SYSTEM IDENTIFICATION FOR THE DIGITAL RF CONTROL SYSTEM AT THE TESLA TEST FACILITY

M. Hüning, RWTH Aachen, Germany, S.N. Simrock, DESY, Hamburg, Germany

Abstract

The rf control system for the TESLA Test Facility employs a digital feedback system to provide flexibility in the choice of feedback algorithms and extensive diagnostics for rf system operation and exception handling. The control algorithm makes use of the state space formalism where the state describes the real and imaginary part of the cavity voltage (vector of the accelerating field) and the cavity detuning. The cavity detuning – which is time dependent due to the dynamics of lorentz-force-detuning in a pulsed cavity – can not be measured directly. Knowledge about the time-varying cavity detuning and other rf system parameters such as beam phase are derived by application of system identification to the uncalibrated measured cavity field and incident and reflected wave. In this process the calibrations for incident and reflected wave are determined which includes compensation for the finite directivity of the directional couplers.

1 INTRODUCTION

With the advent of reasonably priced high speed data conversion devices and digital signal processors which combine tremendous computing power and I/O capability, the design of rf control circuits will assume a new direction. The concept of digital control provides enormous flexibility in the control algorithms, diagnostics, and exception handling. The concept of system identification provides the possibility to extract information about rf system relevant parameters from measured data. These measurements can be performed online and are transparent to linac operation.

The model of the cavity relating input power and beam current to the time varying voltage and phase of the accelerating field is well understood. The parameters in the differential equation governing the system dynamics can be determined from the measured data. With the knowledge of the system parameters it is possible to predict the time varying cavity detuning, the phase of the accelerating field relative to the beam, and the loaded quality factor. Based on the assumption of continuity of the rf-waves at the input coupler the amplitudes and phases of the incident and reflected waves can be calibrated. A combination of both, the differential equation and the condition of continuity yield the directivity of the directional couplers.

The question remains which parameterized model to choose for a correct description of the non-linear dynamics of the lorentz force detuning . With system identification one can compare different types of models to find the best description. Surprisingly a 1st order model of the mechanical dynamics of the cavity are qualitatively as good as a model of 2nd order. Better results can be achieved if the derivative of the field amplitude is included in the differential equation, but the physics behind this equation are not understood.

2 PRINCIPLE OF SYSTEM IDENTIFICATION

System identification allows to compare different models such as transfer functions or differential equations by fitting the coefficients to match the measured data. Transfer functions are suited for time invariant linear models. An example is the ARX model where the transfer function is a fraction of two polynomials, $H(z) = B(z)/A(z)$. The difference equation of the system is

$$y_{n+k} = a_0 y_n + \ldots + a_{k-1} y_{n+k-1} + b_0 u_n + \ldots + b_l u_{n+l},$$

where $a_0, \ldots, a_k$, $b_0, \ldots, b_l$ are the coefficients of $A(z)$ and $B(z)$. When describing y_{n+k} as function of $y_n, \ldots, y_{n+k-1}, u_n, \ldots, u_{n+l}$ one can perform a regression to determine the coefficients of $A(z)$ and $B(z)$. The noise is considered to modify only the last value y_{n+k}. For linear models there there exists a selection of models characterized by the order of $A(z)$ and $B(z)$ and in which way the noise is handled. One can test different models until the data is reproduced satisfactory. Of course this way of investigation is empirical and does not necessarily lead to a model in which the physics of the system is well understood.

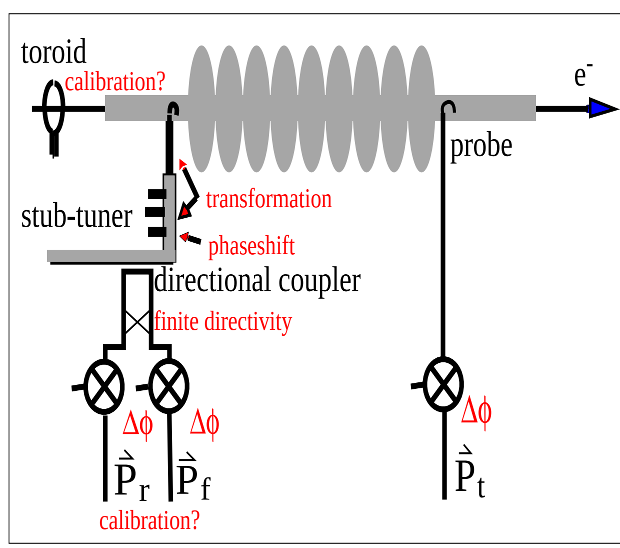

Figure 1: The signals for System Identification

The other approach is based on a parameterized model which is derived from knowledge about the physics of the system. This can be in the same format as the standard models, but one can also choose the differential equation as a description. For time dependent problems this may be the best solution. The algorithm for numerical differentiation of the raw data is critically important for the accuracy to which the parameters in the differential equation can be determined. At the TTF we fit through every data point a 2nd order polynom to the data next to this point. It's derivative is taken as the data's derivative at the specified point. There is no need for the full regression calculation at every point since most of the calculations are repeated for each point and therefore can be taken over. Discontinuities can be detected by comparison with adjacent polynomials. With this information the differential equation can be calculated – even for time varying systems if necessary.

3 MODEL FOR THE RF-CAVITY

Resonant modes in cavities can be described using resonant LCR circuits. For superconducting cavities the differential equation for the complex field envelope can be reduced to a first order equation

$$\begin{aligned}\dot{\hat{V}}_{acc} &= -\left(\omega_{1/2} - i\triangle\omega\right)\hat{V}_{acc} \\ &\quad + \frac{1}{2}\left(\frac{r}{Q}\right)\omega_0\left(2\hat{I}_f - I_b e^{i\psi_b}\right),\end{aligned}$$

with complex amplitudes $\hat{V}_{acc}$ and $\hat{I}_f$. The beam current I_b is real but has to be multiplied with a complex phase factor. It is the Fourier component of the pulsed beam at ω_0 and therefore $I_b = 2I_{b0}$, with I_{b0} the DC current. The normalized shunt impedance is $\left(\frac{r}{Q}\right) = 520\,\Omega$ for TESLA cavities, the bandwidth is $\omega_{1/2} = \frac{\omega_0}{2Q_L}$ with Q_L in the range of $2 \cdot 10^6 \ldots 3 \cdot 10^6$ for TTF.

Due to lorentz force detuning the cavity detuning is time dependent $\triangle\omega = \triangle\omega(t)$, which means that the differential equation is time dependent. Written in polar coordinates the complex differential equation splits up into two decoupled equations whose first depends on $\omega_{1/2}$ and second depends on $\triangle\omega$. The first one is time independent and can be used for calibration purposes. From the second equation one can calculate the detuning of the cavity at every time step of one microsecond at the TTF.

4 RESULTS

4.1 *Cavity Phase*

One of the most important properties of the rf field in the cavities is their phase with respect to the beam. It is desireable for the linac operation that there is the possibility to measure the phase whatever operational mode is active. In the cavity-equation the beam current is introduced as a complex vector. Once $\hat{V}_{acc}$ and $\hat{I}_f$ are calibrated correctly it is possible to extract ψ_b from the data.

Figure 2 shows histograms of some measurements of the beam phase taken in the first module of the TTF-linac. The measurements were taken during standard linac operation with feedback and feedforward applied. It shows that determination of the beam phase is possible with a σ of about $3°$. The measurements were taken when $\hat{V}_{acc}$ and $\hat{I}_f$ were consistent within each other but had some arbitrary phase offset. The right phase calibration can be achieved by correcting all measured phases in such a way that the centroid of the beam phase distributions become zero.

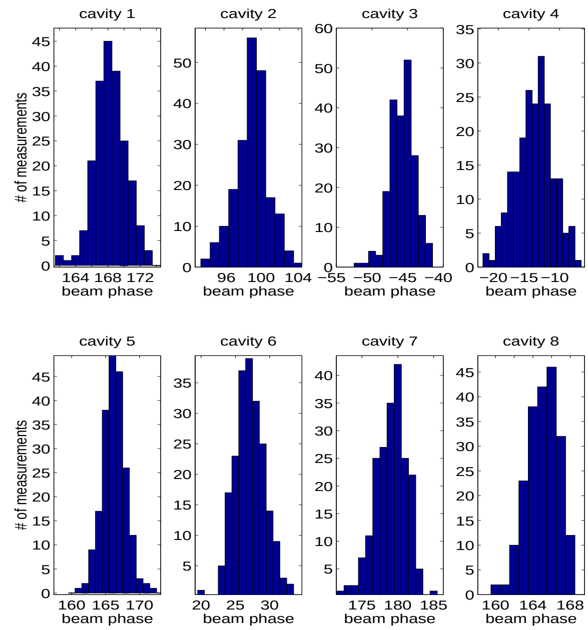

Figure 2: Measurements of the beam phase in the 8 cavities of the first TTF-module.

4.2 *Time varying Cavity Detuning and Q_L*

The TTF linac is operated in pulsed mode so that the cavities are dynamically detuned during every rf pulse. For optimization of the cavity tuning and as an input for sophisticated control algorithms like a smith-predictor it is necessary to know the time dependent detuning of the cavities. Starting about $50\mu s$ after beginning of the rf pulse where the gradient exceeds about 1MV/m it is possible to determine the detuning of each cavity. The main noise sources are the fluctuations of the numerical derivative and noise on the forward power.

Several models have been compared to describe the detuning curves. Reasonable results have been achieved with differential equations of 1st and 2nd order taking $|V_{acc}|^2$ as an input and $\triangle\omega$ as output. The best reproduction of the measured data could be accomplished with a model of first order when including $d|V_{acc}|^2/dt$ as input.

4.3 *Calibration of Directional Couplers*

The quality of the data extracted from the system identification strongly depends on the accuracy of the calibration of the forward power signal. Due to the finite directivity of the directional couplers there is always some crosstalk

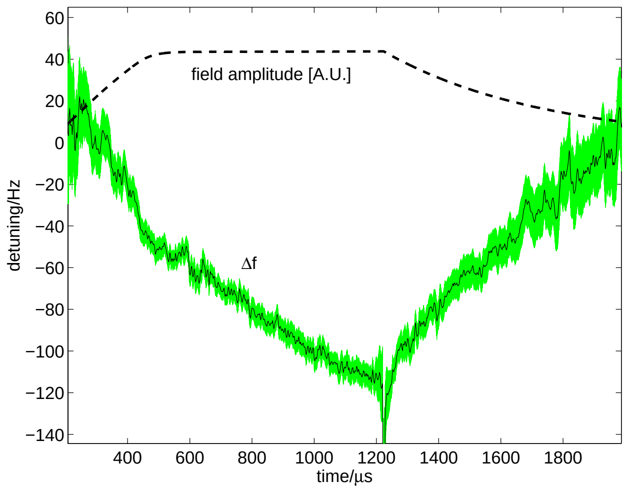

Figure 3: Time varying detuning of cavity D1 at 15 MV/m including one standard deviation of the error. For reference the field amplitude has been added to the plot.

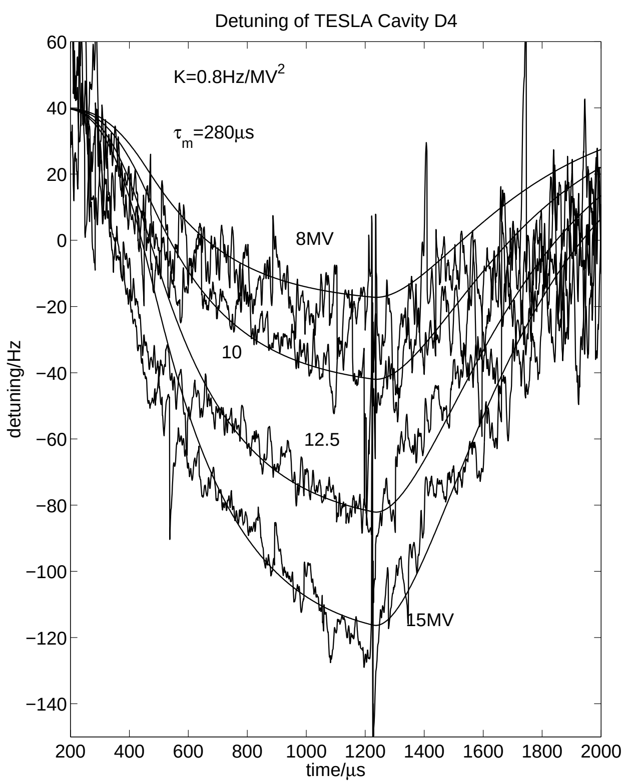

Figure 4: Detuning of cavity D4 at four different gradients. A model of first order has been adapted to the data of the strongest detuning. With this model the detuning has been simulated for all four gradients.

between the signal of the forward power and the reflected power. The reflected power signal can be eliminated from the measured forward power by subtracting $\hat{d}_r \hat{I}_r$ from $\hat{I}_f$ with $\hat{d}_f$ such that $\hat{I}_f \equiv 0$ during the field decay. From

$$\hat{V}_{acc} = R_L(f_f \hat{I}_f + f_r \hat{I}_r)$$

one finds an amplitude and phase calibration for the incident and reflected wave. As long as the reflected power is not corrected for the directivity this calibration will be wrong. From the condition $\omega_{1/2} = const$ one finds the correct calibration for $\hat{I}_f$. The comparison of both calibrations delivers the second correction factor for the directivity.

5 CONCLUSION

The methods of system identification have been applied to the digital rf feedback system at the TESLA Test Facility. Knowing the cavity model - which can be described as a time varying state space model - one can determine rf system parameters such as beam phase, time varying cavity detuning, phases of incident waves and many more by the measurement of the uncalibrated cavity probe, incident wave and refleced wave systems. The knowledge of these parameters has been critically important during the commissioning of the rf system and will be used in the future to automate most of the rf operation relevant procedures.

6 ACKNOWLEDGEMENTS

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7 REFERENCES

[1] M. Hüning: “Selbstoptimierende Parametersteuerung der Hochfrequenz des supraleitenden Linearbeschleunigers TESLA Test Facility”, PITHA 98/7, RWTH Aachen