

Cavity Digital Control Testing System By Simulink Step Operation Method For TESLA Linear Accelerator And Free Electron Laser

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ABSTRACT

The cavity control system for the TESLA - TeV–Energy Superconducting Linear Accelerator project is initially introduced in this paper. The FPGA – Field Programmable Gate Array technology has been implemented for digital controller stabilizing cavity field gradient. The cavity SIMULINK model has been applied to test the hardware controller. The step operation method has been developed for testing the FPGA device coupled to the SIMULINK model of the analog real plant. The FPGA signal processing has been verified according to the required algorithm of the reference MATLAB controller. Some experimental results have been presented for different cavity operational conditions.

Keywords: TESLA Free Electron Laser (FEL), Superconducting cavity control, Linear accelerators

1. INTRODUCTION

The LLRF (Low Level Radio Frequency) cavity control system for the TESLA - TeV–Energy Superconducting Linear Accelerator project has been developed to stabilize the accelerating fields of the resonators. The control section, powered by one klystron, consists of four cryomodules containing eight cavities each. One klystron supplies RF power of 10 MW to 32 cavities through coupled wave-guide with circulator. The cavities are operated at a frequency of 1.3 GHz with pulse duration of 1.3 ms and average accelerating gradients of 25 MV/m. The control feedback system regulates the vector sum of the pulsed accelerating fields in multiple cavities. The fast amplitude and phase control of the cavity field is accomplished by modulation of the signal driving the klystron. The cavity RF signal is down-converted to an intermediate frequency of 250 KHz preserving the amplitude and phase information. The ADC and DAC converters link analog and digital part of the system. The digital signal processing is realized for the field vector detection and filtering. The digital controller stabilizes the detected real (in-phase) and imaginary (quadrature) components of the incident wave according to the desired set point. Additionally the adaptive feed-forward is applied to improve compensation of repetitive perturbations induced by the beam loading and by the dynamic Lorentz force detuning (figure 1).

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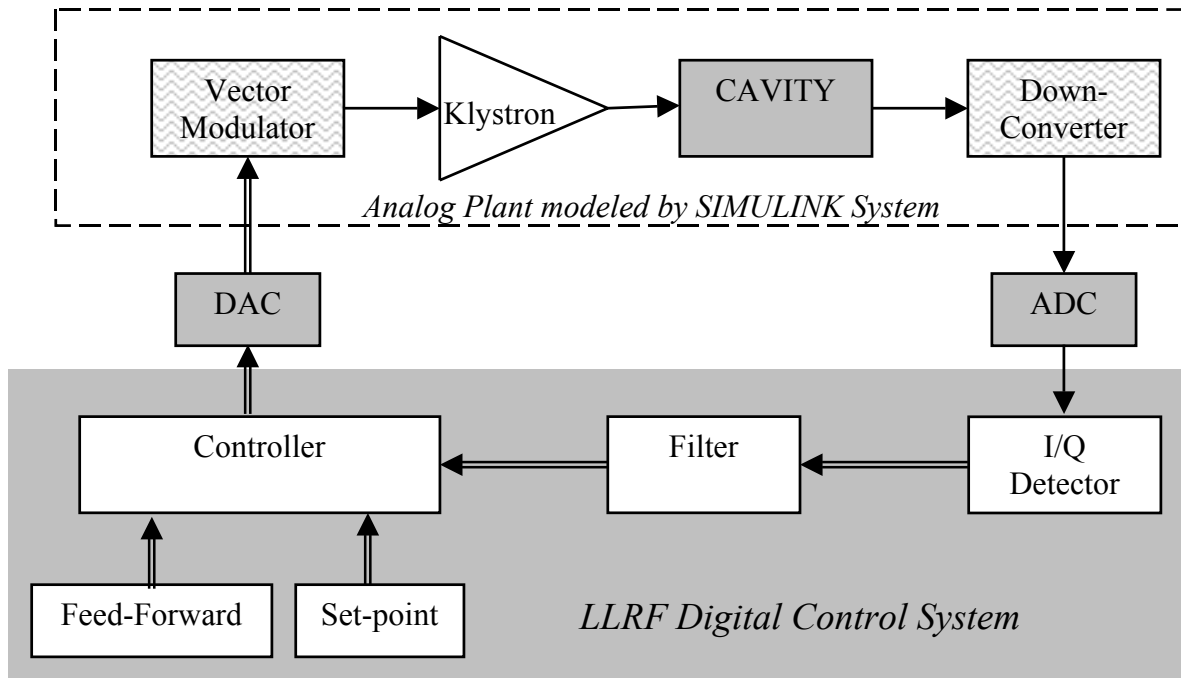


Figure 1. Simplified block diagram of cavity control system with analog and digital sections.

The digital LLRF controller has been implemented applying the very fast FPGA technology. The single cavity SIMULINK model has been applied to test the hardware controller in feedback and feed-forward operation. A communication interface has been developed coupling the model and the real device. The SIMULINK model can be effectively coupled to the real digital controller in step operation mode only. This method gives the same results as the *real time* process and verifies the performing of the digital controller.

2. STEP OPERATION METHOD

The step operation method is based on general feature of synchronized digital systems where signal processing consists of sequential finite micro steps in discrete time domain determined by the relative clock. The state of the system is definitely established and can be held at any instant synchronized by the clock according to the requirements. Then the simulation process for the digital model of the real plant can be separated in real time with the real process of the plant with digital structure. Every simulation step corresponds to the sampling time and every response of the real controller corresponds to the previous appropriate simulation step according to the latency of the digital conversion. The schematic diagram of data exchange and time relation during one cycle step operation for the Simulink model managed by Matlab system is presented on figure 2. During a simulation step the Simulink model is driven by constant vector input and all vector outputs and states are sending to the Matlab *workspace*, which registers the step simulation process. Subsequently the communication interface acquires data from the Matlab *workspace* and sends them to the real system. The digital controller converts succeeding data with its finite latency and after that holds this processing. The Simulink model “waits” for the vector response, which is as well set to the Matlab *workspace*. Then initializing parameters and states again activates the Simulink model and the next simulation step is carrying on. Thus the new vector input drives the model. In reality the plant “does not wait” for the current response but accepts the previous one according to the latency of the digital conversion.

Therefore step operation system is characterized by two timing parameters: sampling time corresponding to the simulation step and the controller latency corresponding to the delay of data accepted by the model. The Matlab *workspace* records signals and the system convey properly delayed data to the Simulink model.

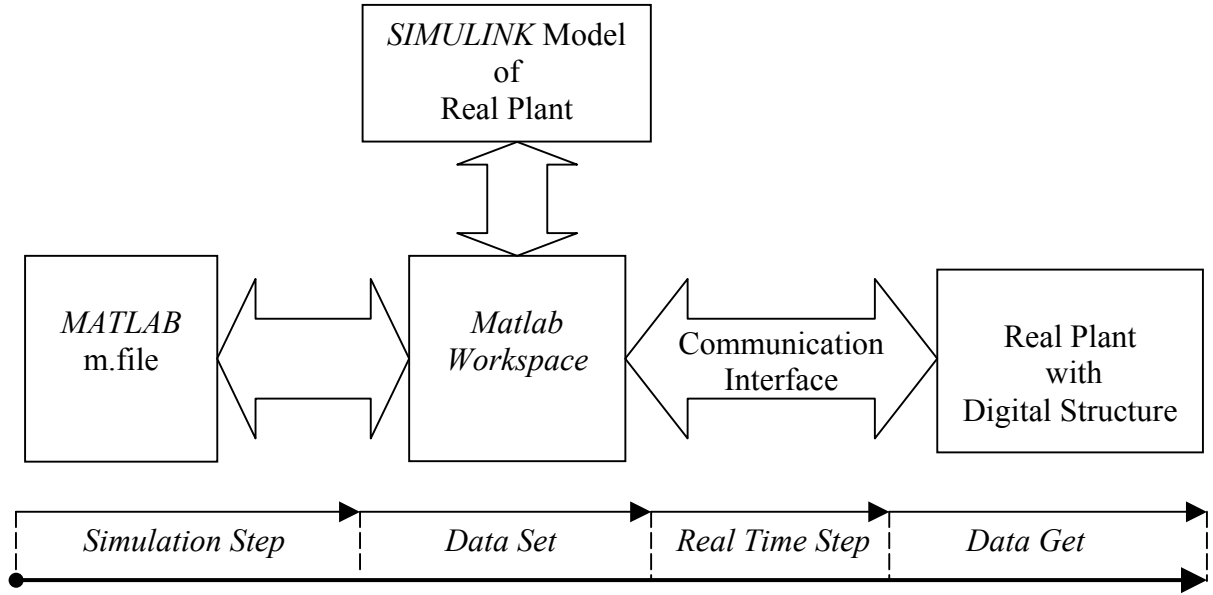


Figure 2. Schematic diagram of data exchange and time relation during one cycle of step operation mode.

3. CAVITY CONTROL TESTING SYSTEM.

The Simulink implementation of the control system for the cavity is presented in figure 3 in relation to the functional block diagram. The cavity control system is simulated as a continuous model with fixed micro step of $0.1 \mu\text{s}$ process duration. The electromechanical model represents the single cavity. The I/Q Drivers subsystem generates signals with *In-phase*, *Quadrature* components for the beam, feed-forward F_F and set point S_P according to the system requirements. The proportional controller amplifies the error signal and closes the feedback loop. The feedback and feed-forward operation can be performed independent resulting in the controller output signal Ctrl. The transducers match properly signals level to the controller circuit and the cavity environment. The monitoring subsystem collects and outputs signals to the Matlab *workspace*. The intermediate frequency modulator converts the cavity output vector to V_IF signal of frequency 250 kHz. During simulation step $T=1 \mu\text{s}$ of the process, the cavity is driven by constant **IQ** vector and all resulting data are sending to the Matlab *workspace*.

The cavity model can be driven by the SIMULINK controller or by outer one applying workspace data.

The MATLAB controller has been coded according to the equivalent FPGA system algorithm (figure 4). It has been implemented as a reference one for testing and comparing purposes. Simulink generated signal data V_IF, S_P, F_F are sampled every $1 \mu\text{s}$ step of the process from the Matlab *workspace* and are conveyed to the Matlab and FPGA system for the required controller processing.

The FPGA controller has been implemented according to the algorithm described below.

The sequence of two $\pi/2$ shifted consecutive samples $\mathbf{u}_k = \mathbf{u}(kT) = (\mathbf{u}(kT), \mathbf{u}(kT-T)) = (\mathbf{u}_k, \mathbf{u}_{k-1})$ of the V_IF signal is applied to detect the discrete approximation of the (I,Q) components using complex representation as follows

$$\mathbf{v}(kT) = \mathbf{v}_k = 1/g \cdot \exp(-i(2\pi f_i \cdot kT - \Delta\phi)) \cdot \mathbf{u}(kT) = 1/g \cdot \exp(i\Delta\phi) \cdot (-i)^k \cdot \mathbf{u}_k = \mathbf{R}_k \cdot \mathbf{u}_k,$$

where coefficient $\mathbf{R}_k = 1/g \cdot \exp(i\Delta\phi) \cdot (-i)^k$ includes initial calibration factor (attenuation coefficient g , phase shifting $-\Delta\phi$) and successive $-\pi/2$ rotation phasor what corresponds to the demodulation process for signal of frequency $f_i=250 \text{ kHz}$.

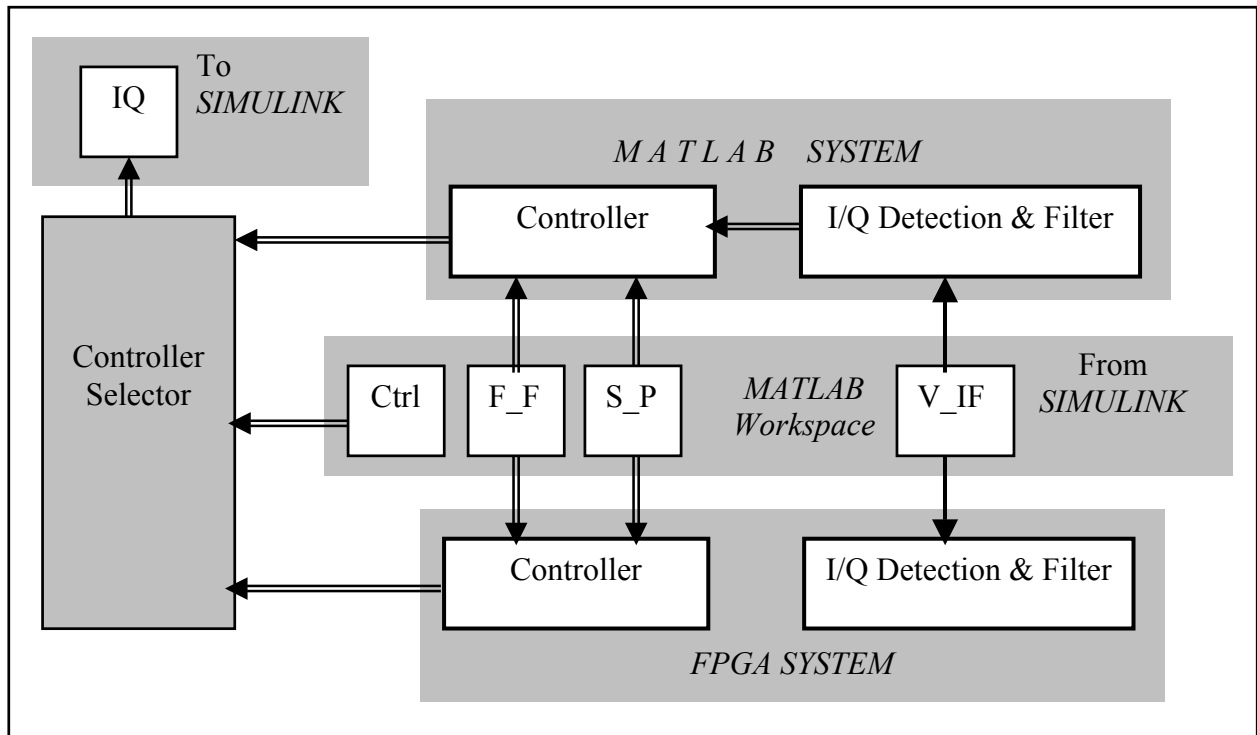


Figure 4. Functional diagram of cavity control testing system.

4. EXPERIMENTAL RESULTS.

The control testing procedure performs with Simulink single cavity model. The cavity model is driven in feed-forward and feedback mode simulating operation in a typical working condition. In the real operational condition the cavity is driven in 1.3 ms pulse mode forced by the control feedback supported by feed-forward. The cavity is *filling* with constant forward power during the first stage of the operation. It results an exponential increase of the electromagnetic field according to its natural behavior in the resonance condition. The beam loading current is injected when the cavity gradient has attained half of the final value (~ 0.5 ms) and the reflected power has reached the minimum value. The cavity voltage is set stable as a result of the *flattop* operation for time duration of ~ 0.8 ms. Turning off both generator and beam current yields an exponential *decay* of the cavity field.

Each of the signals driving the FPGA controller has been considered separately for the testing purpose and the results are compared with the Matlab controller.

The set-point signal **S_P** dictates the desired cavity voltage during *filling* time and *flattop* level.

The feed-forward **F_F** represents the necessary driving signal for desired cavity voltage. The driving signal is phase modulated step tracking the cavity resonance frequency during *filling time*. The driving signal is properly modulated to obtain a desired constant cavity voltage during *flattop* level. It applies the time varying cavity detuning to compensate the cavity impedance variation.

The modulated **V_IF** signal represents the real down-converted RF cavity signal of 250 kHz frequencies.

Experiments have been carried out for signals corresponding to the main parameters of the cavity model combined in the table below.

Beam current, average value [mA]	8
Amplitude of cavity voltage [MV]	25
Phase of cavity voltage [rad]	0
Loaded quality factor [10^6]	3
Lorentz force detuning constant vector [Hz/(MV) ²]	(0.4, 0.3, 0.2)
Mechanical resonance frequency vector [Hz]	(280, 350, 440)
Mechanical quality factor vector	(100, 100, 100)

The relative average numerical error for amplitude and average error for phase has been estimated on the *flattop* level of the cavity voltage for the FPGA controller relatively to the MATLAB controller.

The results of experiments for the calibration coefficients $g=1$, $\varphi=0$, filter coeff. =1 are presented in figures 5-7.

The experimental results for feedback operation for gain =50, 100 and filter coeff. = 1, 0.25 are presented in figures 8-9.

Additionally the simulation testing for hypothetical different FPGA latencies is presented in figure 10.

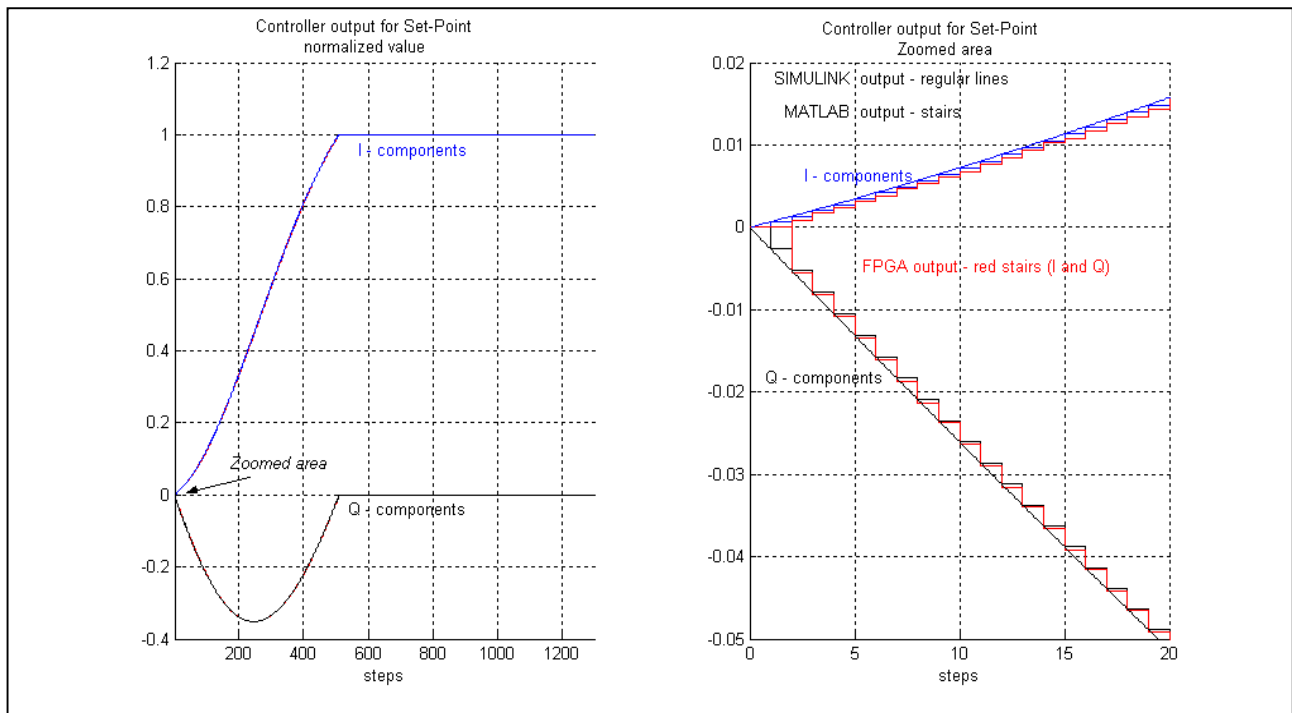


Figure 5. Controller output for Set-Point driving signal only ($V_{IF}=0$, $F_F=0$, gain=1).
Relative average error for amplitude = $-1.3e-3$; average error for phase = $-2.2439e-4$ rad.

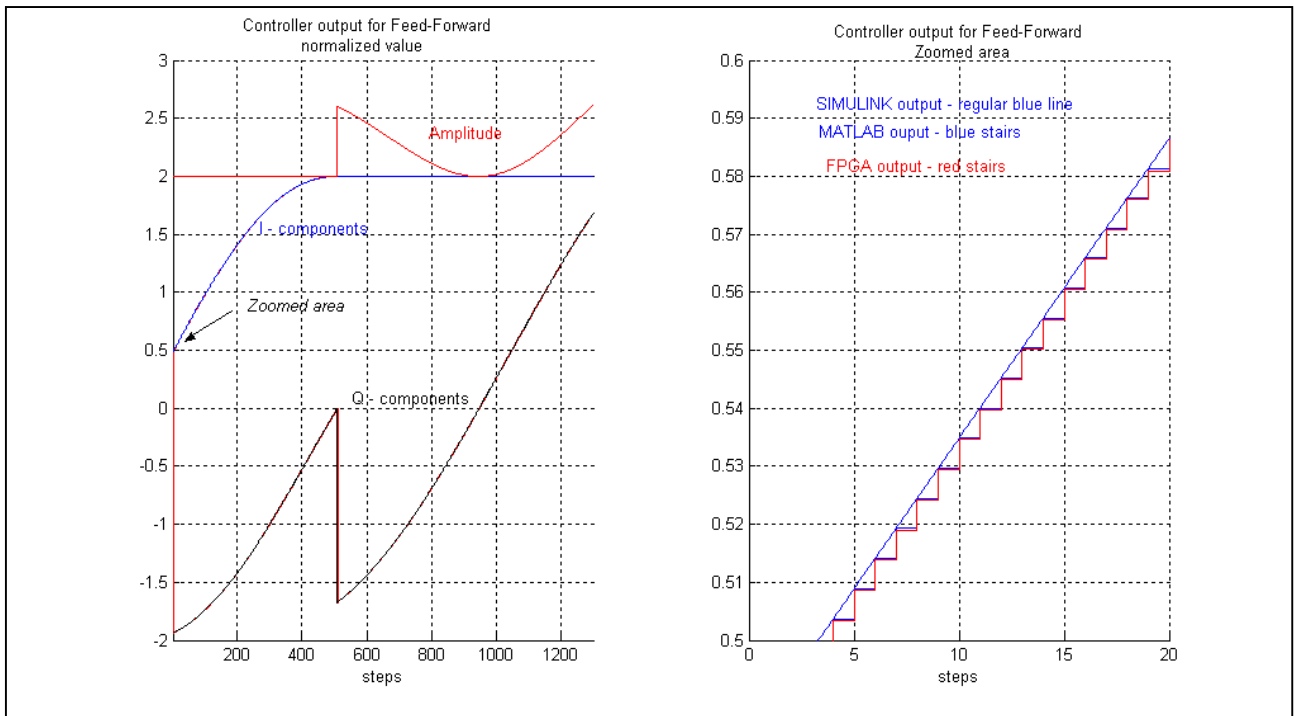


Figure 6. Controller output for Feed-Forward driving signal only ($V_{IF}=0$, $S_P=0$, gain=1). Relative average error for amplitude = $-4.6381e-4$; average error for phase = $-1.4982e-4$ rad.

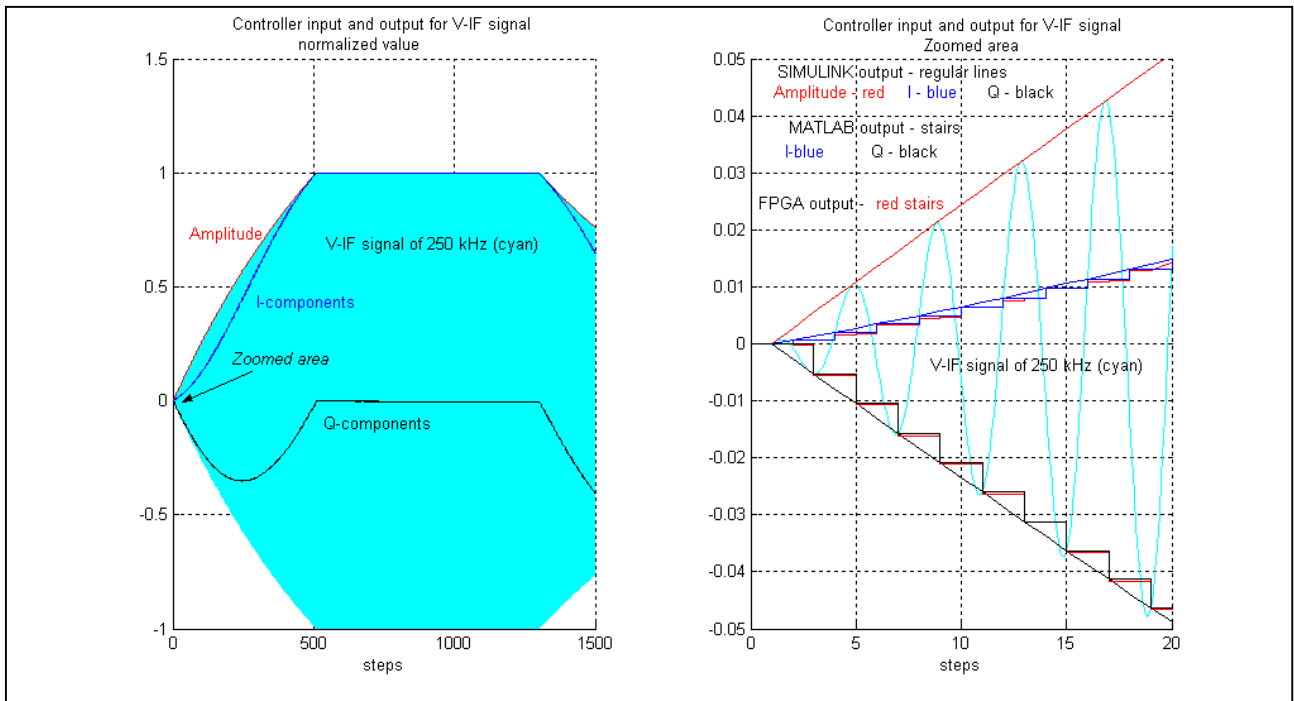


Figure 7. Controller input and output for V_{IF} driving signal only ($S_P=0$, $F_F=0$, gain= -1). Relative average error for amplitude = $-2.7316e-4$; average error for phase = $-2.2466e-4$ rad.

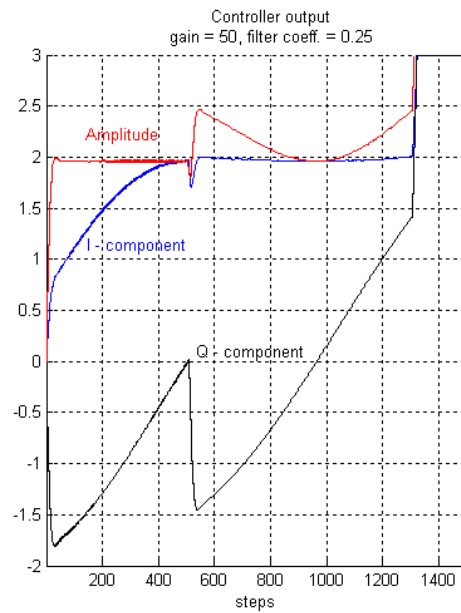
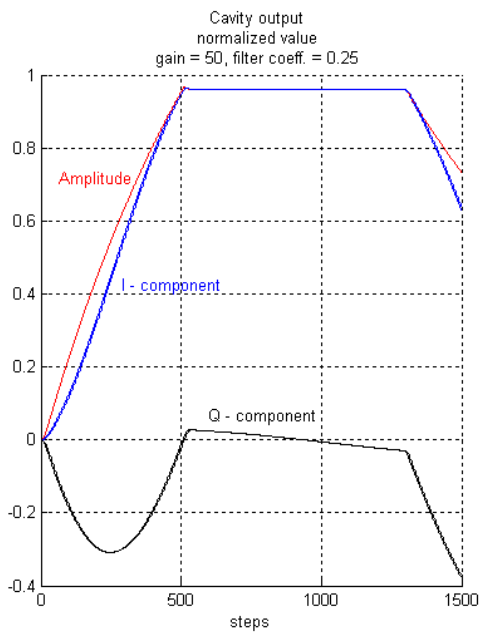
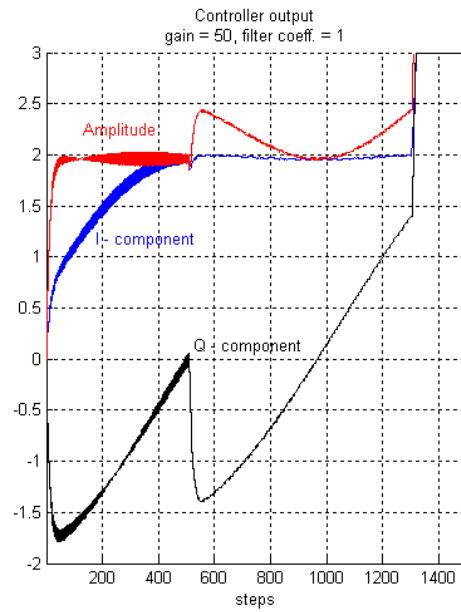
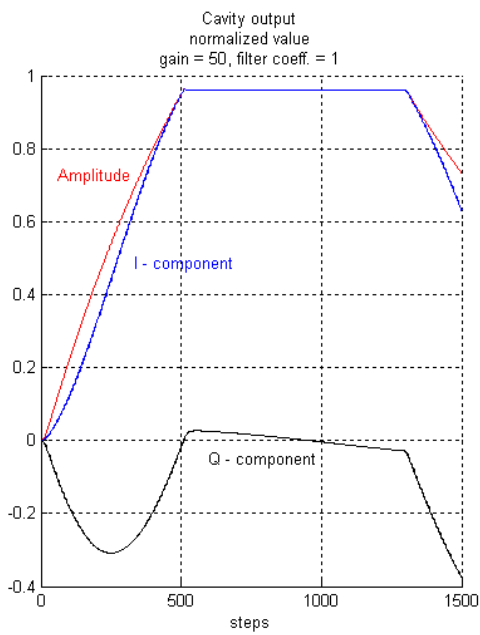


Figure 8. Cavity and FPGA controller output for feedback operation with gain =50 and two different filter coefficients. Relative average error for amplitude = $-4e-3$ ($f=1$), $-3e-3$ ($f=0.25$). Average error for phase = $-2.1e-3$ rad. ($f=1$), $-1.5e-3$ ($f=0.25$)

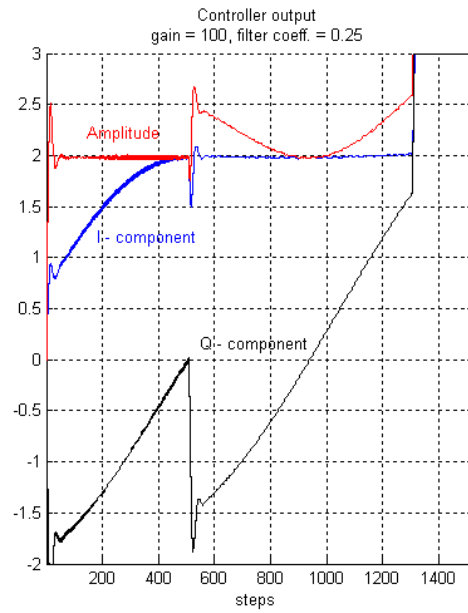
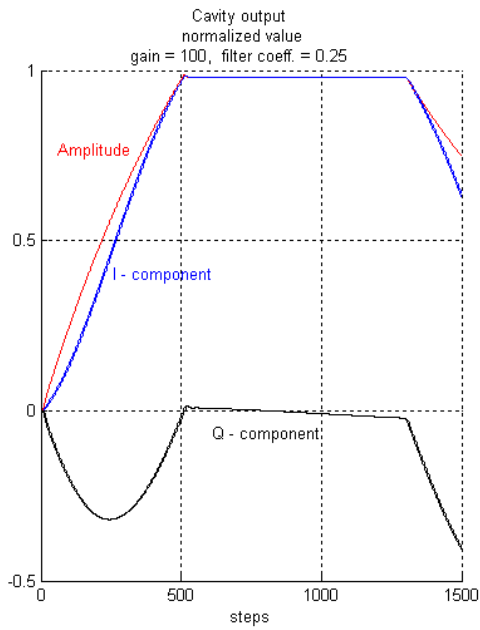
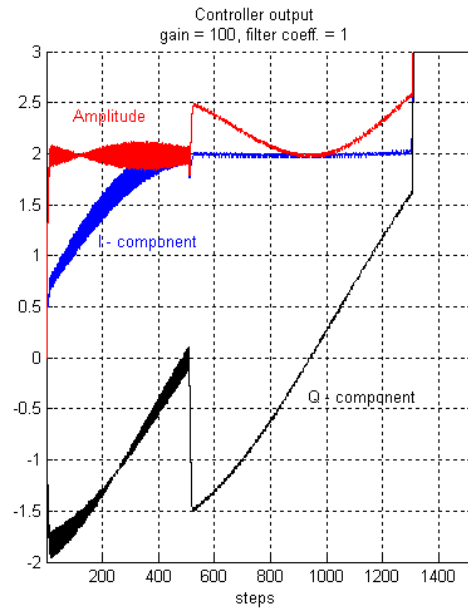
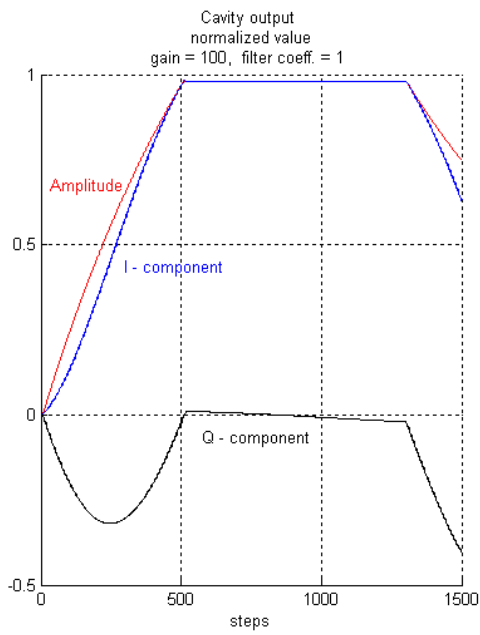


Figure 9. Cavity and FPGAcontroller output for feedback operation with gain =100 and two different filter coefficients. Relative average error for amplitude = $-7e-3$ ($f=1$), $-4.6e-3$ ($f=0.25$). Average error for phase = $-3.6e-3$ rad. ($f=1$), $-3e-3$ ($f=0.25$).

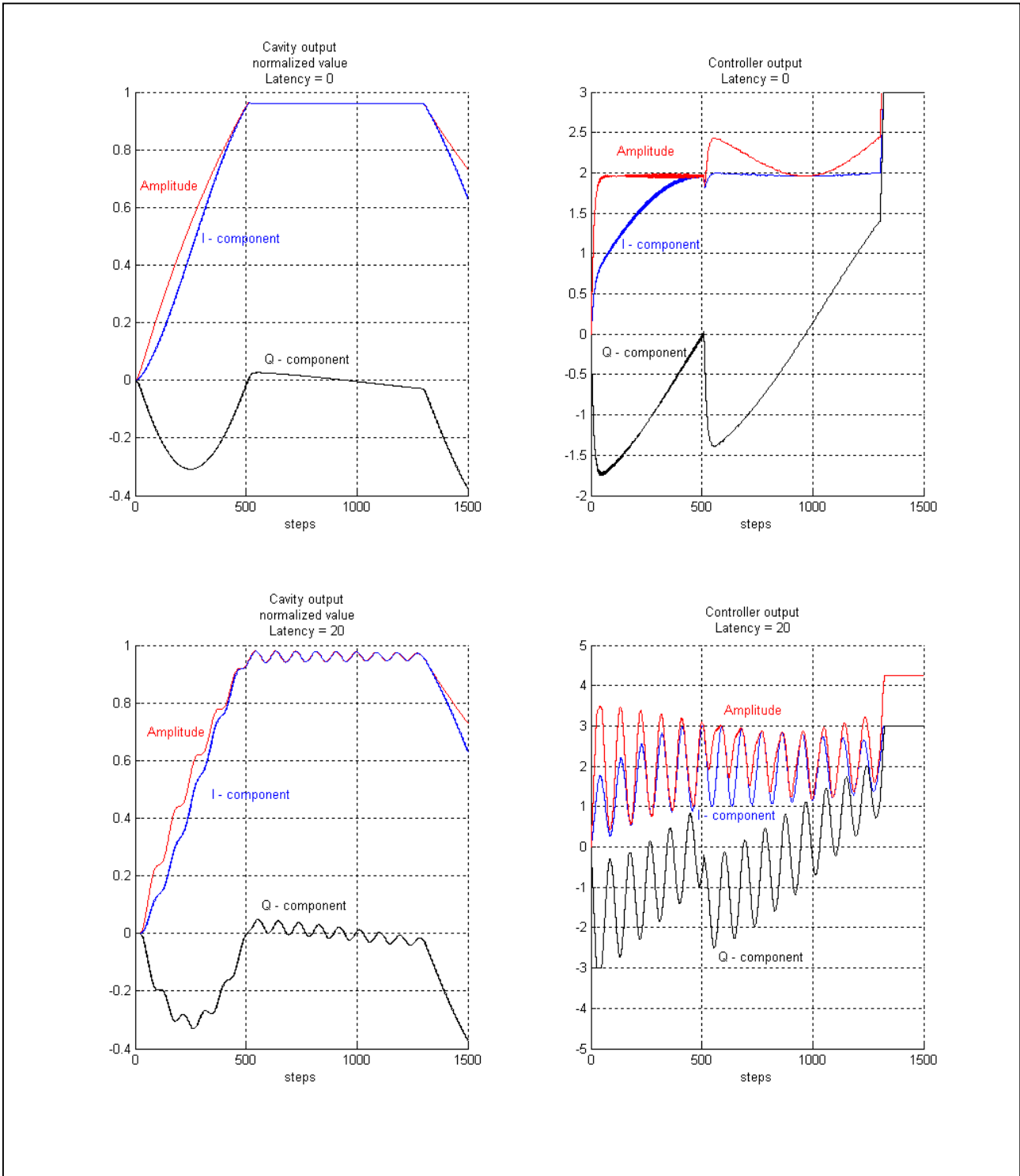


Figure 10. Cavity and FPGA controller output for feedback operation with gain = 50 and filter coeff. = 0.5 for hypothetical controller latency of 0 and 20.

CONCLUSION

The FPGA controller for the cavity control system has been carefully tested for different operational condition. The step operation method has been proved as an efficient one for testing the FPGA device coupled to the SIMULINK model of the analog real plant. The results of experiments have confirmed that required algorithm of signal processing has been strictly performed. The FPGA controller's output has been compared with the reference Matlab one. The relative average numerical error for amplitude and average error for phase has been estimated on the *flattop* level of the cavity voltage. The increased values of errors for feedback mode comparing to the open loop operation are a result of the oscillations caused by the controller latency. But practically it does not affect the cavity output up to the value of latency less then 5.

REFERENCES

1. T.Czarski, R.Romaniuk, K.Poźniak, S.Simrock, TESLA Technical Note, 2003-06,
http://tesla.desy.de/new_pages/TESLA/TTFnot03.html
2. T.Czarski et al., Tesla Technical Note, 2003-08,
3. T.Czarski et al., Tesla Technical Note, 2003-09,