FREEGSNKE: AN OPEN SOURCE, PURE-PYTHON, PREDICTIVE EVOLUTIVE EQUILIBRIUM CODE FOR CONTROL DESIGN AND VALIDATION

Applications at UKAEA

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1. OVERVIEW

Developed in collaboration between UKAEA and STFC Hartree Centre, FreeGSNKE [1,2] is an open source, pure-Python, finite difference solver of the 2D dynamic plasma equilibrium problem. It couples the plasma equilibrium with the currents in both poloidal field (PF) coils and passive vessel. FreeGSNKE can be used to run predictive simulations of the plasma's dynamic evolution in response to the voltages applied to the PF coils by the power supplies, thereby supporting control design and shape control studies. Here we report on its validation on MAST-Upgrade (MAST-U) discharges, on its current applications at UKAEA and on plans for future development.

2. FACILITATING MACHINE LEARNING (ML) APPROACHES TO CONTROL

One of FreeGSNKE's aims is to lower the entry barrier to studies seeking to adopt ML approaches to plasma control. Although a plethora of codes exist to address the different equilibrium related tasks, many of them use licensed languages, which often makes it difficult to inspect and customize algorithmic choices to the needs of specific use cases. By contrast, FreeGSNKE is fully open source and entirely written in Python. As such, it seamlessly integrates with ML libraries and algorithms, overcoming the need for cross-language binders or socket interfaces for multi-language interaction. For the same reasons, FreeGSNKE is a stateful code, which is advantageous in control design and reinforcement learning studies. A set of examples and dedicated documentation are provided to facilitate adoption by new users [2].

3. FREEGSNKE AND THE VALIDATION ON MAST-U PLASMAS

FreeGSNKE builds on FreeGS [3], introducing i) a static Grad-Shafranov (GS) solver based on the Newton-Krylov (NK) method; ii) linear and non-linear solvers for the evolutive equilibrium problem, also based on the NK method. The dynamics are described by the nonlinear coupling between the plasma equilibrium and the circuit equations pertaining to the metal currents [4, 1]. FreeGSNKE's nonlinear solver uses a novel 'staggered' solution strategy, exploiting multiple equivalent formulations of the same evolutive problem [1].

We validate FreeGSNKE's static GS solver on a selection of MAST-U discharges with EFIT++ reconstructed equilibria [5,6]. FreeGSNKE's 'deformable' linear growth rates are validated against RZIp 'rigid' growth rates on a set of toy tokamak configurations designed so as to minimise plasma deformations during displacements, including both limited and diverted plasmas. To validate the evolutive solver on MAST-U discharges, we use a set of vacuum shots to calibrate the MAST-U resistance and inductance models. Given the recorded voltages applied to the PF coils, values of both resistances and mutual inductances are optimised so to fit the measured PF coil currents (see e.g. Fig. 1-a), using a maximum likelihood approach and Markov chain Monte Carlo methods. With such calibrated values we can proceed to simulate MAST-U plasmas. We use the recorded voltages applied to the PF coils and a reconstructed equilibrium as initial conditions to simulate the 'flat-top phase' of MAST-U shots. Fig.1-b illustrates one such FreeGSNKE simulation by displaying a set of standard plasma shape targets. These are compared with the same quantities as reconstructed by EFIT++. Note the transition from a standard divertor configuration to a super-X [7].

4. EMULATED VIRTUAL CIRCUITS FOR REAL-TIME CONTROL ON MAST-U

FreeGSNKE is currently used at MAST-U to support equilibrium modelling of strongly shaped plasmas. In particular, work is underway [3,4] to implement emulated virtual circuits (VCs) in the MAST-U Plasma Control System (PCS). These neural network (NN) based emulators have been trained on a large library of GS equilibria [4,5] generated using FreeGSNKE, and will provide PCS with VCs that are accurate for the observed configuration in real-time. We are currently assessing any improvements using predictive FreeGSNKE simulations.

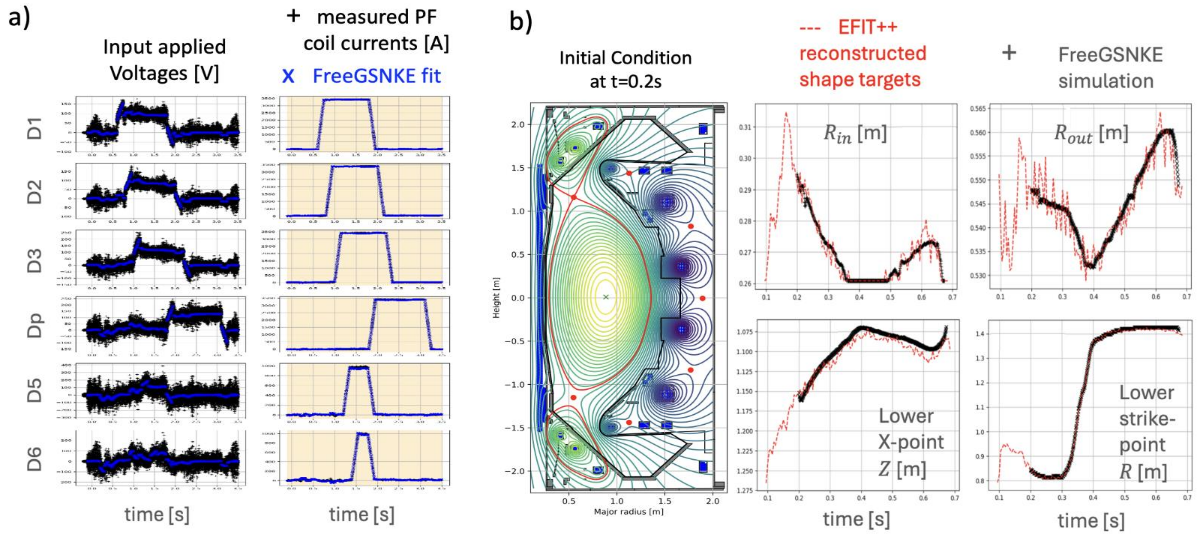

Fig. 1. a) Machine calibration on a vacuum MAST-U shot performed with FreeGSNKE: the left column displays (a selection of) the input voltages applied to the PF coils, the right column shows a comparison between the measured PF coil currents and model values obtained using the calibrated resistance and inductance models. b) Validation of FreeGSNKE non-linear evolutive solver on a MAST-U shot: the left panel displays the plasma equilibrium used as initial conditions, from the t=0.2 EFIT++ reconstruction; the set of panels on the right shows a comparison between the observed shape targets (from EFIT++ reconstructions) and the shape targets obtained in a FreeGSNKE simulation.

5. FUTURE DEVELOPMENTS

Several development lines are being pursued. First, use of the JAX library to develop a differentiable and GPU-compatible version of FreeGSNKE. This will allow gradient-based optimisation, as well as facilitate the integration with a transport module (e.g. TORAX [10]). The latter coupling will enable integrated modelling studies with time evolving free boundary equilibrium. Compatibility with the IMAS data formats is also being considered, to enable coupling with JETTO [11]. Second, a mesh refinement scheme is being developed to deal with the resolution requirements imposed by the current sheet of STEP plasmas. This will enable STEP vertical stability studies, as well as a quantification of the EM loads during VDEs.

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