Development of linear models for T-15 plasma control system

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1. Introduction

Presented work is associated with the development of magnetic plasma control system of modernized at the moment T-15 tokamak [1]. Known controller design technology for magnetic control of tokamak plasma parameters (such as the position, shape, and current) requires the development of simplified linear models of the evolution of these parameters. For such models the identification procedure [2] were used, which is based on the direct calculation of the dynamic responses of plasma parameters to the voltages applied to poloidal field coils (PFCs) or currents in its. Previously such procedure was not used fully for such purposes. Dynamic response calculations were carried out by use of a non-linear numerical model implemented in the DINA code [3], during which responses of the currents in the coils of the poloidal magnetic system T-15, the plasma current, the gaps between the plasma boundary and given geometric points (Fig. 1), the position of the magnetic axis of the plasma (electromagnetic identification system and plasma equilibrium) to the step voltages, applied to PFCs were obtained. Then the dependences of the plasma parameter responses were approximated by a linear model by use of the identification system theory [2]. Plasma parameter evolutions calculated by identification linear models were compared with T-15 plasma behaviors simulated by both non-linear DINA model and standard linear models [4] obtained by the direct linearization of non-linear plasma model at specified time moments.

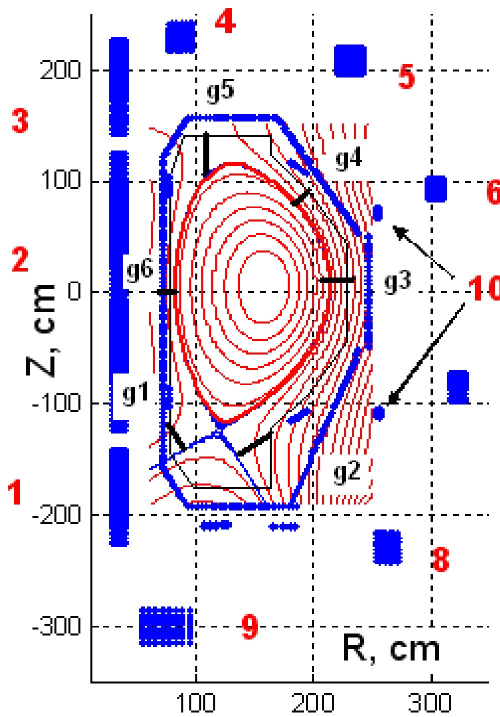


Fig. 1. Poloidal field system of T-15 and gaps between plasma and first wall

2. Implementation of identification linear model

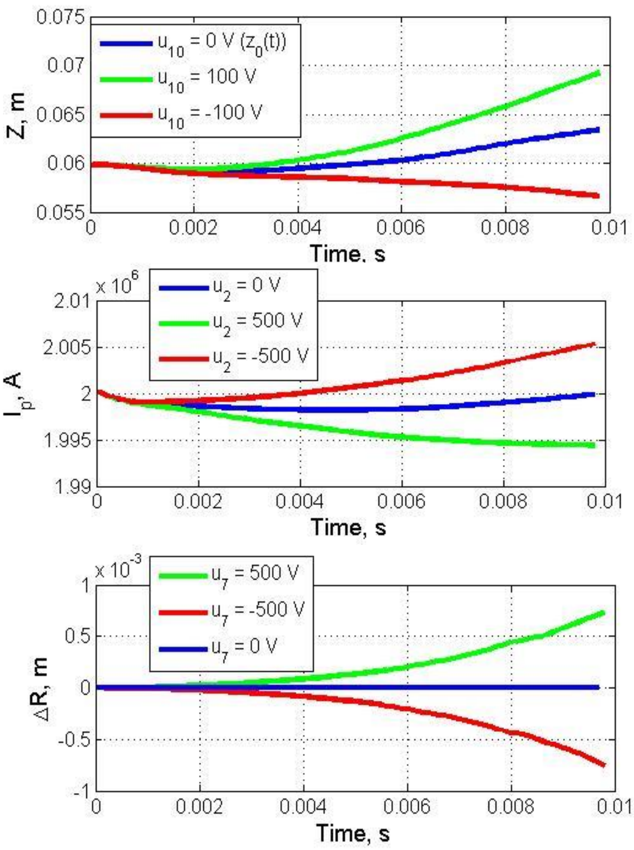
The linear model in state space form looks like:

$$\begin{cases} d\vec{x}(t)/dt = A\vec{x}(t) + B\vec{u}(t) \\ \vec{y}(t) = C\vec{x}(t) + D\vec{u}(t) \end{cases} \quad (1)$$

Here A, B, C, D are the matrixes of the model, $\vec{x}$ is the state vector, $\vec{y}$ is the vector with measured parameters (plasma current, gaps between plasma and first wall, currents in PFCs), $\vec{u}$ is the vector with voltages in PFCs. Identification procedure assumes the quadratic representation of evolution of $\vec{y}$ as result of the $\vec{u}$ disturbance, i. e. y_i reaction to the u_k disturbance can be expressed as

$$y_i(t) = y_{i0}(t) + \sum_k f_{ik} u_k \Big|_{t=0} t + \frac{1}{2} \sum_k g_{ik} u_k \Big|_{t=0} t^2 \qquad (2)$$

or $\Delta y_i(t) = \sum_k f_{ik} u_k \Big|_{t=0} t + \frac{1}{2} \sum_k g_{ik} u_k \Big|_{t=0} t^2$. Here $y_{i0}(t)$ is the y_i evolution when $u_k = 0$.



In Fig.2 one can see that really the non-linear response of T-15 plasma vertical position Z to disturbance u_{10} can be described by $z(t) = z_0(t) + \frac{1}{2} g_{Z10} u_{10} t^2$ .Correspondidly the responces of plasma current and radial position are described by $\Delta I(t) = f_{I2} u_2 t + \frac{1}{2} g_{I2} u_2 t^2$ and $\Delta R(t) = \frac{1}{2} g_{R7} u_7 t^2$.

Unlike standard linear model technique such quadratic representation allows calculating *directly* the state vector $\vec{x}$ for linear model (1) by the measurement parameters vector $\vec{y}$. Identification linear model can be obtaining by replacing the variables in (2): $x_{1i} = \Delta y_i(t)$; $x_{2i} = d\Delta y_i(t)/dt$. Then it can be written:

$$\begin{cases} \dfrac{dx_{1i}(t)}{dt} = x_{2i} + \sum_k f_{ik} u_k \\ \dfrac{dx_{2i}(t)}{dt} = \sum_k g_{ik} u_k \end{cases} \qquad (3)$$

If to define $\vec{x}=\begin{bmatrix} x_{1i} \\ x_{2i} \end{bmatrix}$, then we can represent (3) in standard linear form (1), where

$$A=\begin{pmatrix} 0100...0000 \\ 0000...0000 \\ 00010...000 \\ .... \\ 00000...001 \\ 00000...000 \end{pmatrix}, \quad B=\begin{pmatrix} f_{11}\cdots f_{1m} \\ g_{11}\cdots g_{1m} \\ .... \\ f_{n1}\cdots f_{nm} \\ g_{n1}\cdots g_{nm} \end{pmatrix},$$

$$C=\begin{pmatrix} 100...00000 \\ .... \\ 000...00010 \end{pmatrix}, \; D=0.$$

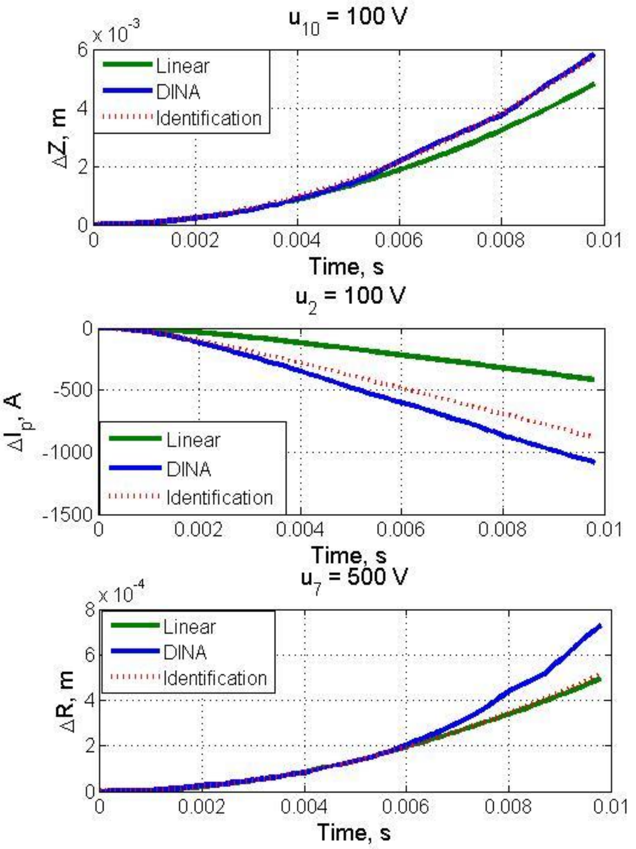


Fig. 3. Comparison of ΔZ, ΔI_p and ΔR evolutions in T-15 tokamak simulated by different models

In Fig. 3 the comparison of T-15 plasma magnetic coordinates (*ΔZ*, *ΔR*) and plasma current (ΔI_p) evolutions during VDE simulated by standard linear, identification linear and DINA non-linear models are presented. One can see that in the initial period of evolution (~ 2 ms) in comparison with DINA non-linear model the identification linear model describes the T-15 plasma behavior much better that the standard linear one (especially *Z* and *I*). Obtained above linear model (1) is used for design of plasma control system with application of voltages to PFCs.

3. Identification by currents in PFCs

Similar to the identification by voltages applied to PFCs, another linear model (1) for T-15 plasma was obtained with identification method by approximation of the plasma parameter responses to the changes of currents in PFCs. At the same time the T-15 plasma was stabilized in vertical direction by regulator $u_{10}=-K\dfrac{d\Delta z}{dt}$. To approximate the responses of gaps and I_p to the increment currents in PFCs the model in the form of transfer functions was used: $\Delta y_i = G_{ik}\Delta I_k$, where $G_{ij}=\dfrac{K_{ik}}{t_{ik}s+1}$. The coefficients K_{ik} and t_{ik} need to be defined. The resulting linear model is used to control the plasma parameters in the prescribed currents. As example the results of DINA calculation of responses to the current changes in the poloidal coil 7 are shown in Fig. 4. Dotted line shows the approximation of responses by transfer functions. Comparison of $\Delta(g4)$, ΔR and ΔI_p evolutions of T-15 plasma parameters simulated by obtained PFC currents identification linear model and non-linear DINA one is presented in Fig. 5. In shown example the simulations were carried out with PFC currents evolution calculated by DINA with current changes in the poloidal coil #2. One can see a good approximation of plasma evolution by linear model obtained with identification method with responses to the changes of currents in PFCs.

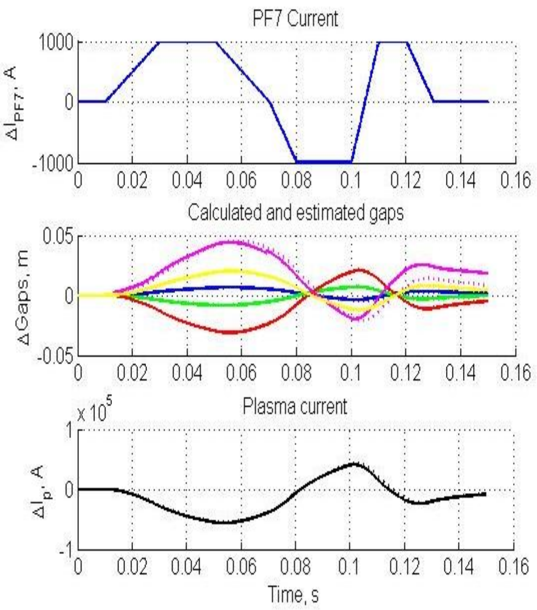


Fig. 4. Results of DINA calculation of responses to the current changes in the poloidal coil 7. Dotted line shows the approximation of transfer functions of responses

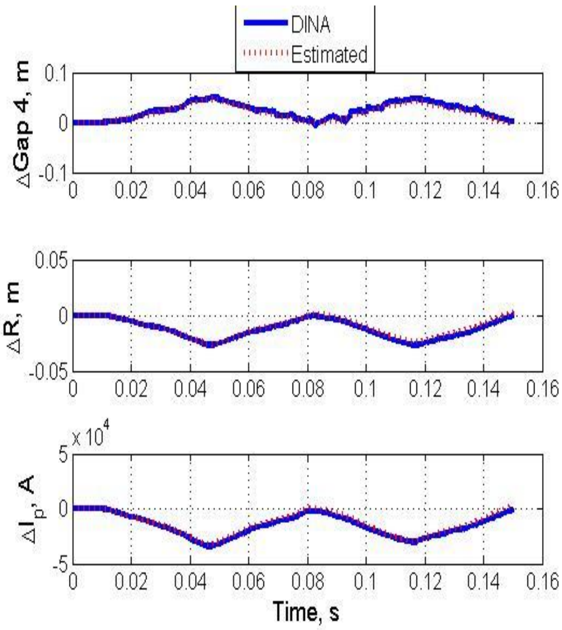


Fig. 5. Comparison of $\Delta(g4)$, ΔR and ΔI_p evolutions of T-15 plasma parameters simulated by obtained linear model and non-linear DINA one

4. Conclusions

On the basis of identification method the linear models of T-15 plasma were obtained for their further use on plasma control system synthesis. Non-linear DINA model was used to simulate the responses of plasma parameters by both PFCs voltage and current disturbances. Identification linear models describe the T-15 plasma behavior much better that the standard linear models.

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