SYSTEM IDENTIFICATION EMBEDDED IN A HARDWARE-BASED CONTROL SYSTEM WITH COMPACTRIO*

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Abstract

The development of innovative model-based design high bandwidth mechatronic systems with stringent performance specifications has become ubiquitous at LNLS-Sirius beamlines. To achieve such unprecedent specifications, closed loop control architecture must be implemented in a fast, flexible and reliable platform such as NI's CompactRIO (cRIO) controller that combines FPGA and real-time capabilities. The design phase and life-cycle management of such mechatronics systems heavily depends on high quality experimental data either to enable rapid prototyping, or even to implement continuous improvement process during operation. This work aims to present and compare different techniques to stimulus signal generation approaching Schröder phasing and Tukey windowing for better crest factor, signal-to-noise ratio, minimum mechatronic stress, and plant identification. Also shows the LabVIEW implementation that requires specific signal synchronization and processing on the main application containing a hardware-based control architecture, increasing system diagnostic and maintenance ability. Finally, experimental results from the High-Dynamic Double-Crystal Monochromator (HD-DCM-Lite) of QUATI (quick absorption spectroscopy) and SAPUCAIA (small-angle scattering) beamlines and from the High-Dynamic Cryogenic Sample Stage (HD-CSS) from SAPOTI (multi-analytical X-ray technique) of CARNAÚBA beamline are also presented in this paper.

Stimulus generation

Multi-sine signals are broadly applied to system identification [5] due to their periodic and flexible structure, as shown by the the equation below:

$$x(t) = \sum_{k=1}^{N} A_k \cos(\omega_k t + \varphi_k)$$

Different approaches exist to define phase for each frequency component. Resulting properties in time and frequency domain such as crest factor (ratio between peak and effective values) and bandpass spectrum were compared for different methods.

Table 1: Crest factor comparison for different multi-sine phasing methods

Phase method	Crest factor
Random	3.5 – 5.5
Linear difference	1.9
Linear phase	64.56
Schröder phasing	1.66

Schröder phasing is defined by the following quadratic relation and offers the best crest factor and a near perfectly distributed bandpass spectrum

$$\varphi_k = -\frac{k(\,k-1)\pi}{N_k}$$

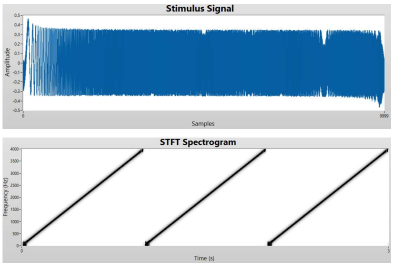

Figure 1: Time signal (single-period) and spectrogram (3 periods) of multi-sine signal with period of 1 second, Schröder phasing and maximum frequency of 4 kHz.

Tukey windowing helps smoothing abrupt start and end of excitation signals, providing a less demanding operation for the tested system and preserving its integrity during prototyping and offline commissioning.

Tukey window:

$$w(t) = \begin{cases} \frac{1}{2}\left\{1+\cos\left(\frac{2\pi}{r}\left[x-\frac{r}{2}\right]\right)\right\}, 0 \le t < \frac{r}{2} \\ 1, \frac{r}{2} \le t < \; 1-\frac{r}{2} \\ \frac{1}{2}\left\{1+\cos\left(\frac{2\pi}{r}\left[x-1+\frac{r}{2}\right]\right)\right\}, 1-\frac{r}{2} \le t \le 1 \end{cases}$$

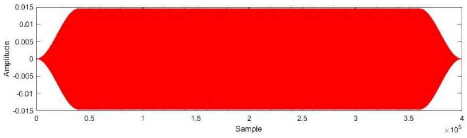

Figure 2: Multi-period signal with Tukey windowing.

Architecture

Generation of multi-sine excitation signals and system response acquisition are performed by the same cRIO unit used to control the system during the offline commissioning.

The new architecture multiplexes the control effort and feedback signal from the pre-existing controller embedded on FPGA, connecting them to the stimulus generator and system response logger, both implemented on the cRIO Real-Time CPU, saving FPGA resources.

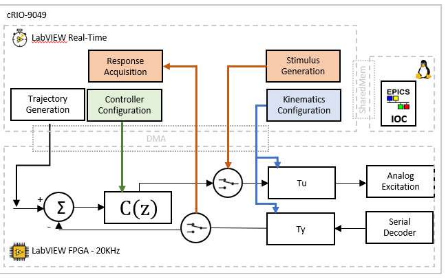
cRIO-9049
LabVIEW Real-Time
Response Acquisition
Stimulus Generation
Trajectory Generation
Controller Configuration
Kinematics Configuration
SharedMem
EPICS
IOC
DMA
+
Σ
-
C(z)
Tu
Ty
Analog Excitation
Serial Decoder
LabVIEW FPGA - 20KHz

Figure 3: System identification modules on cRIO.

A Matlab routine calculates FFT for each period (1 second) of excitation and output signals, from which system frequency responses are calculated and averaged together to improve signal-to-noise ratio (SNR).

Low-level implementation

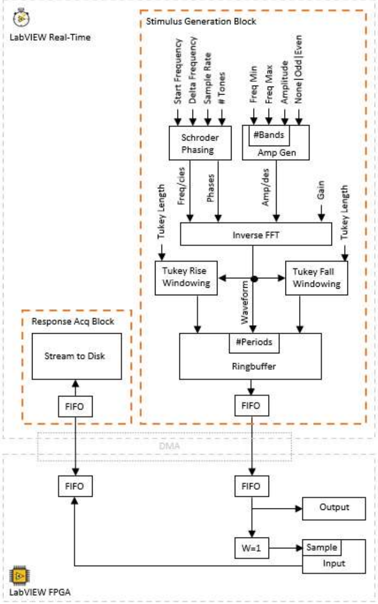
LabVIEW Real-Time
Stimulus Generation Block
Start Frequency
Delta Frequency
Sample Rate
Tones
Freq Min
Freq Max
Amplitude
None|Odd|Even
Schroder Phasing
#Bands
Amp Gen
Tukey Length
Freq/cies
Phases
Amp/des
Gain
Tukey Length
Inverse FFT
Tukey Rise Windowing
Tukey Fall Windowing
Waveform
#Periods
Ringbuffer
Response Acq Block
Stream to Disk
FIFO
FIFO
DMA
FIFO
FIFO
Output
W=1
Sample
Input
LabVIEW FPGA

Figure 4: Block diagram of LabVIEW implementation for stimulus generation and system response acquisition.

System identification results

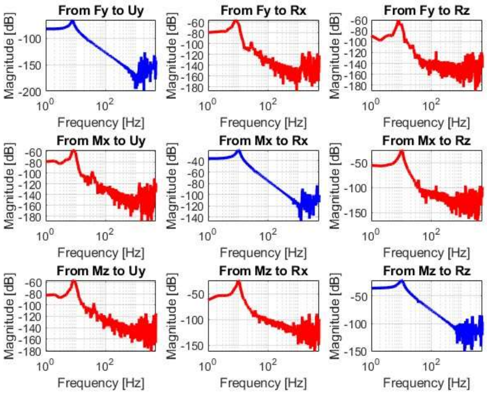

Figure 5: Experimental frequency responses (1 Hz-10 kHz) for short-stroke stage of HD-DCM-Lite using Schröder multi-sine.

Conclusion

The proposed approach for system identification was successfully embedded in a cRIO platform alongside the pre-existing control architecture and infrastructure, providing a flexible and convenient tool for model-based controller design and diagnostics of precision mechatronic systems, such as the new generation of monochromators and samples stages for LNLS beamlines. Different multi-sine excitation signals were compared and the Schröder method was chosen due to its properties both in time and frequency domain. Tukey windowing and multi-periods were adopted to deal with limitations of physical systems under test, such as electro-mechanical restrictions and noise. Frequency response data with up to 10 kHz (resolution of 1 Hz) of a high-dynamic monochromator was obtained, matching simulated results from mechanical modelling. Also, the controller was designed for that experimental plant, and the in-position error (RMS) for all degrees of freedom matched the project expectations.

Acknowledgement

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[1] CNPEM. *Sirius: accelerating the future of Brazilian science*. https://www.lnls.cnpem.br/sirius-en/

[2] A.V. Perna, G. S. de Albuquerque, H. O. C. Duarte, R. R. Geraldes, M. A. L. Moraes, M. Saveri Silva, M. S. Souza. "The HD-DCM-Lite: a high dynamic DCM with extended scanning capabilities for Sirius/LNLS beamlines", presented at MEDSI'2020, Chicago, USA. Paper TUPC11.

[3] R. M. Caliari, R. R. Geraldes, M. A. L. Moraes, and G. Witvoet, "Loop-Shaping Controller Design in the Development of the High-Dynamic Double-Crystal Monochromator at Sirius Light Source", American Society for Precision Engineering Topical Meetings, 2020.

[4] T. R. S. Soares, J. P. S. Furtado, G. S. de Albuquerque, M. Saveri Silva, R. R. Geraldes, "Dynamical modelling and control development for the new High-Dynamics Double Crystal Monochromator (HD-DCM-Lite) for Sirius/LNLS". The International Conference on Accelerator and Large Experimental Physics Control Systems (ICALEPCS), Oct. 2023. Paper MO2AO07. This conference.

[5] T. Kimpián and F. Augusztinovicz, "Multiphase multisine signals – Theory and practice", in Proc. 27th Int. Conf. on Noise and Vibration Engineering (ISMA2016), Heverlee, Belgium, Sept. 2016, pp. 2241-2250.

[6] Schroeder, UR (1970) "Synthesis of Low-Peak Factor Signals and Binary Sequences with Low Autocorrelation", IEEE Transactions on Information Theory, pp. 85-89.

[7] Bloomfield, P. Fourier Analysis of Time Series: An Introduction. New York: Wiley-Interscience, 2000.

[8] NI. cRIO-9049. https://www.ni.com/pt-br/shop/model/crio-9049.html

[9] Fast Fourier transform. https://www.mathworks.com/help/matlab/ref/fft.html

[10] R. M. Caliari, R. R. Geraldes, M. A. L. Moraes, G. B. Z. L. Moreno, "System identification and control of the Sirius high-dynamic DCM", presented at MEDSI'2016, Barcelona, Spain, 2016.

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