the real part of generator current would cause an error in the imaginary part of 7×10^{-4} after 1us. This crosstalk corresponds to a loop phase error of 0.04 deg. and can therefore be neglected.

The cavity is thus represented by a decoupled discrete State Space model with complex input and output vectors. The model parameters are calculated from the cavity bandwidth, which itself is calculated from the voltage decay time constant, and the cavity shunt impedance

$$V_{t+1} = (1 - (\omega_{1/2} \cdot T)) \cdot V_t + R \cdot \omega_{1/2} \cdot T \cdot I_t$$

where V and I stand for either real or imaginary component at time t. T is the sampling time of 1µs.

The model for multiple cavities can be obtained by superposition and can be approximated by that of a single cavity if the spread of the loaded quality factor is not too high. The spread should not exceed 25% to keep the model error below 3%. An improved model could consist of two cavities with different bandwidths. The model parameters are determined off-line.

The delay time can be adjusted in 1 µs steps by storing the control signal in memory and even in finer steps of 0.02 µs by selecting the time at which the 50 MHz DSP writes the data to the DAC. The delay is measured with a test program and then the program with correct DAC output time is written into the DSP. With model delay errors up to 0.1 µs, there's a decrease in maximum allowable gain off about 1% for every 0.01 µs mismatch.

5 PERFORMANCE

The performance of the rf system can be measured in terms of achieved field stability or disturbance rejection, the quality of setpoint tracking (important for fast varying setpoints as needed for FEL operation), and feedback loop stability which should be tolerant (or robust) with respect to parameter variations.

5.1 Stability

The maximum gain for stable operation is limited to 1400 (exactly two times the optimum gain, because overcorrection by more than 100% means instability) due to the 1 µs delay in the internal feedback loop.

While the bode plot without model uncertainties is easily interpreted due to the separation of the delay time, its meaning for the SP with parameter uncertainties is not easily understood. However since a numerical model analysis and the pole-zero map (obtained with a rational approximation of the closed loop SP transfer function) give similar results near the ideal case, stability margins were obtained with these methods. They show that realistic model mismatch of a few percent reduces the critical gain to ~1200.

If the klystron is operated close to saturation, its nonlinearity limits the maximum gain, so that it could be necessary to replace the actuator signal with the measured incident wave to the cavity. This scheme would also include time varying phase errors in the klystron and the vectormodulator. The measured klystron output would provide the correct control signal, thereby increasing stability and reducing sensitivity to klystron power fluctuations.

5.2 Setpoint Tracking

Figure 3 shows the response of the SP to a change of the setpoint. Operation with optimum gain will cause the cavity field to reach the desired setpoint in 1 µs time assuming availability of sufficient power from the klystron. If a beam current induces a voltage ΔV in steady state, the cavity field will change $\Delta V/700$ in 1 µs. The optimal gain for reference tracking is therefore around 700 which is well below critical gain.

5.3 Disturbance Rejection

The ability to suppress disturbances is not improved significantly by the smith predictor, as shown in Figure 4. The slow response to a beam induced perturabtion is due to the presence of the cavity poles in the transfer function from the disturbance to the output,

$$G_{dy} = P \cdot (1 - G_{ry}) .$$

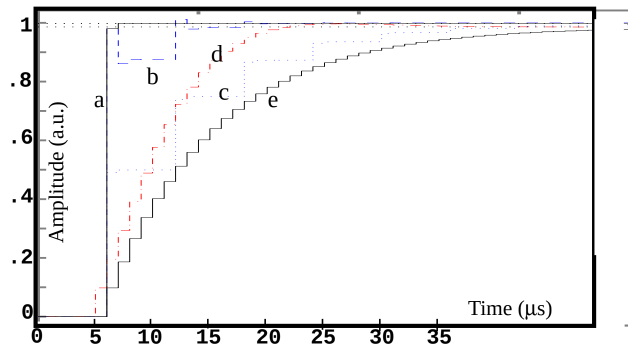

Figure 3: Step response of the transfer Function G_{ry} for a) optimal SP b) SP with 20% lower cavity quality factor c) SP with 50% gain decrease due to klystron nonlinearity d) normal feedback with gain of 70 e) SP with gain of 70.

The first term in the bracket is independent of the feedback gain. This means that the time constant of the error correction is not a function of the gain. It is however possible to modify the model and the controller so that the pole cancels with a zero of the transfer function [4] or to add the difference between cavity and model to the input of the model in order to adapt it to the disturbed cavity (a scheme called observer). Pole cancellation reduces the maximum allowable gain, is sensitive to parameter uncertainties, and slower than the latter method.

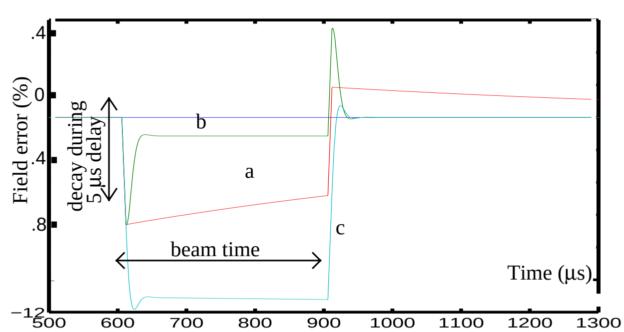

Figure 4: Reaction of the cavity field to a beam induced transient, a) optimal SP b) SP with Observer c) normal feedback.

Even with faster disturbance correction, the beam still causes a drop in the cavity field of 1/700 ~ 0.14 % per μs delay time in the feedback loop after injection. This can only be prevented by the use of feedforward. For the klystron noise, a faster disturbance rejection would have no influence. Errors caused by detuning would be reduced approximately by 50% on flat top with a gain of 700, but much better with an additional observer. The observer is useful against stochastical detuning by microphonics which cannot be suppressed by feedforward.

A controller with an integrator does not perform significantly better, and decreases stability margins due to phase advance.

6 FEEDFORWARD SCHEMES

Because the digital control system can measure the beam current in real time it can compensate it with a delay of about 1-2 μs. This scheme can reduce the beam induced transients considerably.

Another approach is the calculation of a feed forward table which is added to the control signal sent to the plant. This accounts for the absence of the beam in the model and microphonics influences. The feed forward table is repeatedly calculated from the difference between model and plant, with the error decreasing each step. In this way it also adapts itself to slowly changing system parameters. In contrast to this adaptive feed forward, a feed forward table needed to trace the setpoint optimally in the ideal case is calculated with model parameters and proportional gain and is added to both model and plant. This has to be updated only when these parameters are changed. Without Smith Predictor, there would be only one (adaptive) feed forward for all repetitive errors.

7 CONCLUSION

The main advantage of the Smith Predictor is faster setpoint tracking. With the existing feed forward, this workload is removed from the feedback with the exception of stochastic errors. These errors act almost exclusively in or before the plant, so the SP offers only little improvement. A major drawback is the amplification of measurement noise with higher gains, which has to be suppressed significantly. For this purpose a Kalman filter, which estimates the state of the plant in presence of klystron and measurement noise, is currently under development. The measurement is also disturbed by an offset in the rf mixer output which varies over the macropulse. This has to be cancelled out too to allow better performance than present feedback.

The klystron nonlinearity restricts the SP performance. The power margin could be too little for the desired high gains, and with equal gain, a standard feedback controller would outperform the SP. To assure stability the nonlinearity has to be known for the model calculations.

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