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On a scenario assessment tool for the operation of the JT-60SA superconducting tokamak

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HIGHLIGHTS

- A software tool to quickly assess the structural performance of modern tokamaks is presented.
- The tool combines finite element results in real time to provide the user with net forces and force per unit length distributions on the tokamak coils.
- The mathematical formulation of the tool is explained and formally reported.
- The tool is meant to be used for the JT-60SA tokamak, but its use can be easily extended to other tokamaks.
- The structure of the supporting data files is provided.

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ABSTRACT

JT-60SA is a superconducting tokamak to be assembled and operated at the JAEA laboratories in Naka (Japan). The tokamak is designed, manufactured and operated under the funding of the Broader Approach Agreement (between the government of Japan and the European Commission) and of the Japan Fusion National Programme; JT-60SA aims to prepare, support and complement the ITER experimental programme. The European contribution to the JT-60SA is, for a large fraction, procured by France, Germany, Italy, Spain and Belgium.

This paper summarizes the activities carried out at F4E to develop a user-friendly software tool able to assess in real-time if an operational scenario could be structurally withstood by the magnet system of JT-60SA. Such tool is based on a theoretical formulation which is supported by a series of dedicated finite element method (FEM) calculations, and is able to provide a comparative assessment of any candidate scenario with respect to the baseline scenarios, and a quantitative assessment of all electro magnetic (EM) forces acting on the magnet system at any time during the candidate scenario. The tool as it is presented is specifically designed to be used for the JT-60SA tokamak, though it is designed so to that its usage could be extended easily to any other tokamak.

1. Introduction

JT-60SA is a superconducting tokamak to be assembled and operated at the JAEA laboratory in Naka (Japan). The tokamak aims to prepare, support and complement the ITER experimental programme towards the preparation of DEMO.

The JT-60SA will be capable of confining break-even equivalent class high-temperature deuterium plasmas at a plasma current I_p of 5.5 MA and a major radius of ~3 m lasting for a duration longer than the timescales characteristic of plasma processes, pursue full non-inductive steady-state operation with high plasma beta close to and exceeding no-wall ideal stability limits, and establish ITER-relevant high density plasma regimes well above the H-mode power threshold.

The JT-60SA has a large operational flexibility, which allows investigating several plasma configurations (e.g. single null, double null, ITER-like, etc.). During the design phase, all these configurations have been verified, by means of finite element analyses, to investigate the structural behaviour of the magnet system under the operational electromagnetic loads [1].

Such detailed structural and electromagnetic analyses can often be rather time and resources consuming, but at the same time lead to accurate results in terms of magnetic field in the coils, electromagnetic forces, and stress and strain distributions through the whole magnet system. Given the high level of detail of such analyses, they are normally needed for verification purposes, rather than exploration of the possible operational boundary of the device.

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At the same time it is often necessary to obtain quicker results, for example while investigating newly developed scenarios.

In order to address this requirement, a user-friendly software tool has been developed. This can explore in real-time, but rather accurately, the structural consequences of any given plasma scenario. The input includes plasma and coils currents while the output consists of easily readable table and graphical data, together with a "traffic light" system for immediate feedback on the feasibility of the input scenario and interlocking with the machine safety system.

This paper describes the steps carried out to conceive, create and verify this software tool, called scenario analysis tool (SAT), and provides an overview of its functionalities in view of its future utilization in the daily activities at JT-60SA. Additionally, possible improvements and extensions to its utilization are presented and critically analysed.

2. Background and motivation

The electromagnetic problem of a tokamak, limited to the evaluation of the forces acting on its coils and supporting structures, can be simplified down to the application of the Ampere's law for the definition of the magnetic field in the space around the current-carrying coils, followed by the application of the Biot–Savart law on each single current filament immersed in the magnetic field to evaluate the local contribution of electromagnetic force.

These two steps are usually carried out in sequence by the finite element solvers, like ANSYS, in order to evaluate field and forces at any location in a given domain. Clearly, such process is based on a discretization of the domain, and on a complete parsing of each current-carrying element, in order to obtain the local elementary force contributions which will be then summed at each location.

The magnitude of this process grows with the square of the number of current-carrying elements, and reaches the time scale of several tens of minutes CPU time for a single tokamak current configuration even on modern personal workstations. Such timescale makes such a process not suitable for a rapid assessment of a plasma scenario, consisting of several time steps, in the framework of the daily activities of an experimental device.

To circumvent this problem, a different analytical approach has been explored, where the time consuming problem of applying the Biot–Savart law on a large number of current-carrying elements is replaced by a linear combination of large datasets. These datasets contain electromagnetic forces contributions at each current-carrying element, obtained by means of finite element analysis of specific binary configurations of the tokamak coils.

By using this approach, the long CPU times normally required for the solution of each plasma configuration are spent only during the preparation of the datasets, while during the real use of the software tool, only the datasets are loaded in memory and linearly combined to obtain the full electromagnetic load distribution on the tokamak coils at each time step. The details of such process are explained in the following section.

3. Solution process

3.1. Definition of the domain

Assuming that the tokamak to be studied consists of 18 toroidal field coils (with equal current), 10 poloidal field coils and plasma current, the minimum symmetry unit of the system consists of 12 independent currents. Under these assumptions cyclic symmetry is used (i.e. only one toroidal segment of the tokamak is modelled) and the plasma current is modelled as a poloidal field coil of proper size and current density. Such symmetry unit for the JT-60SA tokamak is graphically represented in Fig. 1.

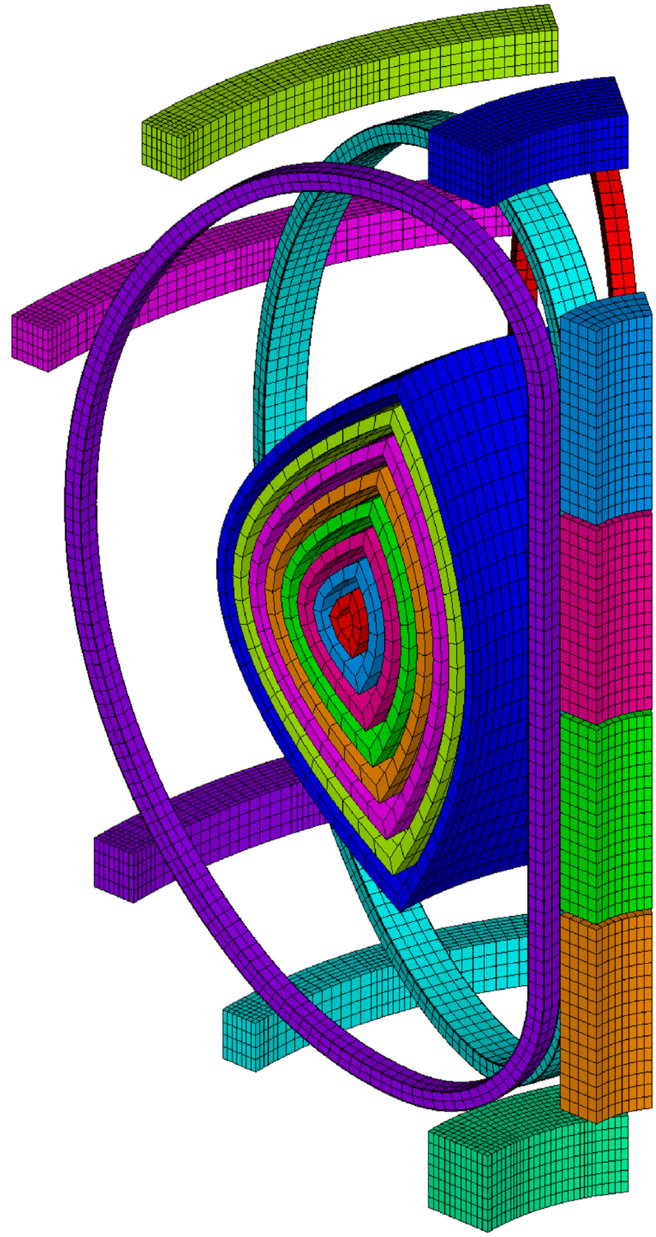

Fig. 1. The computational domain for the JT-60SA tokamak.

3.2. Preliminary ANSYS runs

Once the domain has been defined, a dedicated ANSYS model is created, containing a discrete representation of all the coils. By solving this model any current configuration of the tokamak can be analysed and electromagnetic forces at each node can be extracted.

This model is used to solve a definite number of current sets. Each of these current sets is defined so that two coils are crossed by a unitary current, while the other coils are off. The number of analyses to be run is given by the number of unique coil pairs among all N coils. This number includes also the pairs made of the same coil, which accounts for the electromagnetic forces due to each coil self-field.

For the JT-60SA tokamak, with a total number of coils $N = 12$, the number of runs of the ANSYS model to be carried out is:

$$N_r = N + \binom{2}{N} = 12 + \binom{2}{12} = 78$$