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Adaptation of the MAST passive current simulation model for real-time plasma control

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Abstract

Successful equilibrium reconstruction on MAST depends on a reliable estimate of the passive current induced in the thick vacuum vessel (which also acts as the load assembly) and other toroidally continuous internal support structures. For the EFIT reconstruction code, a pre-processing program takes the measured plasma and PF coil current evolution and uses a sectional model of the passive structure to solve the ODEs for electromagnetic induction. The results are written to a file, which is treated by EFIT as a set of virtual measurements of the passive current in each section.

However, when a real-time version of EFIT was recently installed in the MAST plasma control system, a similar function was required for real-time estimation of the instantaneous passive current. This required several adaptation steps for the induction model to reduce the computational overhead to the absolute minimum, whilst preserving accuracy of the result. These include:

- conversion of the ODE to use an auxiliary variable, avoiding the need to calculate the time derivative of current;
- minimise the order of the system via model reduction techniques with a state-space representation of the problem;
- transformation to eigenmode form, to diagonalise the main matrix for faster computation;
- discretisation of the ODE;
- hand-optimisation to use vector instruction extensions in the real-time processor;
- splitting the task into two parts: the time-critical feedback part, and the next cycle pre-calculation part.

After these optimisations, the algorithm was successfully implemented at a cost of just 65 μs per 500 μs control cycle, with only 27 μs added to the control latency. The results show good agreement with the original off-line version. Some of these optimisations have also been used subsequently to improve the performance of the off-line version.

Keywords: Induced current; Model reduction; Discretisation; State space; Plasma control

1. Introduction

The main tool for plasma equilibrium reconstruction on MAST is EFIT [1], a free-boundary Grad Shafranov equilibrium solver. This code fits the plasma current distribution to a constrained current profile function that is consistent with the measured signals from the flux and field diagnostics, the measured coil currents and the Grad Shafranov equation.

The "coil set" as configured in EFIT (see Fig. 1) actually consists of both active poloidal field coils and passive (toroidally continuous) vessel elements and support structures, but only the active currents are measured. The MAST vacuum vessel also serves as the load assembly, so it is much thicker than is needed for a mere vacuum boundary and the total-induced passive current can be of the order of 100 kA. Since this is significant enough to adversely affect the reconstruction of the plasma equilibrium, the EFIT code needs to be given an estimate of the induced passive currents and their distribution so that it can take them into account.

1.1. Passive current simulation model

In many tokamaks the passive current is simply fitted resistively to the voltage measured from several loops attached to

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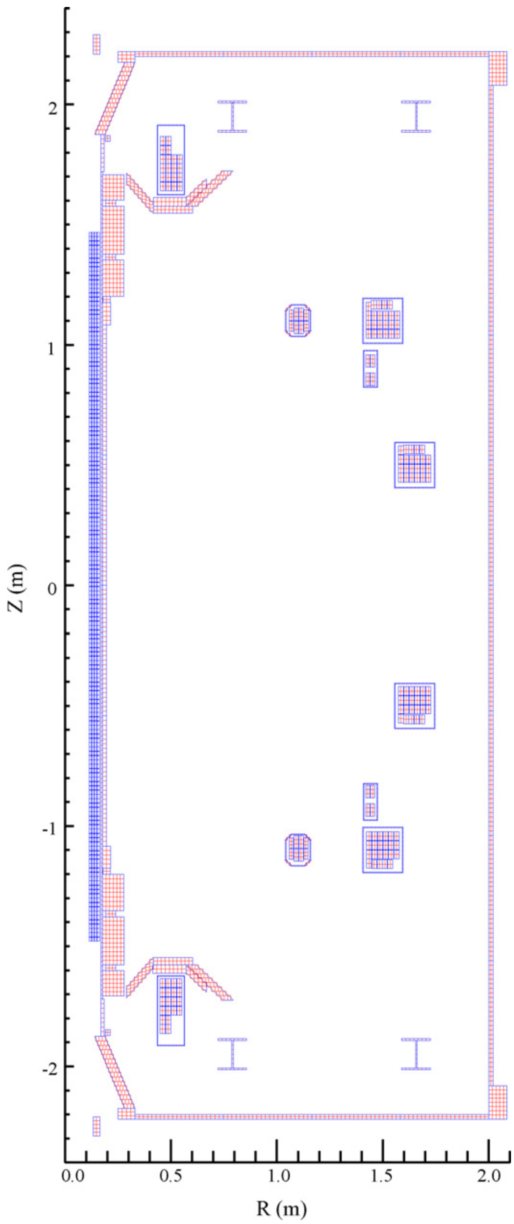

Fig. 1. Poloidal cross-section of the MAST conductor model used by EFIT.

the passive structures. This is not currently possible for MAST because such measuring loops are only available on the centre tube of the vessel. The induced passive current is therefore estimated by solving the induction equation for the passive circuit model as a 'pre-processing' stage before EFIT is run.

If $\mathbf{I}_\mathrm{v}$ is a vector of vessel (and other passive) element currents, $\mathbf{I}_\mathrm{c}$ is the vector of active coil currents (here we include plasma current modelled as a diffuse 'coil' with a generic current distribution), $\mathbf{R}_\mathrm{v}$ is a diagonal matrix of vessel element resistances, $\mathbf{L}_\mathrm{v}$ the inductance matrix of the vessel elements, $\mathbf{M}_\mathrm{vc}$ is the mutual inductance matrix between the vessel elements and the active coils, then since there is no external voltage applied to the passive conductors, the induction equation is

$$(V =)\ 0 = \mathbf{R}_\mathrm{v} \cdot \mathbf{I}_\mathrm{v} + \mathbf{L}_\mathrm{v} \cdot \dot{\mathbf{I}}_\mathrm{v} + \mathbf{M}_\mathrm{vc} \cdot \dot{\mathbf{I}}_\mathrm{c} \quad (1)$$

which can be rearranged to the following ordinary differential matrix equation:

$$\dot{\mathbf{I}}_\mathrm{v} = (-\mathbf{L}_\mathrm{v}^{-1} \cdot \mathbf{R}_\mathrm{v}) \cdot \mathbf{I}_\mathrm{v} + (-\mathbf{L}_\mathrm{v}^{-1} \cdot \mathbf{M}_\mathrm{vc}) \cdot \dot{\mathbf{I}}_\mathrm{c} \quad (2)$$

The passive current estimator for EFIT solves this ODE using the recorded data for $\mathbf{I}_\mathrm{c}$.

1.2. The need for a real-time version

A real-time version of the EFIT code, rtefit [2], was developed by General Atomics for use in their Plasma Control System (PCS, [3]). The same software infrastructure is also in use on the MAST PCS [4], and rtefit has recently been installed and configured in MAST PCS.

The runtime of the EFIT induction model is longer than the pulse duration (although this includes loading of files and saving of results). An equivalent version of this passive current simulation model was required for PCS to be used with rtefit. For this version to be useful in real time it was required to provide an instantaneous estimate of the passive currents for each control cycle, ready to be used by rtefit for real-time boundary reconstruction.

2. Optimisations for real-time operation

The algorithm for passive current estimation was adapted for real-time application using several optimisations as presented below.

2.1. Change of variables to avoid differentiation

The source term in Eq. (2) is the time derivative of active currents. However, the available measurement is normally $\mathbf{I}_\mathrm{c}$, and it is wasteful to differentiate the measured value only to integrate it again when solving the ODE. Introducing the variable $\mathbf{x}$, where

$$\mathbf{I}_\mathrm{v} = \mathbf{x} - \mathbf{L}_\mathrm{v}^{-1} \cdot \mathbf{M}_\mathrm{vc} \cdot \mathbf{I}_\mathrm{c} \quad (3)$$

and substituting this into Eq. (2) we get:

$$\frac{\mathrm{d}\mathbf{x}}{\mathrm{d}t} = (-\mathbf{L}_\mathrm{v}^{-1} \cdot \mathbf{R}_\mathrm{v}) \cdot \mathbf{x} + (\boldsymbol{L}_\mathrm{v}^{-1} \cdot \boldsymbol{R}_\mathrm{v} \cdot \boldsymbol{L}_\mathrm{v}^{-1} \cdot \boldsymbol{M}_\mathrm{vc}) \cdot \mathbf{I}_\mathrm{c} \quad (4)$$

i.e. it is no longer necessary to differentiate the measured coil current $\mathbf{I}_\mathrm{c}$, not even to recover $\mathbf{I}_\mathrm{v}$ from $\mathbf{x}$ with Eq. (3). Eqs. (3) and (4) can be expressed in standard state-space notation:

$$\frac{\mathrm{d}\mathbf{x}}{\mathrm{d}t} = \mathbf{A} \cdot \mathbf{x} + \mathbf{B} \cdot \mathbf{u} \quad (5)$$

$$\mathbf{y} = \mathbf{C} \cdot \mathbf{x} + \mathbf{D} \cdot \mathbf{u} \quad (6)$$

with obvious variable substitutions.

2.2. Model reduction

The vector $\mathbf{x}$ is a state vector of internal dynamical state variables for the system with input vector $\mathbf{u}$ and output vector $\mathbf{y}$. However, any invertible full-rank transformation matrix can be