DEAD BEAT FILLING AND FEEDFORWARD RF CONTROL FOR THE SPALLATION NEUTRON SOURCE SNQ

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Summary

For the 1.1GeV-100 mA Spallation Neutron Source SNQ[1] operation costs and beam losses ask for the possible potential of rf control improvements. Two novel methods are investigated.

First, in order to increase the overall rf efficiency[2], the cavity field is built up as fast as possible in the open loop state of feedback control and in detuned position of the cavity in such a manner that the cavity with beam is matched to the generator. It is shown that this requires the simultaneous application of a generator amplitude and a generator phase step.

Secondly, a feedforward control system is proposed, which reduces the amplitude and phase control error caused by an arbitrary beam transient into the limits of ± 0.1 % and ± 0.1° and maintains these error limits also in the presence of parameter drift. This is done by an adaptive parameter adjustment procedure using a digital model of the control system. The system structure and a promising digital simulation are discussed.

Equivalent circuit

The well-known rf equivalent circuit of a beam loaded cavity[3] in figure 1 a is transformed for the general case of detuning to a dynamic equivalent circuit in figure 1 b for the complex amplitude (amplitude and phase), which is useful for control applications. Figure 1 b represents a sufficiently good approximation for high Q-values under the assumption: $G_i Z_L = 1$ and $l = n \cdot \lambda/2$. The detuning is $\Delta\omega = \omega - 1/\sqrt{LC}$, β is the coupling factor and b the beam loading factor defined as ratio of the real beam power to the cavity losses. Because of the particle phase shift ϕ_s the beam admittance is complex. The decay time of the unloaded cavity is given by $T_0 = 2\ C/G$.

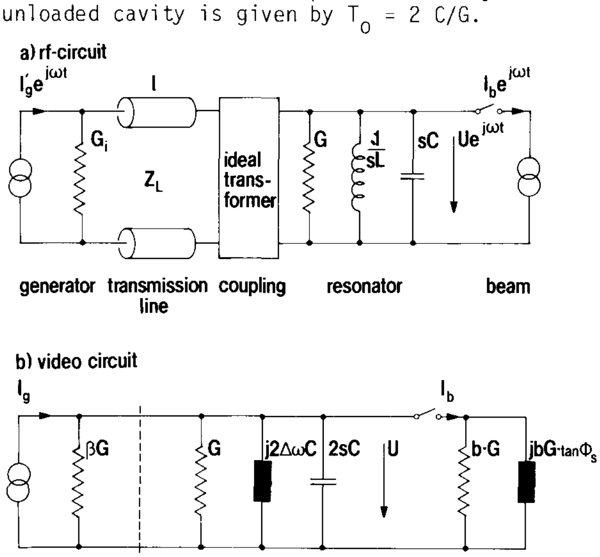


Fig. 1: Equivalent circuits of the beam loaded cavity

The condition of power matching of the generator admittance $\beta \cdot G$ to the beam loaded cavity admittance leads to the equations:

$$\beta = 1 + b \quad (1)$$

$$2\Delta\omega C = -\ bG \cdot \tan\phi_s \quad (2)$$

With the decay time of the loaded cavity $T_L = T_0/(1+\beta)$ it is convenient to express the detuning by the transmission phase Θ:

$$\tan\Theta = -\ \Delta\omega \cdot T_L = b/(b+2) \cdot \tan\phi_s \quad (3)$$

It is obvious, that the generator amplitude $|Ig_0|$, which produces the field level $|U|$ in the beam loaded case is larger than $|Ig_1|$, which is necessary to generate the same field level without beam.

Using the admittance ratio and the formulas above we obtain:

$$|Ig_0/Ig_1| = 2\ (b+1)/(b+2) \cdot \cos\Theta \quad (4)$$

Exactly this generator amplitude margin can be used to shorten the filling time of the cavity.

Dead beat filling

Unlike in the resonance case, in the detuned cavity adjustment the forced and the eigensolution have different frequencies. Therefore, a frequency beat occurs and no steady state can be obtained at $t < \infty$. Is it possible to cancel this beat? From figure 1 b one can conclude that the step response of the first order differential equation with complex coefficients must be an exponential function with complex argument:

$$U(t) = U_0\ (1 - \exp(-\ t/T_L\ (1 - j\ \tan\Theta))) \quad (5)$$

A typical step response is plotted in figure 2 a. At the time T_F - the filling time - the generator amplitude is switched from $|Ig_0|$ to $|Ig_1|$ and no parameter combination can be found, which makes the steady state at T_F possible. But, if one adds a certain generator phase step simultaneous to the amplitude step, again like in the resonance case (shown in figure 2 c for comparison) the steady state can be reached at T_F as it is illustrated by figure 2 b.

Applying the theory of "dead beat response" the following condition holds:

$$Ig_0/Ig_1 = 1/(1 - \exp(-\ T_F/T_L\ (1 - j\ \tan\Theta))) \quad (6)$$

The phase angle of Ig_0/Ig_1 is the phase step $\Delta\phi$ in figure 2 b:

$$\Delta\phi = \measuredangle\,(Ig_0/Ig_1) \quad (7)$$

For a given amplitude margin Ig_0/Ig_1, which depends on the beam loading factor, there is only one possible value for the filling time T_F and the phase step $\Delta\phi$, which fulfill the dead beat condition.

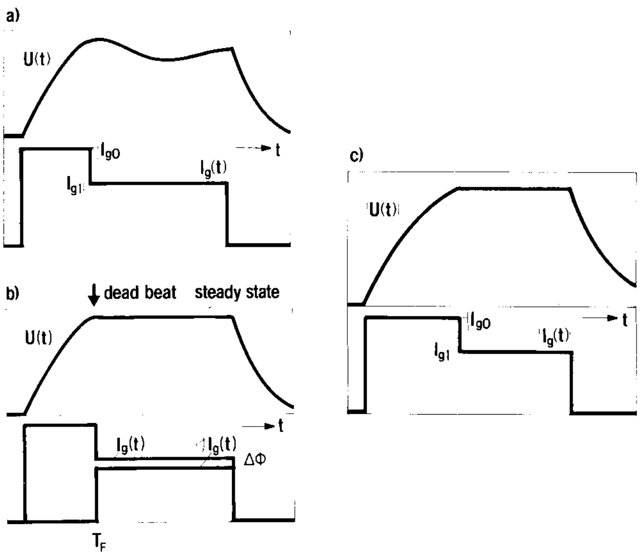


Fig. 2: Cavity amplitude response to a generator step excitation
a: detuned - amplitude step only
b: detuned - amplitude and phase step
c: resonant

In figure 3 the quantitative relations between filling time, amplitude and phase step and beam loading factor are plotted for a synchronous phase ϕ_S = - 30°. The maximum possible phase step occurs at high beam loading and reaches about 2/3 of the synchronous phase ϕ_S.

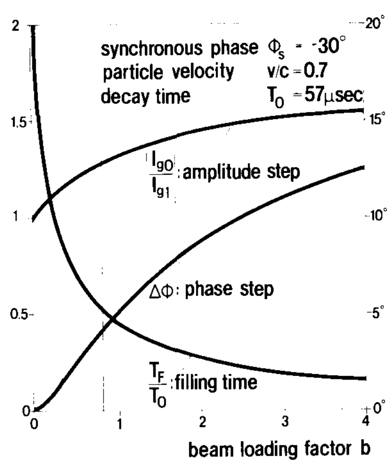


Fig. 3: Phase step, amplitude step and filling time vs beam loading factor b

Typical parameters for the SNQ disk-and-washer structure at v/c = 0.7 and ϕ = - 30° are
b = 0.8, T_0 = 57 µsec, T_F = 30 µsec, $|I_{g0}/I_{g1}|$ = 1.27 and $\Delta\phi$ = 4 degrees[5].

Up to now we have considered the cavity in the open loop state of the feedback system. Before the beam enters the cavity the amplitude and phase feedback loops have to be closed, which might cause a minor transient because of misadjustment. Therefore, in practice the total time consumption from rf turn-on is somewhat larger than the calculated filling time.

It should finally be mentioned, that the generator impedance differs from the line impedance Z_L and there might be reasons to choose the line length $l \neq n \cdot \lambda/2$. This more general case can also be treated with the dead beat response method presented above. The necessary phase and amplitude step will depend then on G_i and l, but no fundamental change of the results are expected.

Feedforward control (FFC)

It is state of the art in proton linear accelerators with heavy beam loading to support the amplitude and phase feedback loops[6,7,8] by a feedforward signal derived from the beam[9].

Our concept is based on the assumption of the most severe beam transient, a step function. If the field error in this case can be tolerated, the control system would be even more efficient for all other real beam transients. The feedforward pulse shape can only be a step function, which is simply generated by a pulse generator and is fed to the amplitude/phase modulator. Because the FFC pulse rise time is increased afterwards by the power transmitter, a complete compensation of the transient beam loading is not possible.

A computer simulation for the SNQ amplitude/phase control loop with a PID controller results in a maximum dynamic cavity amplitude error of - 2.5 %,[1,5] if only feedback is used. A reduction to 0.6 % can be obtained, if a FFC pulse with proper amplitude is fed synchronous to the beam pulse into the modulator. This case is illustrated by the lower curve in figure 4.

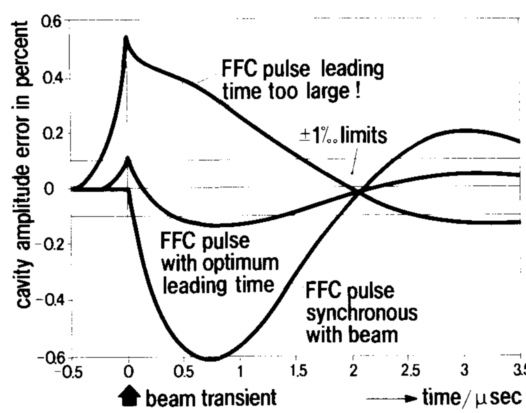


Fig. 4: Computer simulation of the dynamic amplitude control error caused by a beam transient for different delay time of the feedforward (FFC) pulse

A further drastic reduction can be obtained, if the FFC pulse and thereby the klystron power is raised before the beam enters the cavity. At an optimum leading time of 0.25 µsec the resulting error is within the desired ± 0.1 % limits (figure 4: middle curve). If the leading time becomes too large, again the error is increasing (upper curve).

The ± 0.1 % error limits discussed above are achieved in the LAMPF accelerator by slowing down the beam transient.

These digital simulation results had been confirmed also by an analog model of the feedback loop[11].

The simulation proves that the combined use of feedback and feedforward stabilizes the rf field sufficiently against the expected beam disturbances. Figure 4 shows on the other hand the large sensitivity of the error on the delay time. A drift of less than 100 nsec causes the error to increase by a factor of 2. Therefore, an absolute condition for an improved feedforward control is the elimination of parameter drift by an automatic adjustment procedure.

Adaptive parameter adjustment

The proposed adjustment procedure is based on two technical developments, the availability of fast transient recorders with sufficient resolution and low cost digital processors.

The solution is outlined in figure 5. The control signal sample is picked up from the "real world" by a transient recorder. The equivalent signal calculated by the computer model of the control system is changed by means of a multidimensional parameter optimization as long as it fits well enough to the real signal.

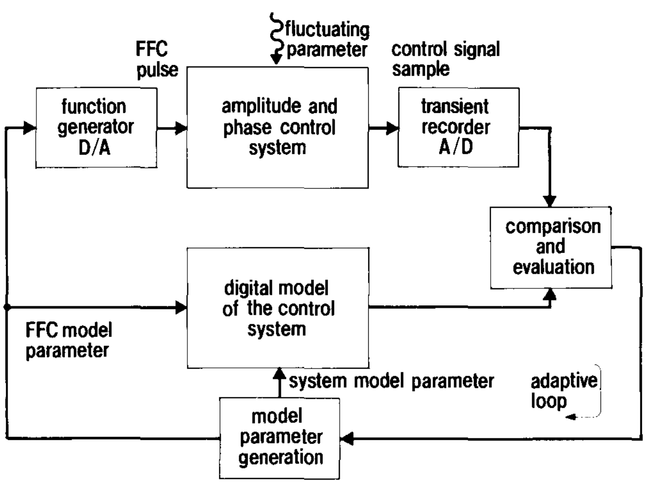


Fig. 5: Block diagram of the adaptive parameter adjustment procedure

This new parameter set is used either for correction of the FFC pulse generator (delay and amplitude) or for marginal checking (loop gain and stability etc.), if control loop parameters had been changed. The advantage of this scheme is that only one sample of the "real world" is necessary and the adaption takes place completely in the "computer world". Obviously, the quality of the adaption depends on the quality of the computer model, the digital simulation.

Digital simulation

The digital simulation must represent sufficiently the dynamic structure of the control loop, which is here approximately an 8th order system with delay. The execution time of one simulation cycle determines the number of periodic beam bunches, which pass the cavity until the parameter correction takes place. This last requirement favors direct methods against such transformation methods as Fast Fourier Transformation (FFT) or the State Space Transformation or the timewasting method of convolution integrals.

The most appropriate direct method seems to be the transfer of the differential equation system into an approximate system of difference equations that are solved successively. In addition, with this method the time delay can be treated exactly.

In figure 6 a the normalized representation of a Nth order dynamic system with delay and feedback is shown in Laplace notation, where the integration operator occurs as 1/s.

The nominator coefficients a_k and the denominator coefficients b_k are easily obtained from the time constants of control plant and the PID controller.

There are several well-known approximations of the integration operator[12], which can be expressed in terms of the z-transform as follows:

$$\frac{1}{s} \simeq h_m \left(\frac{1 + P_m(z)}{1 - z^{-m}}\right) \quad (8)$$

with the definition of the z-transform $z = \exp(-T \cdot s)$, T is the sample time and m the order of approximation. For explanation of (8) two examples are given: m = 1 the trapezoidal rule with $P_m(z) = z^{-1}$ and $h_m = T/2$, m = 2 the Simpson rule with $P_m(z) = 4z^{-1} + z^{-2}$ and $h_m = T/3$.

In order to get a successively solvable system of difference equations, the system of figure 6 a under use of equation (8) must be reorganized in such a way, that the state variable $X_{N-1}(z)$ depends only on the other state variables of one step before present time. This is performed by the coefficient transformation[13]:

$$c_k = \sum_{i=0}^{K} h_m^{k-i} \cdot a_i \; ; \; 0 \leq k \leq N \quad (9)$$

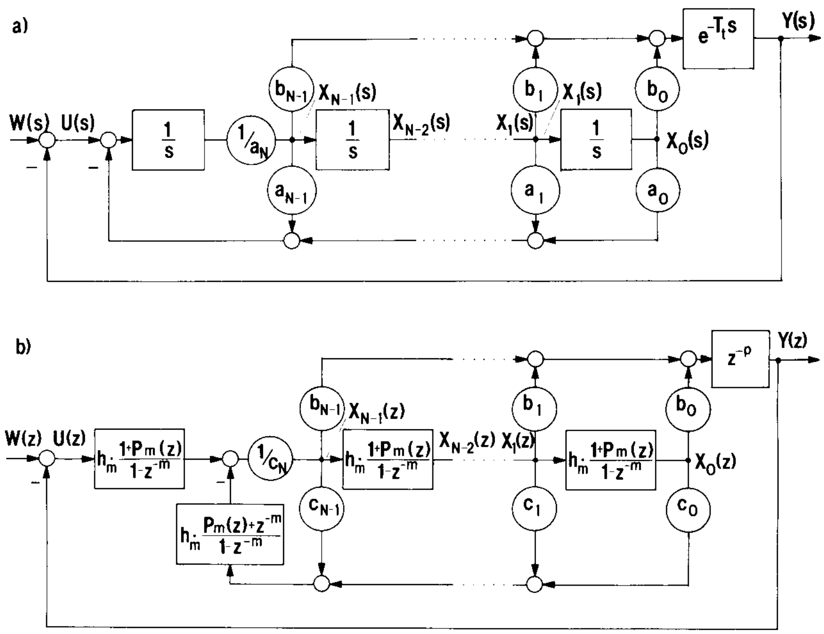
With the condition, that the delay time T_t is a multiple of the sample time:

$$T_t = p \cdot T \; ; \quad p \geq 1 \quad (10)$$

We obtain the solvable system of difference equations in figure 6 b.

If this program structure is compared with the FFT, it should not be difficult to develop a digital processor like the FFT processor. If a typical 5 µsec transient (error or control sample) is sampled with a 10 MHz transient recorder, we have typical 50 sample points. It is estimated, that the execution time of the digital processor for these 50 sample points could be less than 0.5 msec (FFT processors with 1024 sample points have an execution time of 5 msec[14]). That means, in the interval between two SNQ beam pulses (100 Hz repetition rate) about 20 transients with different parameter sets can be calculated. This should be sufficient, if only one or two fluctuating parameters have to be tracked in the practical accelerator operation. If more parameters have to be tracked or if the parameter deviation between two samples is large (i.e. at first turn-on of the adaptive loop) the time consumption may increase considerably, but the total adaption time should be less than 1 sec.

The simulation method in figure 6 b had been tested with the closed loop response of the SNQ feedback



a) Differential equation system in Laplace representation

b) Approximate difference equation system expressed by the z-transform

Fig. 6: Nth order dynamic system with delay and feedback

system. As a next step the digital simulation will be implemented in the adaptive adjustment loop.

Acknowledgement

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