Multi-Dimensional Feedforward Controller at MAX IV

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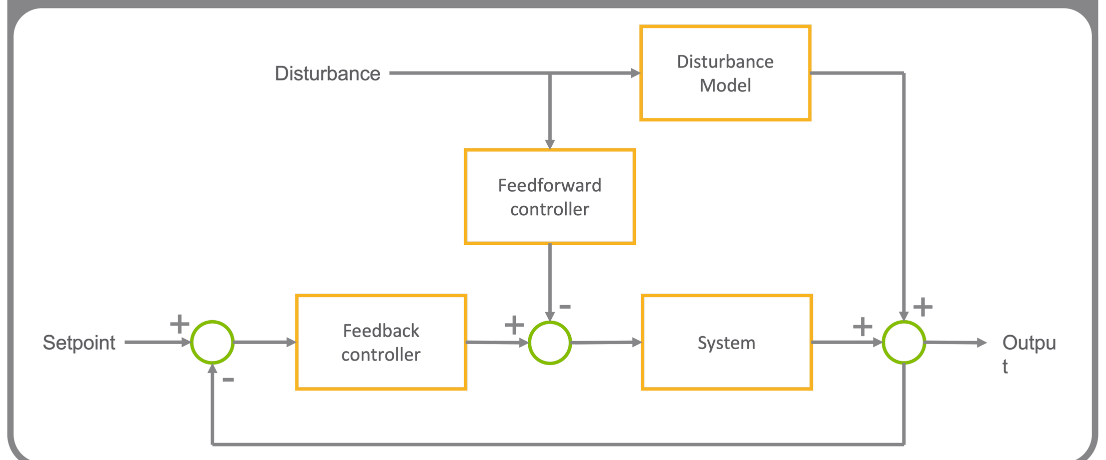
Motivations

At MAX IV, the beam orbit and optics system are well controlled with great performance; however, they are subject to disturbances depending on the insertion devices' positions. Thus, it became necessary to implement a Multi-Dimensional Feedforward device to compensate that. Considering that the transverse stability of the beam is essential for the requirements of the light source provided by the facility, the orbit is strictly controlled through several layers. In this control system, Libera Brillance+ devices are used for beam positioning monitors and for hardware-based Fast Orbit Feedback (FOFB) control, and a TANGO MIMO controller device is used for Slow Orbit Feedback (SOFB) control[1]. Nonetheless, the beam orbit is subject to distortions caused by the insertion devices(IDs) undulators.

Feedforward Control

Feedback Feedforward control loop



Pragmatically, feedforward devices can compute preemptive control actions according to mathematical approximations instead of using a model. The controller action can compensate for disturbances according to any arbitrary approximation. Thus, the feedforward controller response in time can be given by:

$$g_f(t) = f(d(t)) \quad (1)$$

in which $g_f(t)$ is the feedforward controller output, $d(t)$ is the disturbance in the time domain and $f(\cdot)$ is an arbitrary function.

Orbit Correction

The insertion devices cause a disturbance on the beam orbit, which vary according to the undulator configuration, such as the gap distance and the phase translation [2]. In this context, the feedforward controller minimizes the insertion devices' effects on the beam orbit. The feedforward tango device is configured with:

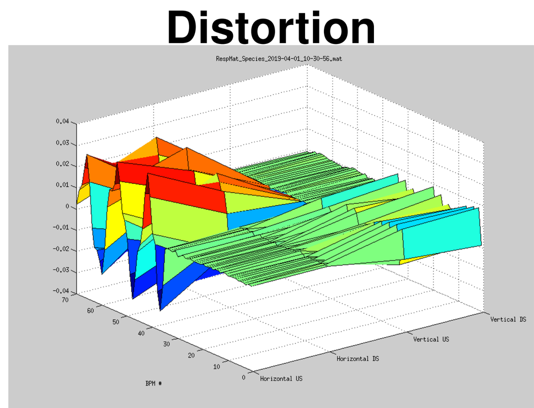
- SensorList: ID position TANGO attribute (representing the gap distance)
- ActuatorList: Corrector Magnets/Coils/Strips PowerSupplies current TANGO attributes

The Response matrix is derived according to an exhaustive process that can be summarized as follows:

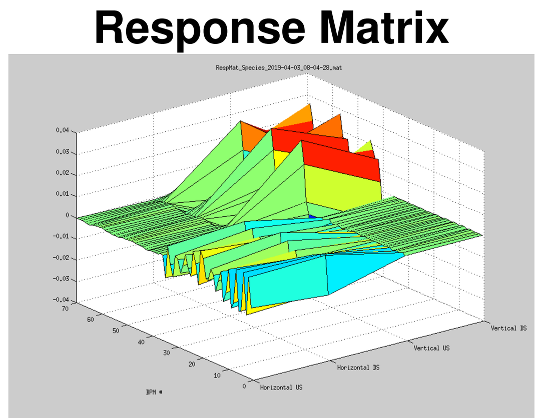
Move ID to maximum Gap and initial Phase.
Correct the orbit.
`Golden Orbit` ← orbit.
for each phase in possible phases **do**
  while gap ≥ minimum gap **do**
    Correct orbit to match `Golden Orbit`
    `ResponseMatrix` ← Actuator values
    Move to next gap
  end while
end for

Corrector Magnets Intensity

Distortion



Response Matrix



Optics Correction

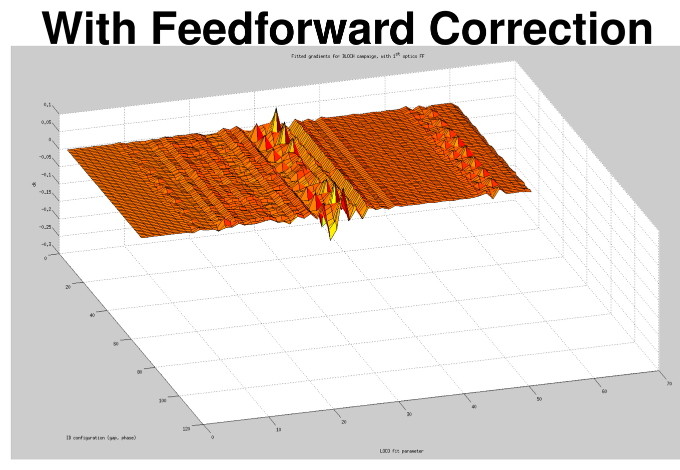
Insertions devices can also cause a focusing effect on the beam, affecting the ring lattice's symmetry and periodicity. In this context, a small quadrupole focusing is also expected, as imperfections on the ID would cause its residual magnetic field integral to being different from zero. Differently from the ID disturbance on the orbit, which results in a displacement of the orbit, the ID's residual quadrupole field causes a beam shape distortion. In this case, the beam optics is affected, and a correction needs to be applied to magnets around the storage ring. The feedforward tango device is configured with:

- SensorList: ID position TANGO attribute (representing the gap distace)
- ActuatorList: Corrector Magnets PowerSupplies current TANGO attributes

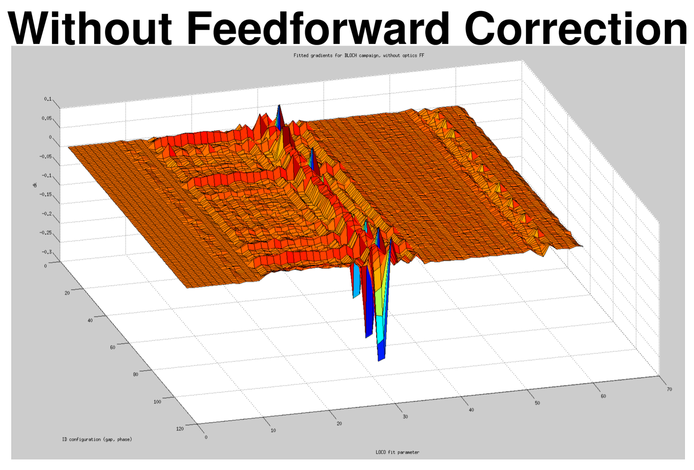
The `ResponseMatrix` is derived using the LOCO algorithm. The Linear Optics model is obtained with the gaps fully opened and again with closed gaps. The `ResponseMatrix` receives the reverse of the difference between the closed gaps models and the open gap model in order to compensate the distortions in the intensity of the magnets.

SQFO gradients

With Feedforward Correction



Without Feedforward Correction



TANGO Device

The control action of the Tango feedforward controller device is implemented according to Eq. 1, and behaves as:

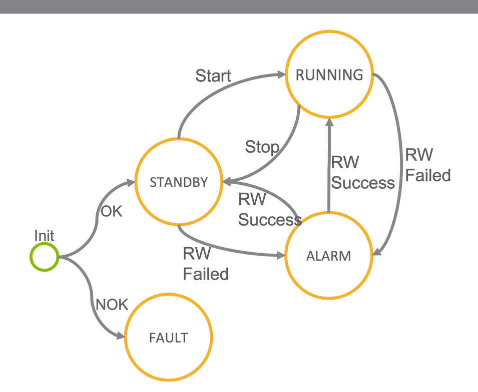
Initialization

`linearInterpolator` ← piece-wise linear interpolation given (`SensorsMatrix`, `ResponseMatrix`)
`nnInterpolator` ← nearest-neighbor interpolation given (`SensorsMatrix`, `ResponseMatrix`)

Periodic Taks

sensors_last ← ReadSensors(`SensorsList`)
actuators_next ← `linearInterpolator`(sensors_last)
if actuators_next is out of range **then**
  actuators_next ← `nnInterpolator`(sensors_last)
end if
if state is RUNNING **then**
  WriteActuators(actuators_next)
  actuators_last ← actuator_next
end if

FF TANGO device state-machine



Properties	Description
ActuatorsList	List of TANGO attributes used as actuators.
SensorsList	List of tango attributes used as sensors.
SensorsMatrix	Matrix with disturbance values for the controller response interpolation.
ResponseMatrix	Matrix with measured feedforward responses for the controller response interpolation.
Attributes	**Description**
sensors_last	Current values of sensors signals.
actuators_last	Current values of actuators signals.
actuators_next	Next values of the actuators signals, regardless of the state.
Time	Timestamp of last control loop action.
Commands	**Description**
Start	Start control loop.
Stop	Stop control loop.
UpdateTime	Trigger control action. It is a polled command.
States	**Description**
STANDBY	Control loop is not running.
RUNNING 2	Control loop is running.
FAULT 1	Critical error in the loop.
ALARM 2	Error to read or write to sensors or actuators.

References

[1] P.J. Bell et al. "A General Multiple-Input Multiple-Output Feedback Device in Tango for the MAX IV Accelerators". In: *Proc. 17th Int. Conf. on Acc. and Large Exp. Physics Control Systems (ICALEPCS)* (New York, NY, USA). 17. JACoW Publishing, Aug. 2020, pp. 1084–1088. DOI: 10.18429/JACoW-ICALEPCS2019-WEPHA012.

[2] H. Månefjord et al. "Commissioning of the First Insertion Devices on the 1.5 GeV Storage Ring in MAX IV". MA thesis. Lund, Sweden: EIT, LTH, Lund University, 2018.

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