Cavity parameters identification for TESLA control system development

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Abstract

The control system modeling for the TESLA - TeV–Energy Superconducting Linear Accelerator project has been developed for the efficient stabilization of the pulsed, accelerating EM field of the resonator. The cavity parameters identification is an essential task for the comprehensive control algorithm. The TESLA cavity simulator has been successfully implemented by applying very high speed FPGA – Field Programmable Gate Array technology. The electromechanical model of the cavity resonator includes the basic features - Lorentz force detuning and beam loading. The parameters identification bases on the electrical model of the cavity. The model is represented by the *state space* equation for the *envelope* of the cavity voltage driven by the current generator and the beam loading. For a given model structure, the over-determined matrix equation is created covering the long enough measurement range with the solution according to the least squares method. A low degree polynomial approximation is applied to estimate the time-varying cavity detuning during the pulse. The measurement channel distortion is considered, leading to the external cavity model seen by the controller. The comprehensive algorithm of the cavity parameters identification has been implemented in the Matlab system with different modes of the operation. Some experimental results have been presented for different cavity operational conditions. The following considerations have lead to the synthesis of the efficient algorithm for the cavity control system predicted for the potential FPGA technology implementation.

Keywords: Super conducting cavity control, model identification, system modeling and simulation.

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1. Introduction

The TESLA – XFEL project bases on the nine-cell super conducting niobium resonators to accelerate the electrons and positrons. The acceleration structure is operated in a standing π-mode wave at the frequency of 1,3 GHz. The RF oscillating field is synchronized with the motion of a particle moving at the velocity of light across the cavity.
The LLRF – Low Level Radio Frequency TESLA cavity control system has been developed to stabilize the accelerating fields of the resonators (figure 1). The control section, powered by one klystron, may consist of many cavities. One klystron supplies the RF power to the cavities through the coupled wave-guide with a circulator. The fast amplitude and phase control of the cavity field is accomplished by modulation of the signal driving the klystron from the vector modulator. The cavities are driven with the pulses of 1.3 ms in duration and the average accelerating gradients of 25 MV/m. The cavity RF signal is down-converted to the intermediate frequency of 250 KHz preserving the amplitude and phase information. The ADC and DAC converters link the analog and digital parts of the system. The digital signal processing is applied for the field vector detection, calibration and filtering. The control feedback system regulates the vector sum of the pulsed accelerating fields in multiple cavities. 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 the compensation of repetitive perturbations induced by the beam loading and by the dynamic Lorentz force detuning. The control block applies the value of the cavity parameters estimated in the identification system and generates the required data for the FPGA based controller.
A comprehensive digital system modeling has been developed for the investigation of the optimal control method for the cavity. The software model is applied as a pattern for the potential FPGA implementation in the real system. The design of a fast and efficient digital controller is a challenging task and it is an important contribution to the optimization of the TESLA accelerator.

Fig.1.

2. Cavity modeling and parameters description

2.1 General consideration

The recognition of cavity features can lead to the efficient algorithm stabilizing the EM field with the reasonable power consumption.
The primary parameters of the cavity model correspond to the resonant RLC circuit representation. The secondary parameters, derived from the primary ones and practically applied, are as follows: resonance frequency ≡ $\omega_0 = 2\pi f_0 = (LC)^{-½}$, characteristic resistance (normalized *half-shunt* impedance) ≡ $\rho = (L/C)^{½}$, load resistance (*half-shunt* impedance) ≡ R_L, loaded quality factor ≡ $Q_L = R_L/\rho$, half-bandwidth (HWHM) ≡ $2\pi f_{1/2} = \omega_{1/2} = 1/2CR_L = \omega_0/2Q_L$. The resonance frequency f_0 and characteristic resistance ρ is the invariant feature of the stationary circuit and are considered as the basic parameters with the well-defined nominal value. The diverse operational conditions influence the loading of the resonator and determine mutually the corresponding parameters R_L, Q_L and $\omega_{1/2}$.

The super-conducting resonator has an extremely high loaded quality factor $Q_L \sim 3\cdot10^6$ and the narrow bandwidth of about 430 Hz (FWHM). Hence, the cavity is very sensitive to the mechanical distortion caused by microphonics and the Lorentz force, changing the resonator's frequency (LC product). Therefore, the cavity model is a non-stationary one with the time varying *detuning* $\Delta\omega = \omega_0 - \omega_g = 2\pi\Delta f$, as the deviation from the generator nominal frequency

ω_g. The cavity detuning value can be comparable to the cavity bandwidth in the real operation condition. This cavity parameter has two dominate the deterministic components: the Lorentz force detuning and the initial *predetuning*. The mechanically biased *predetuning* attempts to compensate the EM forced detuning factor, during the operational condition of the cavity.
The identification of the time varying detuning is desired to generate the proper feed forward and set point tables for the required cavity performance. Additionally, it can be applied for the dynamic compensation of the cavity detuning by the piezo-translator system.
The mechanical model of the super-conductive cavity has been created for the simulation purpose. The model describes the Lorentz force detuning, which is a function of the square of time varying field gradient. It bases on the heuristic relationship for the independent mechanical modes of the cavity with the resonance frequency f_m, the quality factor Q_m and the Lorentz force detuning constant K_m for the given *m* mode. Three dominating resonance frequencies are considered in the cavity model and the superposition of all modes yield the resultant detuning.
The super-conducting cavity electro-mechanical model has been implemented in the Matlab system and the main parameters of the model for the simulation purpose are combined in the table 1.

Table 1.

The simulation results for the cavity real operational condition are presented in figure 2. The cavity is driven in the pulse mode forced by the control feedback supported by the feed-forward. During the first stage of the operation, the cavity is *filling* with constant forward power, resulting in an exponential increase of the electromagnetic field, according to its natural behavior in the resonance condition. When the cavity gradient has reached the required final value, the beam loading current is injected, resulting in the steady-state *flattop* operation. Turning off both, the generator and the beam current yields an exponential *decay* of the cavity field.

Fig.2.

2.2 Signal-dependent modeling of cavity parameters and direct identification for deterministic condition

The cavity parameters can be estimated for a given model structure, applying the input-output relation of the real plant. The cavity electrical model is based on the *state space* equation for the *envelope* of the cavity voltage v(t) driven with the current generator $i_g(t)$ and the average beam loading $i_{b0}(t)$ as follows:
$dv(t)/dt = A_e \cdot v(t) + \omega_0 \cdot \rho \cdot [i_g(t) - i_{b0}(t)]$, (1)
where, phasor $A_e = -\omega_{1/2} + i\Delta\omega$ for complex representation, or matrix $A_e = [-\omega_{1/2}, -\Delta\omega; \Delta\omega, -\omega_{1/2}]$ for vector representation.
The term $\omega_0 \cdot \rho = 2\omega_{1/2} \cdot R_L = 1/C$ is a, relatively stable and well-defined, driving factor. Therefore, the cavity bandwidth and detuning are responsible for the cavity behavior and should be carefully recognized.
Discrete samples of the input $[i_g(nT) - i_{b0}(nT)] = [(i_g)_n - (i_{b0})_n]$ and the output $v(nT) = v_n$, signals with the sampling interval of T, are considered for the digital implementation of the cavity model.
The complex solution of the *state space* equation for the successive n-1, n samples yields the difference equation, as follows:
$v_n = v_{n-1} \cdot \exp(T \cdot A_e) + \omega_0 \cdot \rho \cdot [(i_g)_{n-1} - (i_{b0})_{n-1}] \cdot [\exp(T \cdot A_e) - 1)]/A_e$. (2)

Applying the linear approximation: $\exp(A_e \cdot T) \approx 1 + T \cdot A_e$, for the small enough value of the sampling time T, a discrete form of the *state space* equation is as follows:

$v_n = (1 + T \cdot A_e) \cdot v_{n-1} + T \cdot \omega_0 \cdot \rho \cdot [(i_g)_{n-1} - (i_{b0})_{n-1}]$. (3)

Providing new symbols, yields:

$v_n = E \cdot v_{n-1} + u_{n-1} - (u_b)_{n-1}$, (4)

where, the cavity parameters phasor $E = (1-\omega_{1/2} \cdot T) + i\Delta\omega \cdot T$, for complex representation,
or system matrix $E = [1-T \cdot \omega_{1/2}, -T \cdot \Delta\omega; T \cdot \Delta\omega, 1-T \cdot \omega_{1/2}]$, for vector representation,
unified input signal samples: $u_{n-1} = T \cdot \omega_0 \cdot \rho \cdot (i_g)_{n-1}$ for generator, and $(u_b)_{n-1} = T \cdot \omega_0 \cdot \rho \cdot (i_{b0})_{n-1}$ for beam loading.

Solving the above recursive equation, the phasor E can be estimated for every step 'n' as the *signal-dependent* model of the cavity parameters as follows:

$E_n = (v_n - u_{n-1} + (u_b)_{n-1})/v_{n-1}$ for $v_{n-1} \neq 0$. (5)

Therefore, the cavity parameters can be identified for every n>2 step of the iterative processing as follows:

half-bandwith: $(\omega_{1/2})_n = (1- \mathit{Re}(E_n))/T$ (6)

detuning: $(\Delta\omega)_n = \mathit{Im}(E_n)/T$. (7)

The above *on-line* algorithm has been implemented in the Matlab system for the time interval T = 1μs. The initial parameters for the first two steps of the algorithm have been set from the table ($f_{1/2}$ and Δf).

The cavity response and the estimated parameters for the current generator step, without the beam, are presented in figure 3. For a deterministic and noiseless condition, the estimated cavity parameters are in perfect agreement with the given ones from the model.

Nevertheless, the cavity parameters identification algorithm is very sensitive to any disturbances in the real operational condition: stochastic noise, bit-resolution errors and I/Q detection inaccuracy. The FPGA cavity simulator has been used for its parameters identification in the step operation mode. The 18-bit resolution signal with the noise (variance of 1e-4 MV^2) after modulation and demodulation has been considered to investigate the on-line parameters identification. The Matlab cavity model has been applied as a reference one. The root of mean square error (RMS) has been calculated as the assessment of the cavity parameters identification. The simulation results are presented in figure 4 for driving current of i_g=16 mA. For the case of direct estimation of the cavity detuning, the RMS equals to 67 Hz. For the constant value of the cavity bandwidth, the off-line averaging gives a reasonable results. For the time-varying cavity detuning, several stochastic methods can be considered. A sophisticated filtering of the cavity output voltage could improve the results, but the additional delay can be expected. The cavity detuning identification is efficient only when the obtained result is useful for the control development. The applied estimation of the cavity parameters for the real operational condition is considered in the next chapter.

Fig.3.

Fig.4.

3. Cavity parameters identification

3.1 Total identification of cavity parameters in real operational condition

The cavity input and output signals are not available directly for the control purpose in the real operational condition. Furthermore, in the presence of noise, the stochastic approach should be performed for the cavity parameters identification. Assuming the static and linear distortion of the measurement channel, according to figure 5, the cavity discrete model, seen by the controller, can be expressed in the general vector form for the step 'k':

$v_k = E_k*v_{k-1} + u_0 + G*u_{k-1} - C\cdot(u_b)_{k-1}$ (8)

where, measured vectors: v_{k-1}, v_k, u_{k-1} – output and input values for step k-1 and k, respectively; $(u_b)_{k-1}$ – normalized beam loading vector for step k-1; the unknown parameters are: system matrix $E_k = [1-T\cdot\omega_{1/2}, -T\cdot\Delta\omega_k; T\cdot\Delta\omega_k, 1-T\cdot\omega_{1/2}]$; resultant distortion matrix - $G = [g_1, g_2; g_3, g_4] = C*D$; input distortion matrix – D; output distortion matrix $C = [c_1, -c_2; c_2, c_1]$; resultant offset vector - $u_0 = C*u'_0$; u'_0 – input offset vector.

Fig.5.

The cavity discrete model can be expanded to the scalar equations, applying the corresponding vector components as follows:

$(v_1)_k = -T\cdot\Delta\omega_k\cdot(v_2)_{k-1} + (1-T\cdot\omega_{1/2})\cdot(v_1)_{k-1} + u_{01} + g_1\cdot(u_1)_{k-1} + g_2\cdot(u_2)_{k-1} - [c_1\cdot(u_{b1})_{k-1} - c_2\cdot(u_{b2})_{k-1}]$ (9)

$(v_2)_k = T\cdot\Delta\omega_k\cdot(v_1)_{k-1} + (1-T\cdot\omega_{1/2})\cdot(v_2)_{k-1} + u_{02} + g_3\cdot(u_1)_{k-1} + g_4\cdot(u_2)_{k-1} - [c_1\cdot(u_{b2})_{k-1} + c_2\cdot(u_{b1})_{k-1}]$ (10)

The unknown parameters of the cavity, which are nine constant values and *step-varying* detuning $\Delta\omega_k$, can be extracted from the above equations moving again to the vector format for step k as follows:

$v_k = [-(v_2)_{k-1}; (v_1)_{k-1}] * T\cdot\Delta\omega_k + h_k * y$ (11)

where, $y = [(1-T\cdot\omega_{1/2}); u_0; g_1; g_2; g_3; g_4; c_1; c_2]$ - column vector (9x1) of constant parameters, $h_k = [v_{k-1}, eye(2), [(u^T)_{k-1}; 0,0], [0,0; (u^T)_{k-1}], -(u_b)_{k-1}, [(u_{b2})_{k-1}; -(u_{b1})_{k-1}]]$ – *signal-dependent* matrix (2x9) of the model structure related to the parameters.

Let us assume the *step-varying* cavity detuning $\Delta\omega_k$ as a L-order discrete series for the successive steps k = m:n, as follows:

$\Delta\omega_k = w_k * x$, (12)

where, the column vector 'x' contains L unknown series of coefficients, and the row vector w_k describes the given L-order series structure of the *step-varying* detuning model.

Applying the above equations for all N = m-n+1 steps within the range k = m:n, the cavity model consists of 2N equations expressed by the matrix, as follows:

$V = X * x + Y * y = [X, Y] * [x; y] = H * z$ (13)

where, V – total output vector (2N x 1), thus $V(2k-1:2k) = v_k$; X – structure matrix (2N x L) of the model part related to the detuning, thus, $X(2k-1:2k, :) = T\cdot[-(v_2)_{k-1}; (v_1)_{k-1}]*w_k$; Y – structure matrix (2N x 9) of the model part related to the parameters, thus $Y(2k-1:2k, :) = h_k$
H = [X, Y] – total structure matrix (2N x L+9), z = [x; y] – total vector of unknown L+9 values.

The vector 'z' can be effectively estimated in the noisy condition with the over-determined matrix equation created for the long enough range k = m:n. Multiplying two sides of the above equation by matrix transposition H^T, the solution for the vector z is given by:

$z = (H^T*H)^{-1}*H^T*V$ (14)

It is a unique and optimal solution, according to the *least square* (LS) method for the measured data of the vector V and the matrix H.

The simultaneous estimation of the all parameters is quite efficient in the presence of noise, but less accurate than the consecutive method described below.

3.2 Separated identification of stable cavity parameters

The time-varying detuning $\Delta\omega_k$ can be eliminated from the general scalar equations, in the first stage of the cavity parameters identification. The remained, unknown, relatively stable parameters of the cavity model can be extracted from the residual equation, moving again to the vector format. Thus, the compact, reduced relation for step k is obtained as follows:

$(v^T)_k * v_{k-1} = f_k * y$, (15)

where, $y = [(1-T\cdot\omega_{1/2}); u_0; g_1; g_2; g_3; g_4; c_1; c_2]$ - column vector (9x1) of constant parameters,

$f_k = [(v^2)_{k-1}, (v^T)_{k-1}, (v_1)_{k-1}\cdot(u^T)_{k-1}, (v_2)_{k-1}\cdot(u^T)_{k-1}, -(v^T)_{k-1}*(u_b)_{k-1}, \det[v_{k-1}, (u_b)_{k-1}]]$ - row vector (1x9) of the model structure.
Applying the above equation for all the steps, within the range k = m:n, the cavity model can be expressed in the matrix format, as follows:
$U = F * y$, (16)
where, U – total output vector ((n-m+1) x 1), so $U(k) = (v^T)_k * v_{k-1}$, F – structure matrix ((n-m+1) x 9), so $F(k, :) = f_k$.
The vector parameters 'y' can be effectively estimated according to the LS method and the solution is given by:
$y = (F^T*F)^{-1}*F^T*U$. (17)
Thus, the cavity parameters estimation is as follows:
$\omega_{1/2} = (1-y(1))/T$, $u_0 = y(2:3)$, $g = [g_1; g_2; g_3; g_4] = y(4:7)$, $c = [c_1; c_2] = y(8:9)$. (18)
3.2.1. Successive identification of cavity parameters
The process of further identification can be realized, for the better parameters assessment in the practical algorithm implementation. Thus, the different cavity operational conditions are considered to estimate the corresponding part of the parameters according to the decomposed matrix equation as follows:
$U = F * y = F(:, 1:3) * y(1:3) + F(:, 4:7) * y(4:7) + F(:, 8:9) * y(8:9)$. (19)
Three periods of the cavity operation: *filling, flattop, decay* are considered for the successive parameters estimation. Only the part of the parameters vector 'y' is estimated according to the LS method for each range. The vector and matrix of the cavity model of the proper structure are created, applying the part of matrix F and vector U, which were determined earlier, with the parameters according to the table 2.

Table 2.

The successive parameters estimation of the cavity model is excellent in the deterministic condition, but unfortunately it is very sensitive for any external interference.
3.3. Cavity detuning estimation by the *least square fitting* with polynomial approximation
Due to the mechanical inertia, the non-stationary detuning $\Delta\omega_k$ is relatively slowly varying during the pulse and the low degree polynomial approximation can be considered within the partial range. Therefore, for every given range k = m:n, the cavity model is *time–dependent* with the limited amount of unknown constant parameters and the *least squares fitting* (LS) with (n-m+1) samples can be applied for the identification process.
3.3.1. Estimation of cavity detuning *on-line*
Let us assume the *step-varying* L-degree polynomial approximation of the cavity detuning $\Delta\omega_k$, as a partial Taylor series related to the current point n, for the successive, previous k steps k = m:n, as follows:
$\Delta\omega_k = w_k * x$, (20)
where, the column vector 'x' consists of L+1 unknown coefficients and the row vector w_k describes the polynomial structure of the parameter model:
$w_k(1) = 1$; $w_k(1+i) = (n-k)^i$ for i = 1:L. (21)
The resultant column vector $\Delta\Omega$ of the successive values of the cavity detuning within the current approximation range k = m:n is as follows:
$\Delta\Omega = W * x$, so $\Delta\Omega(j) = \Delta\omega_{n-j+1}$, for j = 1:n-m+1, (22)
where, *Vandermonde* matrix W(n-m+1 x L+1) with j-row vector $W(j) = w_{n-j+1}$.
Applying the general matrix format for the total identification of the cavity parameters (chapter 3.1) with the previously estimated vector 'y' of constant parameters, the only vector x remains unknown as follows:
$V - Y * y = X * x$. (23)

The vector coefficients ‘x’ can be effectively estimated according to the LS method again, and the solution is given by:

$x = (X^T*X)^{-1}*X^T*(V - Y*y)$. (24)

Therefore, the estimation of the *on-line* cavity detuning, for the current step n is as follows:

$\Delta\omega_n = x(1)$. (25)

The simulation results for driving current of i_g = 16 mA, without the beam, and with the noise, (variance of 1e-4 MV^2) added to the cavity output, are presented in the figure 6, for different degree of the polynomial approximation. The root of *mean square error* (RMS) is calculated versus the range of the polynomial approximation and the cavity detuning is estimated for the optimal range of the LS algorithm. A 1st-degree polynomial approximation seems to be quite sufficient with its reasonable calculation procedure and can be considered for the future DSP implementation. The adaptive moving range for the different curvature can also be considered.

Fig.6.

3.3.2. Estimation of cavity detuning *off-line*

For the repetitive Lorentz force detuning, the *off-line* identification procedure by the averaging can be applied. The LS algorithm could determine the (n-m+1) estimations for every point within the moving range k = m:n of the polynomial approximation. Taking the average value of them, the smooth detuning approximation can be obtained with the accuracy of ~ 1 Hz (rms), even for the more noisy output signal.

On the other hand, the only higher degree polynomial approximation for the full fixed range can be considered as the *off-line* cavity detuning estimation. The simulation results for the driving current of i_g=16 mA, with two noisy signals (variance of 1 MV^2 and 1e-2 MV^2), and applying different degrees of the polynomial approximation, within the full range of 2000 steps, is presented in figure 7.

In the Matlab implementation of the cavity detuning estimation by the LS algorithm, the total measurement range has been divided into the parameterized array, specified by its dimension and the polynomial degree for each sub-range autonomously.

Fig.7.

4. Initial testing of the real cavity system

The Chechia cavity set-up in DESY has been applied for the initial testing of the FPGA controller and verification of the parameters identification algorithm according to the scheme presented in figure 8. The control data generated by Matlab system are loaded to the part of the internal FPGA memory as a feed-forward (FF) table driving the Chechia cavity. The output data of the cavity are acquired to another area of the memory during the pulse operation of the controller. Subsequently, the chosen data are conveyed to the Matlab system for the parameters identification processing between the pulses. For the comparison, the Matlab cavity model is driven in the same condition: with the same FF table applying the estimated Chechia parameters – half-bandwidth and detuning vector. The estimated parameters of the cavity can be used cyclically for the adaptive improvement of the required control data.

Fig.8.

Initial testing of the Chechia system has focused the attention on the internal cavity parameters - half-bandwidth and non stationary detuning. Thus, the compensation of the environmental features – the *offset*, the scaling and phase calibration has been prepared experimentally.
In the first stage of the experiments, the cavity step response for the different klystron current has been considered for the initial system recognition. The results are presented in figure 9 for two operation periods – *filling* and *decay*.

Fig.9.

The estimation of the cavity detuning has been performed independently in these two periods by applying 1 to 3 degree polynomial approximation. Two curves nearly overlap in the turning point but the electromechanical model does not explain the fast recovery of the cavity detuning. Another surprise is a different half-bandwidth for these two periods.
The next experiments would try to verify the Matlab cavity model and the efficiency of the parameters identification algorithm. The Chechia cavity has been driven with a simple FF table striving to obtain the *flattop* level without the beam loading. Two cases for different operational condition are presented in figures 10 and 11. The Chechia cavity and Matlab model responses have been compared, while driven in the same condition. The presumed detuning determines the initial FF table according to the cavity model. The estimated real detuning has been applied for the Matlab cavity model. When the curves are closer to each other, the better is the amplitude and phase stabilization on the *flattop* level. But independently, a quite good agreement for the envelopes of both objects is observed in all cases. Thus, the Matlab model of the cavity has been confirmed using the Chechia test bed. Consequently, the cavity parameters identification has been verified for the control purpose.
Nevertheless, a set of not favorable stochastic conditions, like microphonics, nonlinearities and other interferences during the measurements may lead to the not expected results. The numerical problems with the bad conditioned matrix can also be expected. Thus, the proposed algorithm of the parameters identification should be carefully checked in diverse conditions of cavity operation.

Fig.10.

Fig.11.

5. Conclusions

The initial tests applying the FPGA based controller have been carried out with the Chechia cavity in DESY. The parameters identification algorithm, according to the algebraic model of the superconductive cavity has been presented. Applying the input-output relation, the over-determined matrix equation has been considered with the least squares solution for the unknown parameters. The low degree polynomial approximation is applied for not stationary detuning estimation. The electrical model of the cavity has been confirmed using the Chechia cavity set-up. The parameters identification algorithm has been verified for the cavity control system development.

6. References

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Table 1.

CAVITY ELECTRICAL parameters	CAVITY MECHANICAL modes parameters
f_0 = 1300 ……… resonance frequency [MHz] ρ = 520 ………. characteristic resistance [Ω] $Q_L = 3\cdot10^6$………..loaded quality factor $R_L = Q_L\cdot\rho$ = 1560…load resistance [MΩ] $f_{1/2} = f_0/2Q_L$ = 216…half band-width [Hz] Δf =390 ………… .pre-detuning [Hz]	f = [235,290,450]…resonance frequencies vector [Hz] Q = [100,100,100]…… quality factor vector K = [0.4, 0.3, 0.2]……Lorentz force detuning constants vector [Hz/(MV)^2]

Table 2.

Range		Signal condition	Parameters vector	Structure matrix	Structure vector
Total pulse		-	y	F	U
1	*decay*	$u_k = 0$, $(u_b)_k = 0$	y(1:3) = [(1-T·$\omega_{1/2}$); u_0]	F(*decay*, 1:3)	U(*decay*)
2	*filling*	$(u_b)_k = 0$	y(4:7) = [g_1; g_2; g_3; g_4]	F(*filling*, 4:7)	U(*filling*) - F(*filling*, 1:3) * y(1:3)
3	*flattop*	$(u_b)_k \neq 0$	y(8:9) = [c_1; c_2]	F(*flattop*, 8:9)	U(*flattop*) - F(*flattop*, 1:7) * y(1:7)

Cavity parameters identification for TESLA control system development

Figures with captions

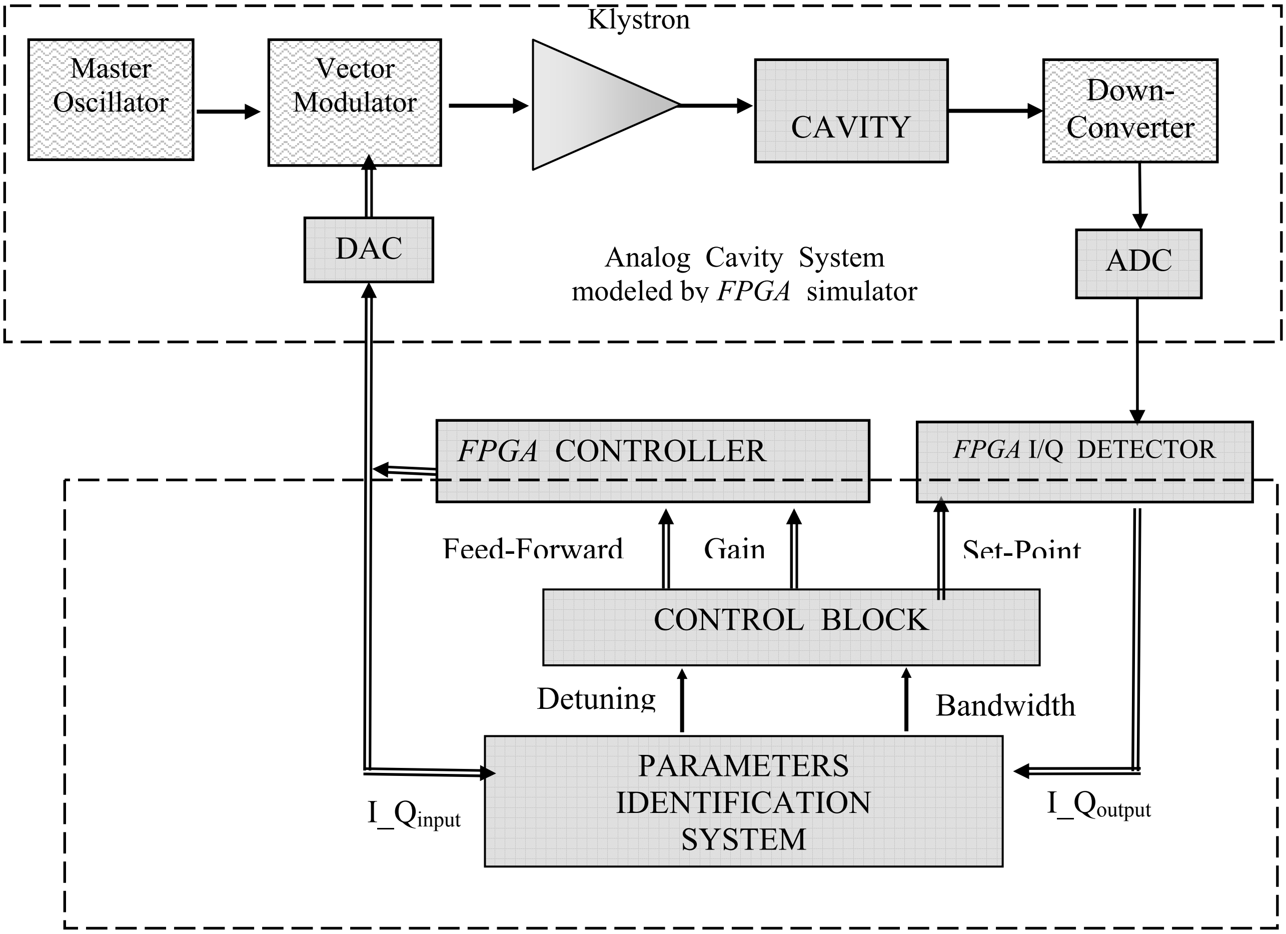

Fig.1. Functional block diagram of LLRF cavity control system (for one cavity)

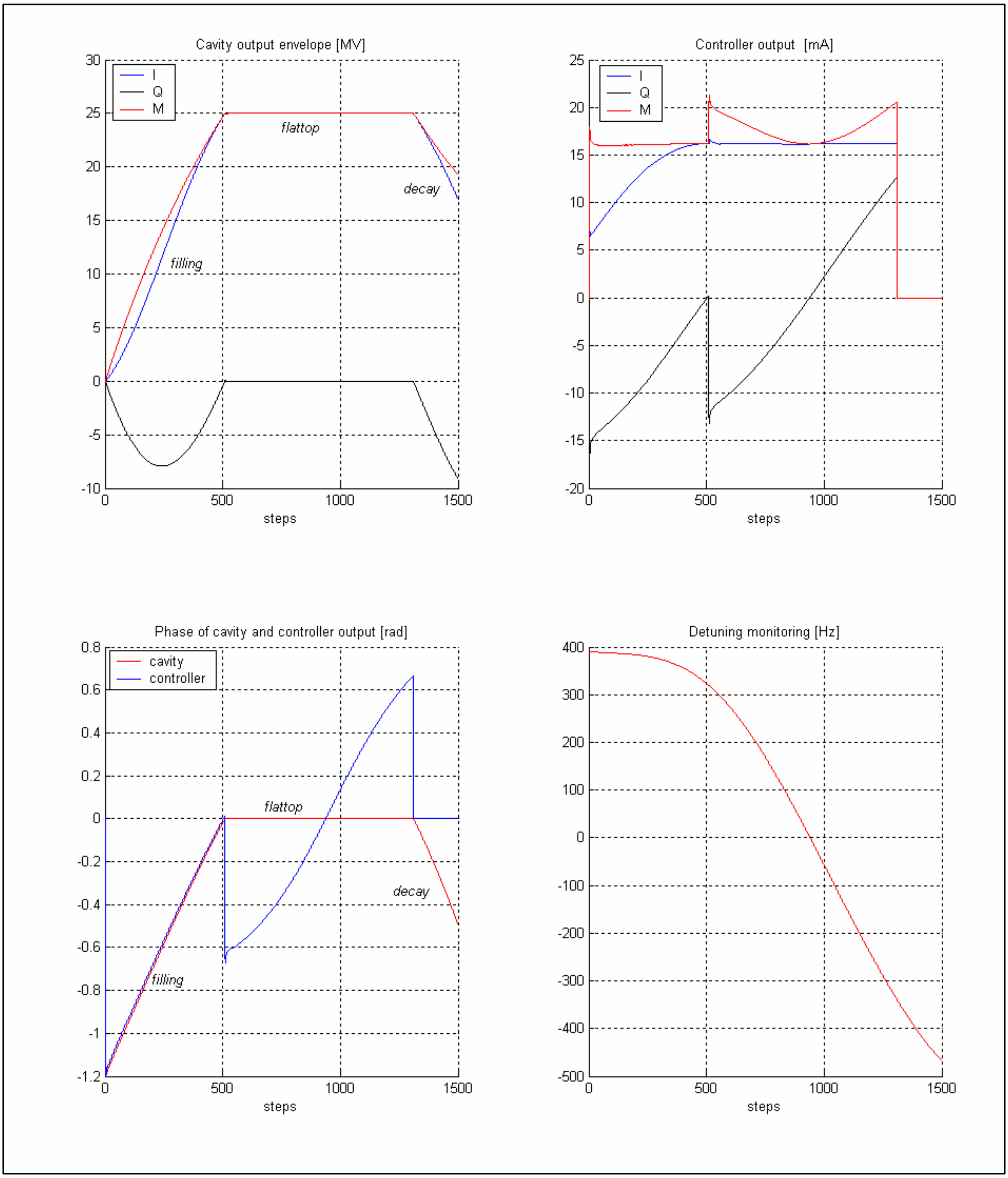

Figure 2. The MATLAB results of simulation for cavity real operation condition

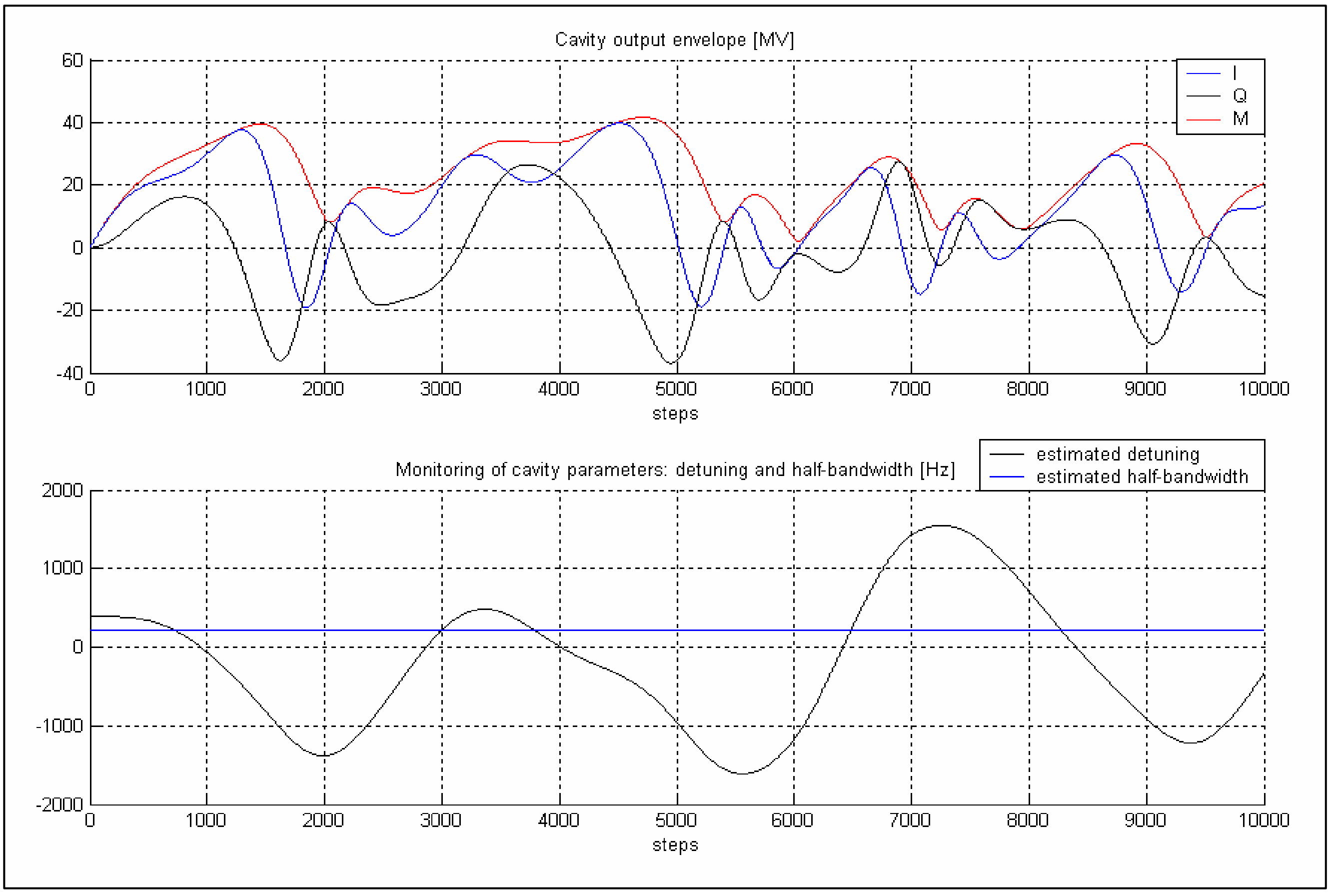

Fig. 3. Cavity step response for driving current of i_g=16 mA (i_{b0} = 0) and cavity parameters monitoring

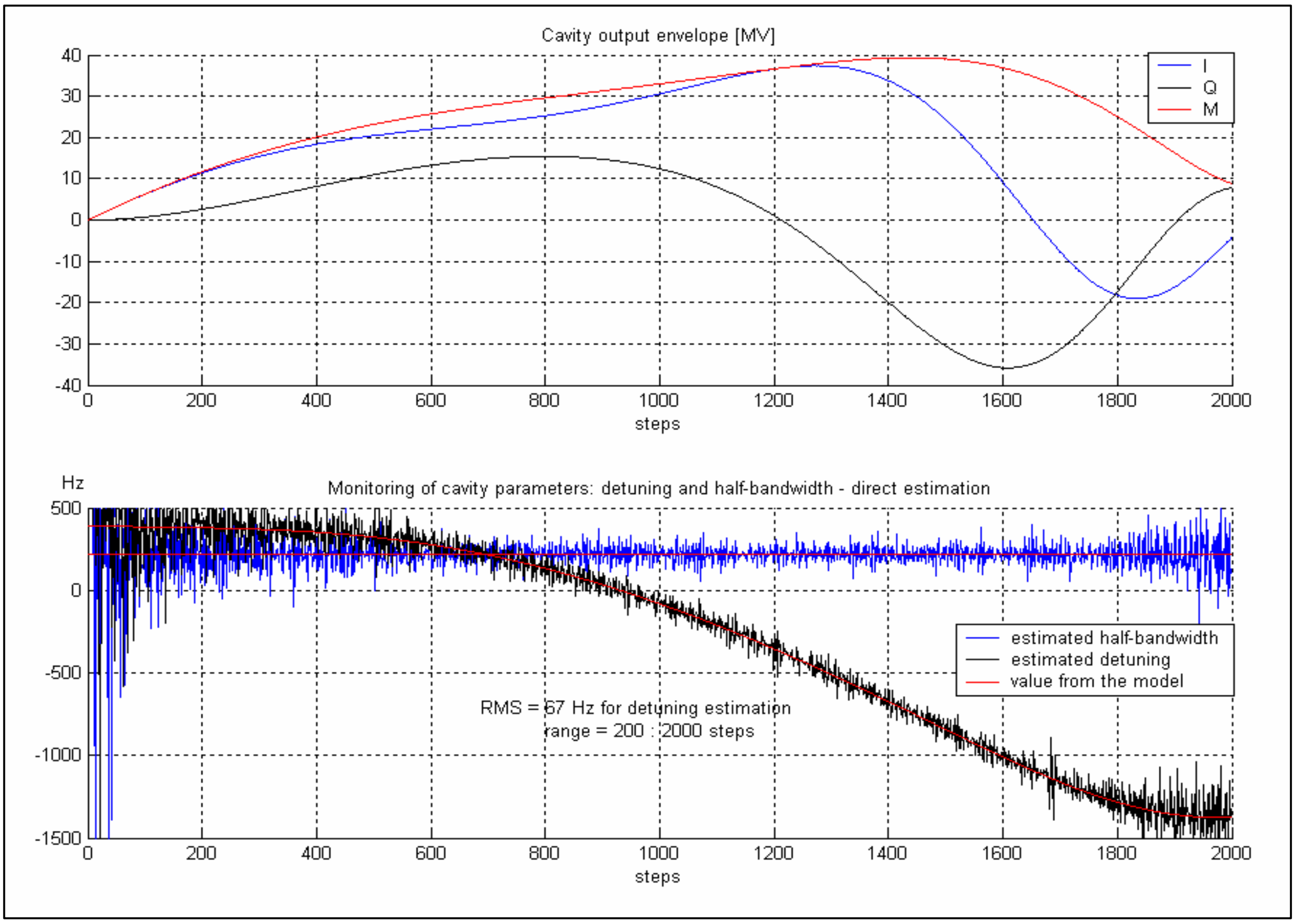

Figure 4. Direct estimation of FPGA cavity parameters for driving current of i_g=16 mA with noisy cavity output (variance of 1e-4 MV^2)

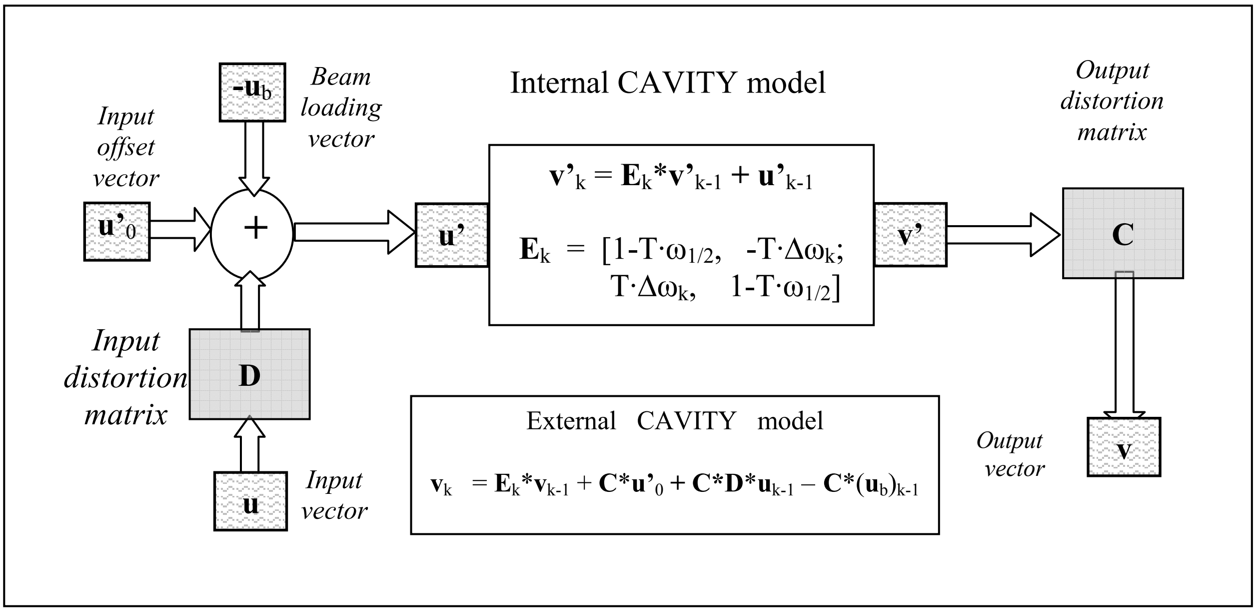

Figure 5. Algebraic model of cavity environment system

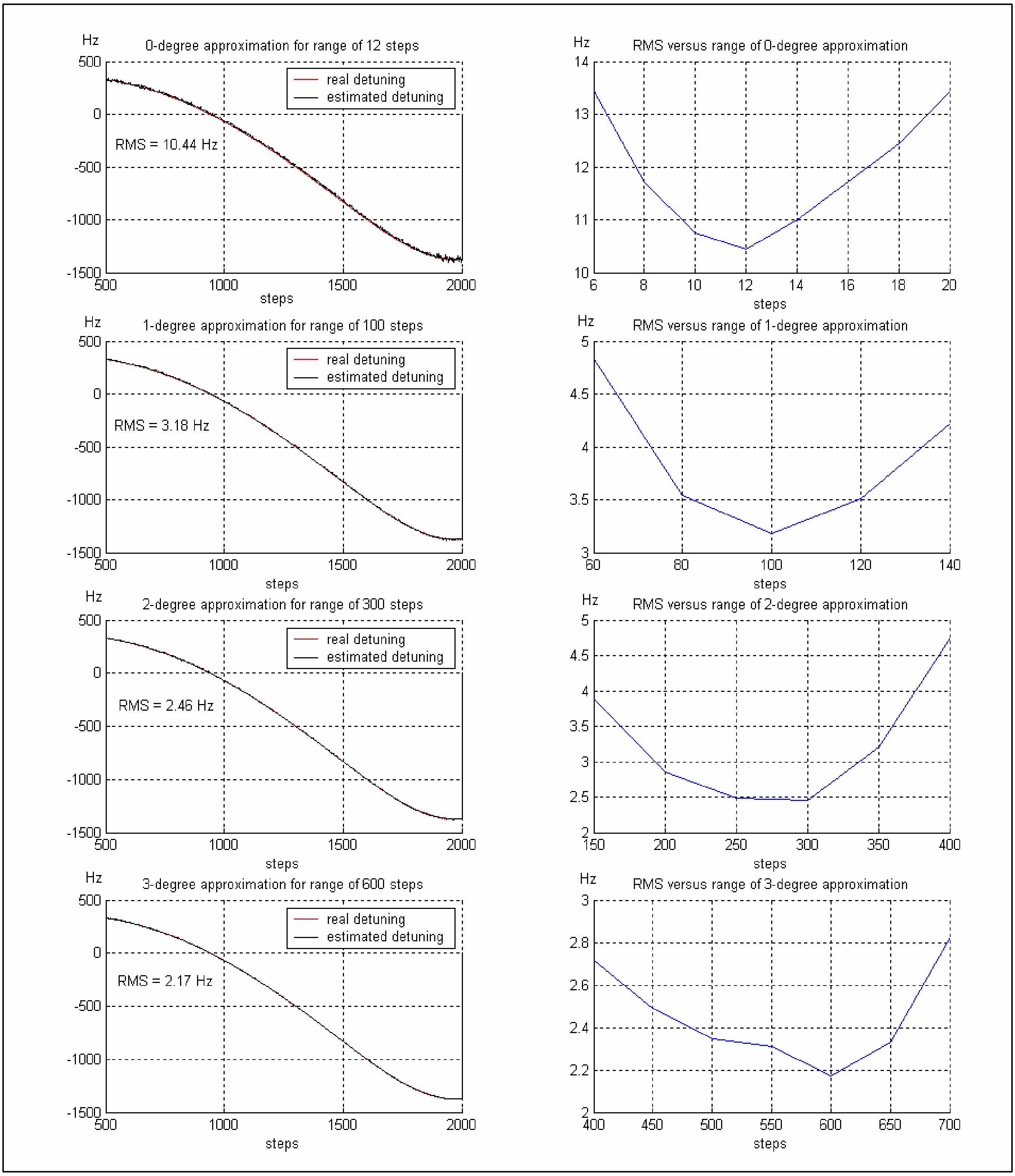

Figure 6. Cavity detuning *on-line* estimation by LS method with noisy cavity output (variance of 1e-4 MV^2) and root of *mean square error* (RMS) for different degrees and ranges of polynomial approximation

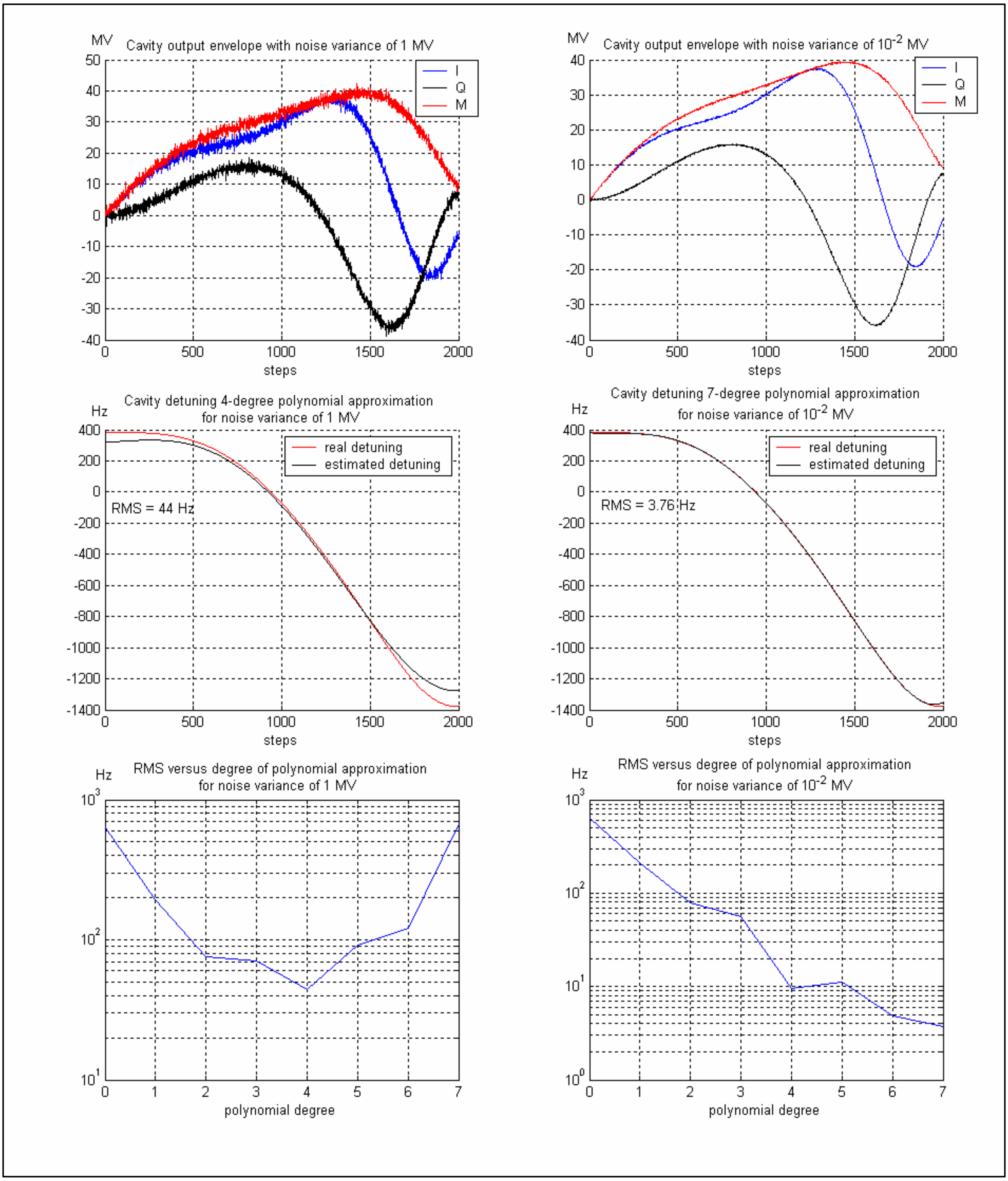

Figure 7. Cavity detuning *off-line* estimation by LS method for two noisy signals (variance of 1 MV^2 and 1e-2 MV^2), and root of *mean square error* (RMS) versus degree of polynomial approximation for range of 2000 steps

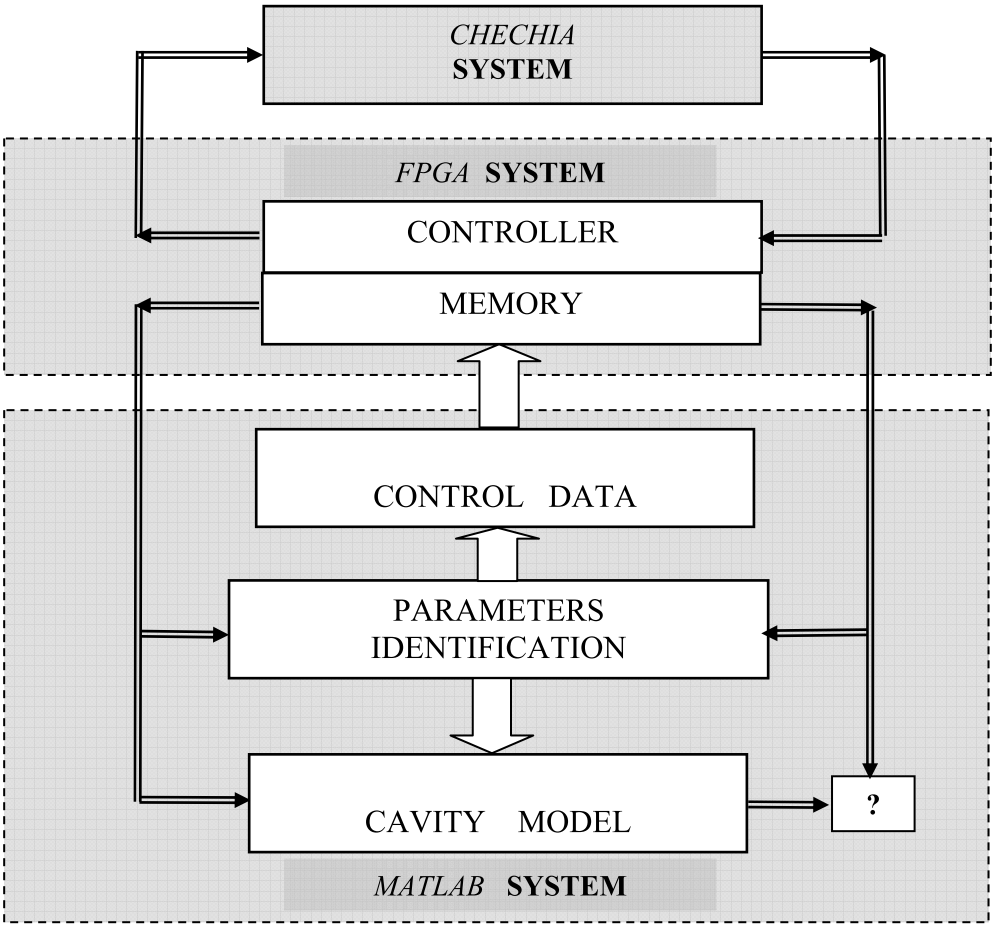

Figure 8. Functional diagram of testing system for CHECHIA cavity driven with FPGA controller supported by MATLAB system

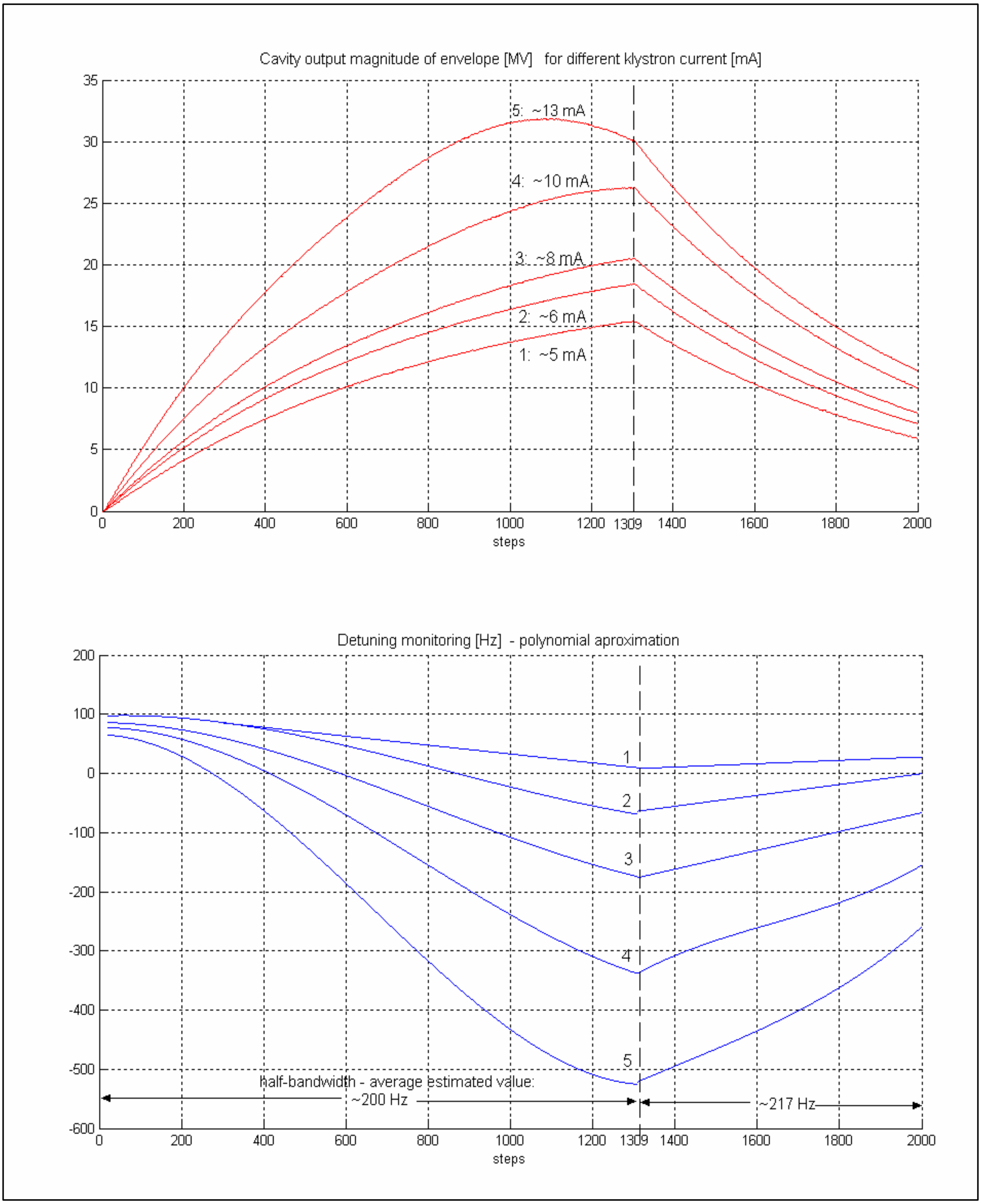

Figure 9. Step response of CHECHIA cavity and estimated detuning for different klystron current

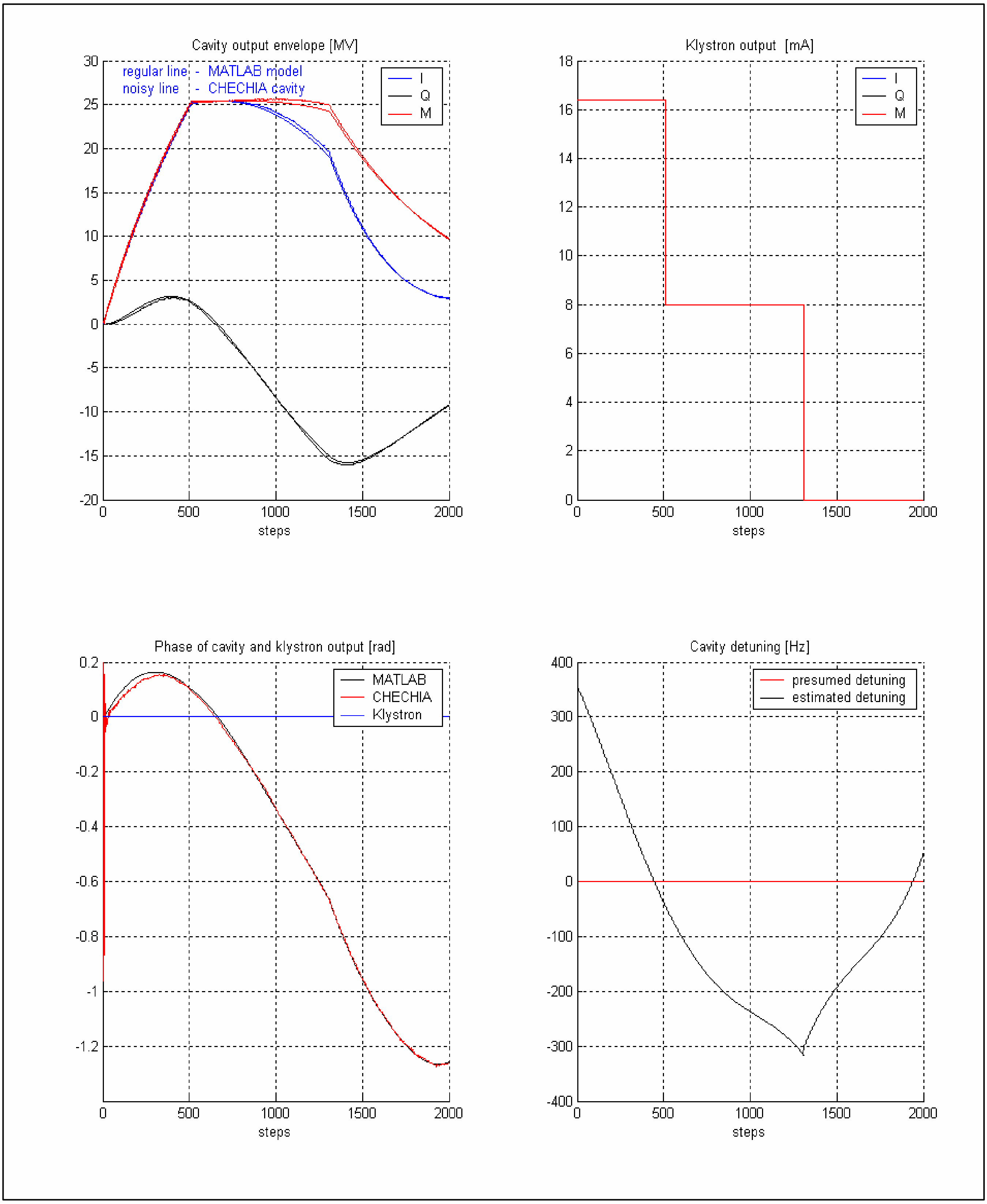

Figure 10. Feed-forward cavity driving – CHECHIA and model comparison (1)

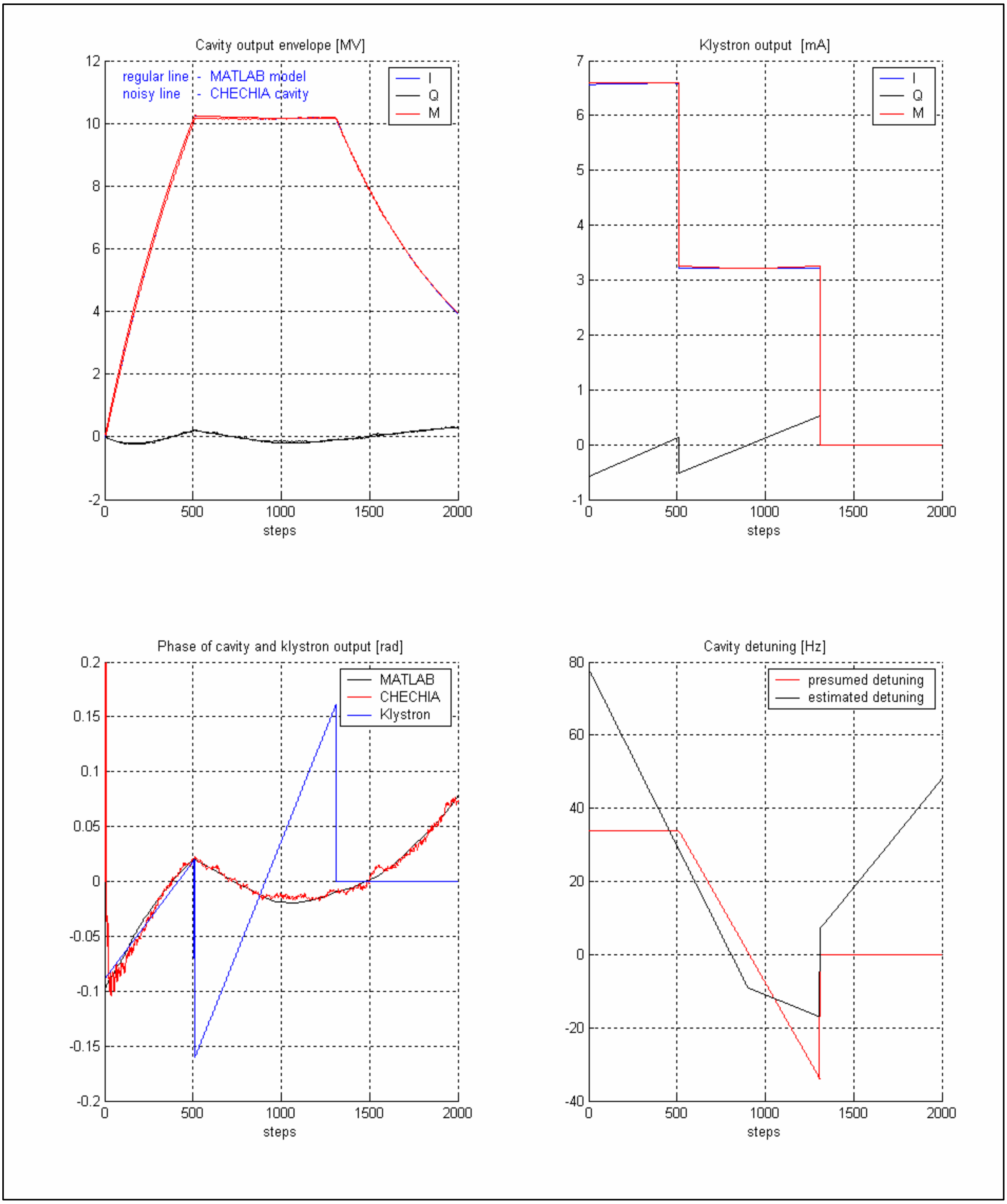

Figure 11. Feed-forward cavity driving – CHECHIA and model comparison (2)