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Vibration of fusion reactor components with magnetic damping

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ABSTRACT

The aim of this paper is to assess the importance of the magnetic damping in the dynamic response of the main plasma facing components of fusion machines, under the strong Lorentz forces due to Vertical Displacement Events. The additional eddy currents due to the vibration of the conducting structures give rise to volume loads acting as damping forces, a kind of viscous damping, being these additional loads proportional to the vibration speed. This effect could play an important role when assessing, for instance, the inertial loads associated to VV movements in case of VDEs. In this paper, we present the results of a novel numerical formulation, in which the field equations are solved by adopting a very effective fully 3D integral formulation, not limited to the analysis of thin shell structures, as already successfully done in several approaches previously published.

1. Introduction

The dynamical behavior of conducting structures in the presence of a strong magnetic damping was the subject of a high scientific interest in the past, leading to several computational models with experimental validation, mainly related to thin shell structures [1,2]. The advent of faster and more efficient computational resources together with larger storage data capabilities has brought a new interest on this activity [3,4]. The numerical models developed up to now are based on differential formulations, which have some drawbacks. As a matter of fact, the treatment of the $\mathbf{v} \times \mathbf{B}$ term deserves a deal of attention if the governing equations are written in the Eulerian coordinate system. Otherwise, if a Lagrangian description is adopted [7], there is the need of re-meshing the air domain, in principle at every time step, for correctly taking into account the deformation of the structure during the transient. In this context, we have studied an alternative approach based on an integral formulation of the electromagnetic problem coupled with the 3D dynamical model of the conducting structures [5].

In this paper, after the validation of this novel formulation against the experimental results of the TEAM-16 benchmark [1] and the problem of a cylinder placed under a transient magnetic field [2], we focus the attention on the coupled electromechanical analysis of the ITER vacuum vessel, in case of a slow downward VDE. This VDE is the most demanding load case in terms of applied net vertical force to the vacuum vessel structure. In fact, fusion reactor components such as the VV, but also for instance the port plugs, experience significant mechanical loads due to the interaction of high static magnetic fields produced by the superconducting coils system and the induced currents and halo currents due to fast electromagnetic events such as the VDEs. Usually these are design-driving loads, which can compromise the integrity of the structures. To this end, the electromagnetic damping effect has been analyzed showing its impact on the mechanical transient of the VV structure. In this paper, the analysis previously done [5] has been improved, by considering a more accurate model of the VV, now including the inner and outer shells, the toroidal and poloidal ribs, the ports and port plugs, the blanket modules, the divertor and divertor rails. Moreover, a specific numerical procedure has been implemented to take into account the presence of the halo currents, neglected in [5].

2. Numerical formulation of the problem

In the presence of time varying electromagnetic sources, eddy currents are induced in a 3D conducting domain V_c giving rise to Lorentz forces when interacting with the magnetic field. In the limit of small displacements, after discretization, the subsequent

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deformation of the specimen can be obtained as the solution of the following dynamical system:

$$M\frac{d^2u}{dt^2}+Ku=f(t) \tag{1}$$

In (1), by using nodal shape functions Ni, the displacement in V_c, is expressed as $\mathbf{u}(\mathbf{r},t)=\sum_{i=1:N_{dof}}\mathbf{u}_i(t)N_i(\mathbf{r})$; the number of degrees of freedom N_{dof} is equal to the product of the number of nodes and the three components of $\mathbf{u}(\mathbf{r},t)$. Then, u is the column vector made by the N_{dof} coefficients u_i. M and K are the sparse mass and stiffness matrix, respectively, while $f(t)$ is the vector of the nodal Lorentz forces defined as:

$$f_i(t)=\int_{V_c}\mathbf{N}_i\cdot\mathbf{J}(\mathbf{r},t)\times\mathbf{N}(\mathbf{r},t)d\tau,\quad i=1:N_{dof} \tag{2}$$

being $\mathbf{J}$ the current density and $\mathbf{B}$ the magnetic induction. The electromagnetic system, in the magneto-quasi-stationary limit, with non-magnetic materials, is described by the following set of dynamical equations, arising after discretization of the electric field integral equation, in the magneto-quasi-stationary limit [6]:

$$\frac{d(LI)}{dt}+RI+\frac{dE^s}{dt}=0 \tag{3}$$

where

$$L_{ij}=\frac{\mu_0}{4\pi}\int_{V_c}\int_{V_c}\frac{\mathbf{W}_i(\mathbf{r})\cdot\mathbf{W}_j(\mathbf{r}')}{|\mathbf{r}-\mathbf{r}'|}d\tau d\tau' \tag{4}$$

$$R_{ij}=\int_{V_c}\mathbf{W}_i(\mathbf{r})\cdot\sigma^{-1}\mathbf{W}_j(\mathbf{r})d\tau \tag{5}$$

$$\frac{dE_i^s}{dt}=-\sum_{k=1,N_{dof}}F_{ik}^s\frac{du_k}{dt}-V_{0,i} \tag{6}$$

$$V_{0,i}=-\int_{V_c}\mathbf{W}_i(\mathbf{r})\cdot\frac{\partial\mathbf{A}_s(\mathbf{r},t)}{\partial t}d\tau \tag{7}$$

$$F_{ik}(t)=\int_{V_c}\mathbf{W}_i(\mathbf{r})\cdot\mathbf{N}_k(\mathbf{r})\times\mathbf{B}_s(\mathbf{r},t)d\tau \tag{8}$$

Here σ is the electric conductivity and $\mathbf{A}_s$ is the vector potential due to the sources outside the conducting domain V_c and $\mathbf{W}_k=\nabla\times\mathbf{T}_k$, being $\mathbf{T}_k$ the kth edge element shape function associated to the elements sharing the kth edge. The uniqueness of $\mathbf{W}_k$ is assured by the tree-cotree gauge [6]. Notice that, with $\mathbf{B}(\mathbf{r},t)=\mathbf{B}_s(\mathbf{r},t)+\mathbf{B}_J(\mathbf{r},t)$, being $\mathbf{B}_s(\mathbf{r},t)$ the field due to the sources, $\mathbf{B}_J(\mathbf{r},t)$ the field due to the eddy currents, and $\mathbf{J}$ given by $\mathbf{J}(\mathbf{r},t)=\sum_{k=1,N}I_k(t)\mathbf{W}_k(\mathbf{r})$, f as defined by (2), is expressed as $f_k(t)=-\sum_{i=1,N}G_{ik}(I,t)I_i$, where

$$G_{ik}(I,t)=F_{ik}+\int_{V_c}\mathbf{W}_i(\mathbf{r})\cdot\mathbf{N}_k(\mathbf{r})\times\mathbf{B}_J(I,\mathbf{r})d\tau \tag{9}$$

The components of the magnetic induction $\mathbf{B}_J$ inside each element e, computed using the Biot–Savart formula, are linear functions of I, given by the following expression:

$$\mathbf{B}_J(I,\mathbf{r}_e)\cdot\widehat{\mathbf{i}}_m=\sum_{i=1,N}B_{ei}^m I_i \tag{10}$$

with $m=x,y,z$ where $B_{ei}^m=\frac{\mu_0}{4\pi}\widehat{\mathbf{i}}_m\cdot\int_V\frac{\mathbf{W}_i(\mathbf{r}_Q)\times(\mathbf{r}_e-\mathbf{r}_Q)}{\left|\mathbf{r}_e-\mathbf{r}_Q\right|^3}d\mathbf{r}_Q$.

Finally, the coupled electro-magneto-mechanical dynamical system (1)–(3), can be written in a compact form as:

$$M\frac{d^2u}{dt^2}+Ku+G^T(I,t)I=0 \tag{11}$$

$$L\frac{dI}{dt}+RI-F(t)\frac{du}{dt}=V_0(t) \tag{12}$$

The inductance matrix has been assumed to be unchanged with respect to time under the hypothesis of sufficiently small displacements.

This system is usually computationally very intensive, and for this reason, we use a suitable modal expansion [7,8]. In this approximation, we compute the N_{mode} dominant modes P^ks by solving the related generalized eigenvalue problem. By using the classic linear transformation $u=\left[P^1P^2\ldots P^{N\text{mode}}\right]x=Px$ and the orthogonality of M and K with P, we have:

$$m\frac{d^2x}{dt^2}+kx+P^TF^T(t)I=0 \tag{13}$$

$$L\frac{dI}{dt}+RI-F(t)P\frac{dx}{dt}=V_0(t) \tag{14}$$

where m and k are diagonal matrices (i.e. $m_{ii}=P^{iT}MP^i$, $k_{ii}=P^{iT}KP^i$). The system (13), (14) is integrated in time by applying the Newmark's β method for solving (13) and the implicit method for (14) [8]. At each time step, the solution of the two subsystems is iteratively computed until the discrepancy of two iterates is below a given threshold. In all cases here examined, only few steps were required for a relative threshold of 10^{-6}.

If necessary, the system can be further simplified by introducing a similar expansion for solving (14).

3. Implementation and validation of the numerical model

Here we illustrate the main features of the implementation of the numerical model described in Section 2. The model has been validated against the experimental results of the TEAM-16 benchmark problem [1] and the published results of the analysis of a cylinder placed under a transient magnetic field [2]. All analyses have been self-consistently performed by implementing the solution of the coupled system in MATLAB. Matrices L and R are imported from the output of the CARIDDI program. The stiffness and mass matrices have been computed by the commercial code ANSYS using the SOLID185 element, by using the same mesh of CARIDDI. They are also imported in MATLAB from the output of ANSYS. The post-processing has been carried out by passing in input to ANSYS the solution of the coupled electro-magneto-mechanical system in terms of the electromagnetic nodal forces at a suitable number of time instants (typically around 300). These forces have been used to execute again the corresponding dynamical analysis with ANSYS, by using the SOLID185 element for crosschecking purposes and exploiting its post-processing capabilities.

3.1. TEAM problem 16

In this problem, a copper rectangular plate ($L_x=115$ mm, $L_y=40$ mm, $L_z=0.3$ mm, electric conductivity $\sigma=5.81\times10^7$ S/m, mass density $\rho=8912$ kg/m^3, Young's modulus $E=1.1\times10^{11}$ Pa and Poisson's ratio $\nu=0.34$), rigidly clamped at one hand (clamped length $L_c=10$ mm) is placed under a steady uniform magnet induction B_y and a pulsed magnetic field generated by a 27 turns circular coil. Its outer and inner diameters are 22 mm and 20 mm, respectively. The coil height is 24.2 mm. The distance between the plate and the coil is 9.5 mm and the coordinates of the coil center are (105, 0 mm). The time variation of the coil current, is $i(t)=800[\exp(-500t)-\exp(-600t)]$ A. The finite element mesh

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