Cryomodule-on-Chip (CMOC) Simulation Engine

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Math and physics of Mechanical and Electromagnetic modes, with nonlinear coupling
Eventually lands in state-space formalism
Can numerically integrate equations in software or FPGA
FPGA is nice because it can run in same chip as controller(s)
Match parameters to experimental evidence
Physics

Electromagnetic world

EM fields store energy
power flows in and out

Mechanical world

deflections store energy
power flows in and out

Coupling
Decompose dynamics into eigenmodes that store energy
use $\sqrt{\text{Joule}}$ as universal amplitude coordinate (thanks, Olof!*)

Electromagnetic

$\frac{d\vec{x}}{dt} = A\vec{x} + B\vec{k} + Ci_B$

$A = A_0 + G\vec{y}$

Mechanical

$\frac{d\vec{y}}{dt} = D\vec{y} + E\vec{w} + F|\vec{x}|^2$

Linear Time Invariant (LTI) until red nonlinear coupling terms are added.
$\vec{k}$ are RF drives
$i_B$ is the beam
$\vec{w}$ are actuators and environmental forces

- Using eigenmode coordinates makes $A$ and $D$ diagonal
- $F$ and $G$ are both based on the same $B^2 - E^2$ surface integral

Translate to hardware

Abstract state space equation, unifying $\vec{x}$ and $\vec{y}$ as $\vec{S}$

$$\frac{d\vec{S}}{dt} = f(\vec{S}, \vec{k}) \quad \text{or} \quad z\vec{S} = \vec{S} + f(\vec{S}, \vec{k}) \cdot dt$$

FPGA clock tick $\sim 5$ ns
$\sim 10$ ns per electromagnetic time step (parallel DSP)
$\sim 250$ ns per mechanical time step (serial DSP)
- Fixed point arithmetic, unlike floating point typical for software
- 22% of XC7K160T, configured for 2 cavities, 3 electrical modes each
Measurements

\[
\sum_k \frac{G_{k1} E_{k1}}{1 + \frac{1}{Q_k} \frac{s}{\omega_k} + \left(\frac{s}{\omega_k}\right)^2}
\]

Also need \( \Delta f / |V_{\text{cav}}|^2 \); want \( I_{\text{piezo}} / V_{\text{piezo}} \), and \( I_{\text{piezo}} / |V_{\text{cav}}|^2 \) as a cross-check. All physics based on the same set of second-order low-pass resonances (\( f_0 \) and \( Q \), embedded in \( \mathbf{D} \)), but with different coupling constants (\( E, F, G \)).
Simple RF pulse response provides some info about Lorentz detuning
Using same resonances as measured with transfer function, fitting coupling coefficients, driven by $|V|^2$
Would be far preferable to frequency-sweep $|V|^2$
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Conclusion

- Physics of the electro-mechanical system is easily understood (if the dynamical part stays linear).
- Numerical treatment is also not hard.
- Acquiring and interpreting data to fit the model involves more work.
- Having a complete controller/model running in real time opens up many possibilities for software development and operator training.
- Specifically has proved useful during development of the automated cavity bring-up process for LCLS-II.

https://github.com/BerkeleyLab/CMOC
https://github.com/BerkeleyLab/Global-Feedback-Simulator
LLRF’15 Shanghai poster: Accelerator-On-Chip Simulation Engine
ICALEPCS’17 talk/paper: Cryomodule-on-Chip Simulation Engine

Thank You!