Simplified equivalent modelling of volumetric blanket modules and 3D vessel in ITER

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Abstract

In this paper we pursue simplified equivalent models of the volumetric blanket modules and of other 3D features of the ITER vessel, for possible inclusion in the design phase of a feedback controller for Resistive Wall Modes (RWM).

Introduction

The dynamics of fusion plasmas can be often described by MHD (Magneto-Hydro-Dynamics) equations, which predict, in specific situations, that some unstable evolution modes may arise. Such plasma perturbations induce in the surrounding conducting structures some eddy currents, which tend to counteract the instability itself, until they decay due to finite resistivity of any conducting structure. Hence, such instabilities can be slowed down by a conducting wall, and are usually called "Resistive Wall Modes" (RWM).

Due to the nature of RWMs, an accurate modelling of the conducting structures is very important. In particular, we want to investigate in details the effect of three-dimensional conducting structures. This is particularly important for future devices like ITER, since 3D features can give rise to conflicting contributions, whose final effect may be difficult to predict. For instance, thick conducting blanket modules certainly have a beneficial effect on passive stability analysis, but they may shield out the field due to active control coils; hence, it is not obvious if their presence makes feedback stabilization easier or not.

A detailed description of the three-dimensional features usually gives rise to computationally demanding numerical models. Conversely, the design procedure of feedback controllers usually requires the system to be described by a model of a sufficiently small order. To this purpose, we aim at developing simplified equivalent models of the volumetric blanket modules and of other 3D features of the ITER vessel, in order to account for such deviations from axisymmetry in the controller design phase.

System modelling with 2D and 3D discretizations

Our starting point is an ITER model developed using the CarMa code [1], which has already been successfully applied to the RWM analysis in presence of complicated volumetric 3D conducting structures [2]. In particular, we refer to the n=0 RWM (axisymmetric vertical instability), recently treated in [3] using a GPU acceleration of the code.

We consider a reference configuration with the following parameters: plasma current I_p=15MA, poloidal beta β_p=0.10, internal inductance l_i=1.01, centroid position R_c=6.103m, Z_c=0.626m, elongation 1.860, triangularity 0.515. The n=0 growth rate is around 13 s^{-1}.

With reference to the latest available geometry for the ITER passive structures, we consider two different 3D finite elements meshes (Fig. 1): a discretization mimicking an axisymmetric conducting structure, as it could be considered in an axisymmetric code like CREATE_L [4], and a discretization including full details of various conducting structures: vacuum vessel (double shell, ribs, rails, ports, port extensions), blanket modules (with volumetric description) and divertor structures (cassette, outer and inner vertical targets, dome).

Applying the CarMa code to this configuration, we get a numerical model of the type:

$$\underline{\underline{L}}^* \frac{d\underline{I}}{dt} + \underline{\underline{R}}\,\underline{I} = \underline{\underline{D}}\,\underline{V} \qquad\qquad \underline{y} = \underline{\underline{C}}\,\underline{I} \qquad (1)$$

where $\underline{I}$ is a vector of three-dimensional currents in conducting structures, $\underline{V}$ is the vector of voltages fed to active conductors, $\underline{y}$ are simulated measurements at given spatial points. Here, $\underline{\underline{L}}^*$ is a modified inductance matrix taking into account the presence of the plasma [1,3], $\underline{\underline{R}}$ is a resistance matrix, $\underline{\underline{D}}$ is a matrix made of 0's and 1's, and $\underline{\underline{C}}$ is the output matrix, again taking into account the presence of the plasma.

In the 2D case the system has dimensions 193, while in the 3D case the dimension is 14083.

We suppose to control the vertical instability using the in-vessel axisymmetric coil system, made of two 4-turn coils (see Fig. 1) connected in antiseries, so as to provide a magnetic field mainly directed radially; the resulting circuit is called VS3. Hence, the input variable of the system is the voltage applied by the controller to VS3. The output variable is the time derivative of the vertical position of the plasma current centroid. The estimation of the vertical position of the current centroid is made using a suitable linear combination of simulated measurements of the magnetic field and flux at the positions where the nominal ITER magnetic sensors will be placed, so that it can be expressed as an output variable with the same form (1). The time derivative is computed by connecting in series to the system a real derivator with a time constant of 7 ms.

Simplified modelling of three-dimensional structures

Let us call $W_{2D}(s)$ and $W_{3D}(s)$ the input-output transfer functions discussed above, computed over the 2D and 3D meshes; s is the Laplace variable. We define the quantity Δ(s) as:

$$\Delta(s) = W_{3D}(s)(s-\gamma_{3D}) - W_{2D}(s)(s-\gamma_{2D}) \tag{2}$$

where γ_{2D} and γ_{3D} are the open-loop growth rates in 2D and 3D cases [3]. Physically, $W_{3D}(s)(s-\gamma_{3D})$ is the "stable part" of 3D transfer functions (the same holds for 2D case), so that Δ(s) can be interpreted as the difference between the 3D and 2D "stable parts" of transfer functions. Being Δ(s) a stable transfer function, it is approximated as:

$$\Delta(s) = K\frac{\prod_{i=1}^{n_z}(1+s\tau_{zi})}{\prod_{i=1}^{n_p}(1+s\tau_i)} \tag{3}$$

The parameters τ_{zi} and τ_i are chosen in such a way to fit the transfer function over the frequency range of interest, with the constraints $\tau_{zi} > 0,\ \tau_i > 0$. In this particular case, we choose $n_z = n_p = 10$.

Having estimated Δ(s), we can correct the 2D transfer function as follows:

$$W_{2Dcorr}(s) = W_{2D}(s)\frac{s-\gamma_{2D}}{s-\gamma_{3D}} + \Delta(s)\frac{1}{s-\gamma_{3D}} \tag{4}$$

Figure 2 shows the effectiveness of this correction, which is very good up to 10^3 rad/s; higher frequencies are not correctly represented by the mesh in any case. Hence, the input-output behaviour of the system of order 14083 resulting from the 3D discretization can be conveniently approximated by the system of order 193, referring to the 2D mesh, connected to low-order systems as depicted in Fig. 3. This is greatly beneficial in the phase of controller design since usual controller design techniques are not effective on high-order systems.

This work was supported in part by Italian MIUR under PRIN grant#2008E7J7A3.

References

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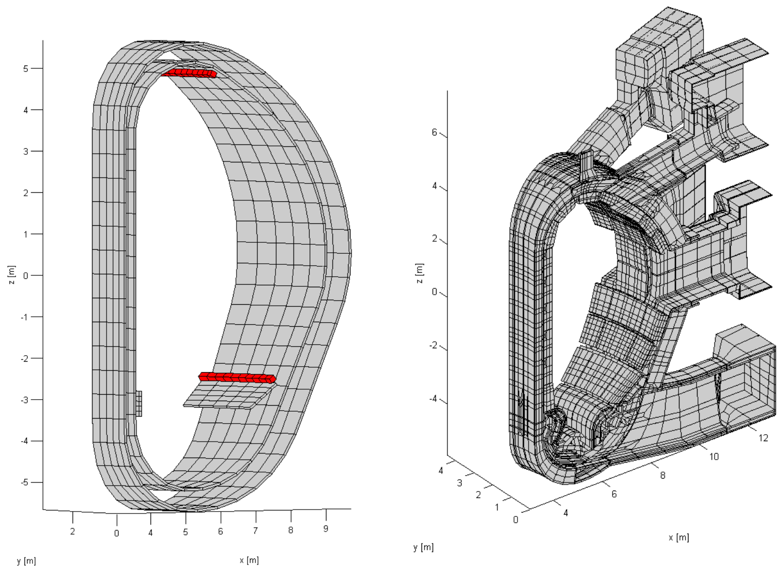
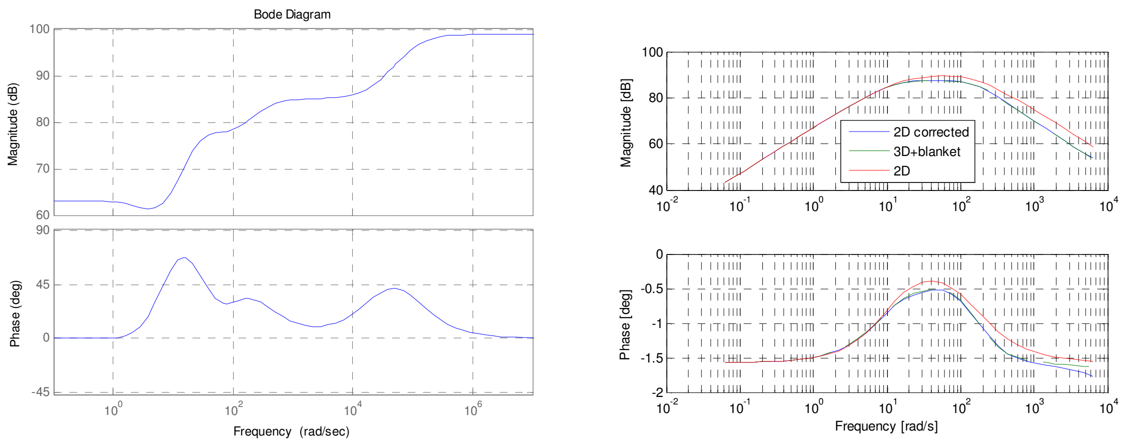


(a) (b)

Fig. 1. ITER discretization: (a) 2D (red: in-vessel coils); (b) 3D mesh



(a) (b)

Fig. 2. Bode plots: (a) $\Delta(s)$; (b) transfer function from VS3 to centroid vertical speed

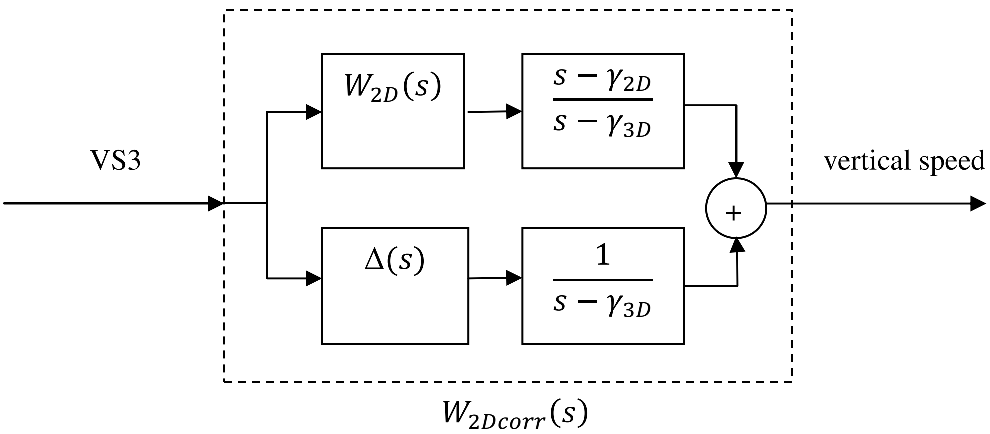


Fig. 3. Block diagram of the equivalent low-order system