Overview of LLRF Control Algorithms
with Emphasis in Beam Dynamics and Simulations

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Outline

Outline

Introduction

LLRF Systems in Beam Accelerator Facilities

- Feedback systems around the RF station
  - Impedance Control, RF cavity field control
  - Low-Order mode Longitudinal control,
  - Impact on Longitudinal beam dilution in hadron machines, etc.
- Auxiliary control systems
  - RF cavity tuner,
  - Microphonic control,
  - Lorentz force detuning control
  - Orbit Control
  - Klystron bias control, etc.
- Slow controls
  - Cavity Temperature control
  - RF station turn ON/OFF system, etc.

Introduction

Why control systems??

- Unstable Systems need feedback loops to became stable and operate
- Stable systems Provide satisfactory performance in the face of system variations, system limitations and uncertaintains.
- Feedback is only required for stable system when system performance cannot be achieved because of uncertainty in system characteristics.
- Prefiltering input signals (open loop control) can change the dynamic response of the system but cannot reduce the effect of system uncertainties.
  - Mere assumption of a feedback structure does not guarantee a reduction of uncertainty. There are many obstacles to achieve uncertainty-reducing benefits.
  - Feedback design problems centers around the tradeoff involved in reducing the overal impact of uncertainties.

Outline

Topology

Global Operation

Can we talk about system stabilty?, Yes

Can we prove 'the system stability'?, Well, ...depends,... what do you mean?, global stability??

Let us consider the finite dimension system modeled by

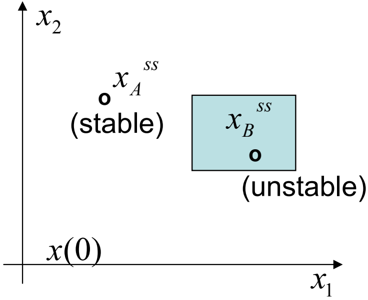
$$\begin{aligned} \dot{x} &= g(t, x(t), u(t)) \\ y(t) &= c(t, x(t), u(t)) \end{aligned}$$

We want to design a control law $u(t) = k(t, x(t), r(t))$, such that the composite system

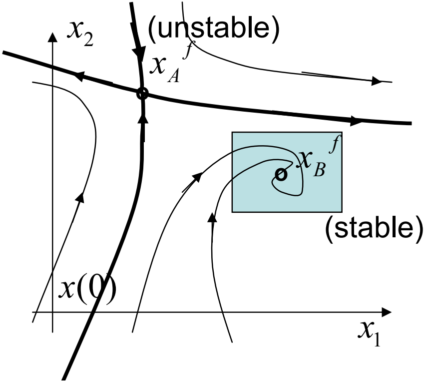
$$\begin{aligned} \dot{x} &= g(t, x(t), k(t, x(t), r(t))) = f(t, x(t), r(t)) \\ y(t) &= c(t, x(t), k(t, x(t), r(t))) = h(t, x(t), r(t)) \end{aligned}$$

is stable and achieves the specified performance for given uncertainties in g, c, k. The set of uncertainties and specifications can be such that the problem has not feasible solution.

Topology



The open loop system $\dot{x} = g(t, x, u)$ has equilibrium points x_A^{ss} and x_B^{ss} ($\dot{x} = g(t, x, u) = 0, \ u = const.$) The system must operate around $x_B^{ss} \rightarrow$ unstable, then feedback.



The closed loop system $\dot{x} = f(t, x, r)$ has now the equilibrium points x_A^f and x_B^f ($\dot{x} = f(t, x, r) = 0, \ r = const.$)
The system now is locally stable around x_B^{ss}.
Feedback can modify region of attraction.

Global Operation

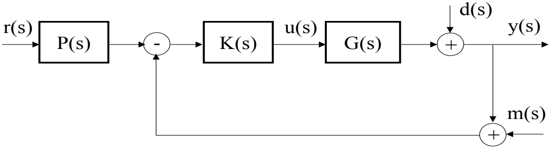
Remarks

- Controllers (LLRF) have to be able to provide 'Global Convergence' of the system toward the operation point.
- Have to be able to define a region of attaction compatible with the transient signal perturbations affecting the system.
- Controller parameters have impact in the region of attraction
- In general, system specifications tend to define the performance of the system around the operation point.
- System performance is affected by uncertainties and perturbations, feedback systems are used to improve the performance around operation point.
- Locally, around the operation point, the system can be linearized to analyze and quantify the performance.

Outline

Signal Uncertainties, Perturbations

Based on the standard feedback configuration



$$
\begin{aligned}
y(s) &= d(s) + G(s)K(s)[P(s)r(s) - m(s) - y(s)] \\
y(s) &= S(s)d(s) + G_c(s)r(s) - T(s)m(s) \qquad \textit{with}
\end{aligned}
$$

$$
S(s) = \frac{1}{(1 + G(s)K(s))}, \qquad T(s) = S(s)G(s)K(s) \qquad G_c(s) = T(s)P(s)
$$

- $S(s)$, $T(s)$ are not independent, $S(s) + T(s) = 1$.
- There is an unavoidable trade-off between attenuating disturbances and filtering out measurement errors.
- These relations defined for Single Input - Single Output (SISO) systems can be extended to Multi Input - Multi Output (MIMO) systems.

Approach to Design: Open Loop Shaping

- Conflict between keeping both $T(s)$ and $S(s)$ small is solved by making one small at some frequencies and the other small in other range.
- Usually the spectra of reference signals and disturbances are concentrated at low frequencies, while the spectrum of measurements errors extends over much wider range.

$$\begin{aligned} \|S(j\omega)\| &< \alpha << 1 \qquad \textit{for} \;\; 0 \leq \omega \leq \omega_l \\ \|T(j\omega)\| &< \beta << 1 \qquad \textit{for} \;\; \omega \geq \omega_h \end{aligned}$$

- Combining this closed loop boundaries with stability conditions, the conditions for the open loop transfer function can be

$$\begin{aligned} \|G(j\omega)K(j\omega)\| &> L >> 1, \qquad \textit{for} \;\; 0 \leq \omega \leq \omega_l \\ \|G(j\omega)K(j\omega)\| &< \epsilon << 1 \qquad \textit{for} \;\; \omega \geq \omega_h \end{aligned}$$

- These requirements can change, $\|G(0)K(0)\| \rightarrow \infty$ to assure zero steady-state error in the face of step disturbances.
- Internal Model Principle. The long-term error in the face of persistent disturbances can be zero only if the poles of the transform of the disturbance are included among the poles of the return ratio $G(s)K(s)$.

Robustness

Plan uncertainties

- Nominal plant is not the true representation of the system because of modeling errors or uncertainties.
- The design must ensure the stability and perfromance for a given set of plants close to the nominal representation.
- Pertubations models: Additive $G(s) = G_o(s) + \Delta(s)$, Multiplicative $G(s) = G_o(s)(1 + \Delta(s))$, Division $G(s) = G_o(s)/(1 + \Delta(s))$.
- Conditions for multiplicative perturbation
  Stability

$$\|1 + K(j\omega)G_o(j\omega)\| > \|\Delta(j\omega)K(j\omega)G_o(j\omega)\| \qquad \omega \geq 0$$

  Performance

$$\left\|\frac{K(j\omega)G_o(j\omega)}{1 + K(j\omega)G_o(j\omega)}\right\| < \frac{1}{\|\Delta(j\omega)\|} \qquad \forall\omega \geq 0$$

Properties, Control Limitations

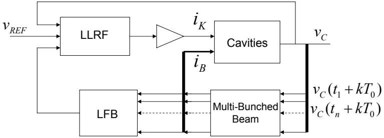
Remarks

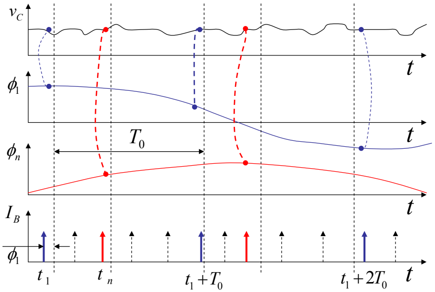
- The design of the control system is a trade-off between specifications, uncertainties and fundamental limitations defined by the original plant.
- Plant uncertainties introduce serious limitations in the control design. Better performance is achieved if the controller is designed for an specific plant.
- To meet stringent specifications a controller have to be designed based on a nominal model of the plant, undertanding uncertainties and perturbations.
- There are fundamental limitations in the control design defined by the plant
  - Non-minimum phase plant forces to reduce the bandwith attainable respect to the equivalent minimum phase system.
  - Unstable systems are conditional stable when operates in closed loop.

Outline

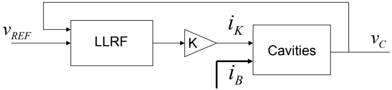
Storage Ring - Low-order mode dynamics

General Model





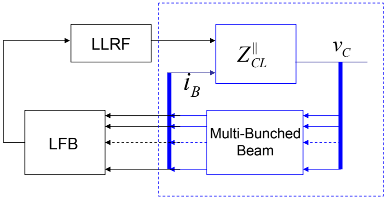
Time Scale Separation - Fast Dynamics



In the fast dynamics, the beam acts as a 'rigid beam perturbation'.
Ideally, the beam dynamics (slow) does not affect the fast dynamics.

Storage Ring - Low-order mode dynamics

Time Scale Separation - Slow Dynamics



- The interaction between the beam and the RF station impedance defines a new dynamics for the beam.
- The low-order mode behavior of the beam is quantified by the eigenvalues $\sigma_l \pm j\omega_l$ for the l^{th} mode, where the modal growth rate σ_l and the synchrotron frequency ω_l are

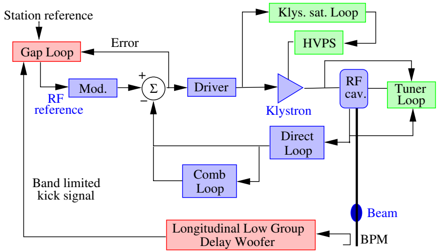
$$\sigma_l \approx -d_r + \frac{\alpha\, e\, I_0 \omega_{\rm rf}}{2E_o T_o \omega_s} \mathcal{RE}\left(Z^{\|\rm eff}(l\omega_0 + \omega_s) - Z^{\|\rm eff}(0)\right)$$

$$\omega_l \approx \omega_s + \frac{\alpha\, e\, I_0 \omega_{\rm rf}}{2E_o T_o \omega_s} \mathcal{IM}\left(Z^{\|\rm eff}(l\omega_0 + \omega_s) - Z^{\|\rm eff}(0)\right),$$

with $$Z^{\|\rm eff}(\omega) = \frac{1}{\omega_{\rm rf}} \sum_{p=-\infty}^{\infty} (pN\omega_o + \omega) Z^{\|}_{CL}(pN\omega_o + \omega).$$

- Eigenvalues for unstable modes can be measured by opening the Longitudinal Feedback (LFB) for a sort period of time, such that the operation point becomes transiently unstable.

PEP-II RF station

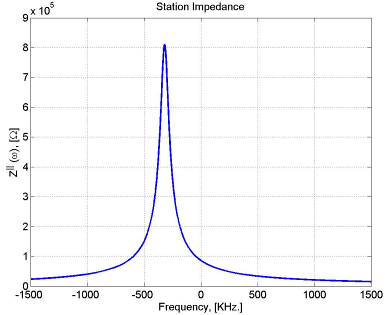


- Tuner loops Cavity tuninng for minimum reflected power.
- Klystron operation point support Adjust HVPS magnitude for a given driver power, compensate klystron gain and phase shift at the carrier frequency

- Direct Loop Extends the beam-loading Robinson stability limit, reduces the effective impedance $Z^{||}_{eff}(\omega)$ seen by the beam, causes the station to follow the RF reference.
- Comb Filter Add selective gain at synchrotron sidebands for further reduction in $Z^{||}_{eff}(\omega)$.
- Gap feedback loop Removes revolution harmonics from the feedback error signal. Avoid klystron saturation due to gap transient.
- Longitudinal feedback uses the RF station as low-frequency kicker.

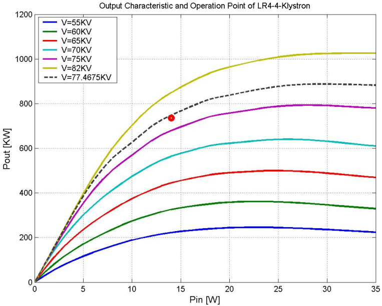
PEP-II RF station model

Cavity Impedance in baseband



The RF station is detuned for different beam currents to minimize the reflected power. $I_b \longrightarrow \Delta\omega$

Klystron output characteristic



At the operation point the small signal gain is defined by a matrix G_K.

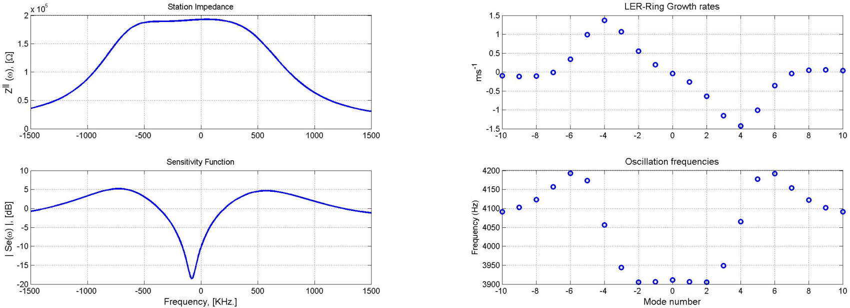
PEP-II RF station model

Direct Loop - Design

- Design criteria: minimize the impedance seen by the beam in a wide frequency range. To improve servo quality, low error from reference at carrier frequency.
- Minimize the impedance: $Z_{CL}^{||}(\omega) \simeq S(\omega) Z_{OL}^{||}(\omega)$; Have the sensitivity function $S(\omega)$ as low as possible is a wide frequency range
- Wide frequency range: limit defined by the delay (non-minimum phase system) $\rightarrow$ LEAD algorithm.
  - $max \| S(\omega) \| < L \simeq 1 \qquad \forall \omega$
  - Similar in this case to a given Phase Margin/Gain Margin
- Low error at $f_{RF} \rightarrow$ baseband: LAG/INTEGRAL algorithm.
- $G_D e^{j\phi_D}$ can be calculated with that criteria.
- Model is parametric, $I_b \rightarrow (\Delta\omega, G_K)$
- $G_D = G_D(G_K), \ \phi_D = \phi_D(\Delta\omega, G_K)$
- Solution: Recalculate $G_D e^{j\phi_D}$ for different I_b to compensate changes due to G_K and include a feedforward term in ϕ_D to compensate for $\Delta\omega$ variations.

PEP-II RF station model

Direct Loop feedback - Results

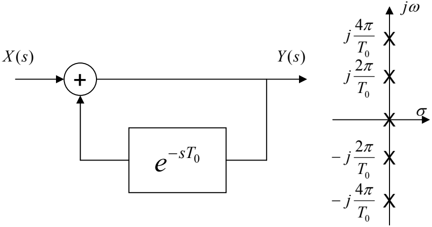


- The $Z^{||}(\omega)$ is reduced in a wide range via a min $\|S(\omega)\|_{\infty}$.
- At $I_b = 750mA$ the system is unstable and the maximum modal growth rate is not admisible for higher currents ($I_b \rightarrow 4A$ in LER).

PEP-II RF station model

Comb Filter - Design

The beam perturbation on the RF station is periodic in steady state.
Repetitive controller: Poles perturbation → poles of the controller (Internal Model Principle).



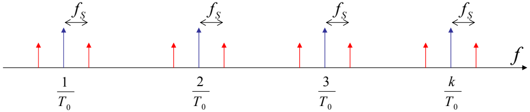
To reject a T_o-periodic perturbation, a repetitive filer based on a T_o-delay can be implemented
The transfer function is

$$\frac{Y(s)}{X(s)} = \frac{1}{1 - e^{-sT_o}}, \qquad \frac{Y(z)}{X(z)} = \frac{1}{1 - z^{-N}}, \ \textit{with} \ \ z = e^{-sT_{sam}}$$

PEP-II RF station model

Comb Filter - Design

The spectrum of the beam perturbation acting on the station has revolution harmonics at $f_r = k/T_o$ due to the ion clearing gap with side bands at $f \simeq f_r \pm f_s$ due to synchroton motion of bunches. The controller has to be able to reject at the output the side band perturbation.



poles: $-\alpha \pm jk\frac{2\pi}{T_o} \pm j2\pi f_s$

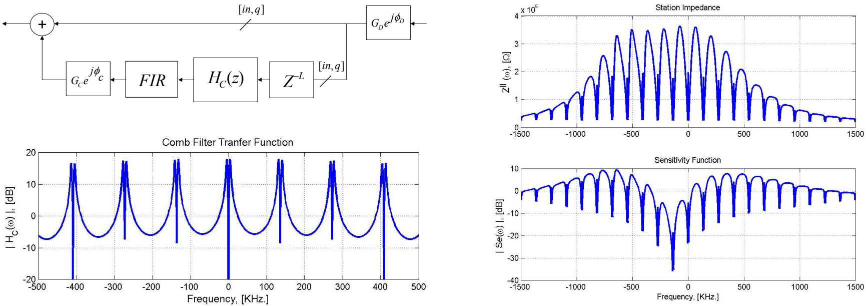
Additionally, no gain revolution harmonic, zeros: $\pm jk\frac{2\pi}{T_o}$, then

$$H_c(Z) = \frac{1 - Z^{-N}}{1 - 2Kcos(2\pi Q_s)Z^{-N} + K^2 Z^{-2N}}$$

$$with \qquad N = \frac{T_o}{T_{sam}}; \qquad Q_s = f_s T_o; \qquad K = e^{-\alpha T_o}$$

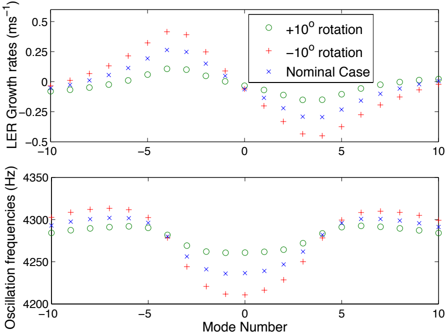
PEP-II RF station model

Comb Filter - Implementation



PEP-II RF station model

Comb Filter - Results



The nominal design ($\Delta\phi_C = 0$) reduces the growth rates, as e.g for $I_b = 1.4A$.

- The growth rates are very sensitive to variations in the controller parameter ϕ_C.
  - It is critical in the controller configuration for normal operation.
  - It can be used to reduce the growth rates.
  - Trade-off between station stability and beam stability.

PEP-II RF station model

Remarks

- The design of the controller combining a direct loop and a comb filter minimizes the RF station impedance at the synchrotron sidebands of the beam current.
- The residual RF station impedance interacting with high beam currents in storage rings makes the beam unstable.
- It is necessary a low-order mode damper feedback to stabilize the beam.
- Minimizing the growth rates of dominant unstable modes in the beam define less restrictions in the design of the longitudinal low-order mode feedback.

Outline

Simulations

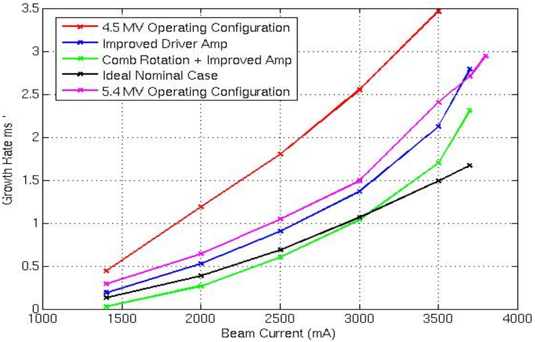
Non-linear simulation of the RF station-beam dynamics interaction

- Control system design is based on a nominal model of the system. Some system uncertainties can be included in the design.
- To include more detailed uncertainties and discrepancies respect to the nominal model a time domain simulation it is necessary.
- At SLAC we developed a simulation tool to analyze the low order mode dynamic interaction between the RF stations and multibunched beams.
- This simulation, based on non linear models, provides a tool to mimic the beam dynamics performance.
- The simulation was validated with measurements in the accelerator. The tool allows to conduct studies without requiring machine time.
- The simulation provides a test bed to study RF station feedback loop configurations and analyze their impact on the beam performance.
- The simulation has been used to predict the ultimate limits of the RF configurations so that new approaches or new hardware implementations can be developed before these limits are reached.

Growth Rates for various possible new RF configurations

Simulated results for PEP-II Low-Energy Ring.

- LER operating with 4.5MV Gap Voltage. Different improved configurations.
- LER operating with 5.4MV Gap Voltage.



- The maximum beam current simulated is set by the maximum power delivered by the klystrons installed at LER.
- Cases: 'Improved Driver Amp.' and 'Comb Rotation + Impr. Amp.' do not include imperfections in the RF processor module.

Acknowledgments

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