Specific Features of Eddy Current Analysis with ANSYS® for Fast Plasma Current Decay Event in W7-X

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During the second operation phase (OP1.2) of the most advanced stellarator Wendelstein 7-X (W7-X), some events of fast plasma current decay with a time constant of about 1 ms were observed (for both toroidal and diamagnetic plasma currents). The events were triggered by Electron Cyclotron Current Drive (ECCD) and were much faster than the assumptions considered during the design phase of W7-X components: 100 kA and 2.7 MA plasma current discharge with the time constants of 140 and 50 ms for toroidal and diamagnetic currents respectively. During the observed 1 ms discharge of maximum expected plasma currents, significant eddy currents are expected to be induced in some components with resulting electro-magnetic (EM) forces.

In order to avoid unnecessary changes on as-built components, evaluation of the eddy currents / EM forces with high accuracy is required, if the conservative simplified estimation shows criticality. As a result, a sophisticated EM model with plasma currents, superconducting (sc) coils, plasma vessel (PV) and multiple ports is developed in ANSYS® using the new element type SOLID236 / 237 (edge-based formulation), which is much more accurate than the legacy elements SOLID97 (vector potential formulation).

The specific features of using SOLID236 elements for eddy current analysis are studied and presented in this paper. This includes the application of boundary conditions on sector EM model, modeling of excitation currents, field and eddy current accuracy, skin effect, shielding effect, voltage in conducting components, etc. Most of the issues are studied in comparison with SOLID97 elements. Finally, the pros and cons of SOLID236 and SOLID97 elements are summarized, and the experiences during the W7-X EM analyses are presented.

Keywords: Wendelstein 7-X (W7-X), stellarator, electromagnetic analysis, ANSYS®, SOLID236, SOLID97.

1. Introduction

Considerable physical experiments with short plasma pulses have been successfully performed on the most advanced stellarator Wendelstein 7-X (W7-X) during the second operation phase (OP1.2) in 2017 and 2018 [1]. During the operation, some events of fast plasma current decay with the time constant of around 1 ms (for both toroidal and diamagnetic plasma currents) are observed. The events are triggered by Electron Cyclotron Current Drive (ECCD) and much faster than the assumptions considered during the design phase of W7-X components, i.e. 100 kA and 2.7 MA plasma current decay with the time constants of 140 and 50 ms for toroidal and diamagnetic currents respectively [2]. Such rapid discharge of the plasma currents inevitably induces significant eddy currents in some components with long conducting path and / or with low resistivity. The interaction between eddy currents and the background field from superconducting (sc) coils results in considerable electro-magnetic (EM) forces, which need to be seriously considered in the preparation to the next operation phase [3].

In order to avoid unnecessary changes on as-built components of W7-X and to define the operation limits on possible plasma currents discharge events, an evaluation of the eddy currents / EM forces with high accuracy is required, if the conservative estimation shows criticality. As a result, a sophisticated EM model with plasma currents, sc coils, plasma vessel (PV) and multiple ports is developed with ANSYS® APDL (ANSYS Parameter Design Language) using the suggested new element type SOLID236 / 237 (with edge-based formulation), which is much accurate than SOLID97 (with vector potential formulation). Since the algorithm of SOLID236 / 237 is different to the legacy elements SOLID97, the following specific features of using SOLID236 / 237 for the eddy current calculations are presented in the paper:

1). The application of boundary conditions (BC) on sector EM model, e.g. the cyclic BC on 1/5 of the full EM model representing the entire domain of five-fold symmetric W7-X [4] including specific BC on machine axis, etc.,

2). Modeling of excitation currents to fulfill the requirement of zero current divergence ($\nabla \cdot J = 0$),

3). Mesh related field and eddy current accuracies,

4). Skin effect, shielding effect of the plasma vessel (PV) and the resulting voltage in conducting components, etc.

Most of the issues are studied in comparison with SOLID97 elements. Finally, the pros and cons of SOLID236 / 237 and SOLID97 elements are summarized. In addition, the experiences / findings during the EM analyses of W7-X components are presented to support similar assessments of components in other fusion devices with magnetic field confined plasma.

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2. Boundary conditions for the sector EM model with SOLID236 / 237

For the EM system with periodically distributed excitation currents and conducting components, the sector EM model with cyclic BC is an effective way to reduce the model size, to accelerate the solution and to minimize the computational resources. Unlike the degree-of-freedom (DOF) of vector potential used in legacy elements SOLID97, the magnetic DOF on the middle-side nodes of SOLID236 / 237 elements is based on edge-flux formulation, which is the line integrals of the magnetic vector potential along the element edges (Az). Therefore, the cyclic BC for the sector EM model with SOLID236 / 237 is different to SOLID97 ones, and including the following aspects:

a). Coupling of Az DOF on master and slave boundary sections with constrain equations (CE). The master and slave sections should have the same mesh style, and are allowed with non-planar surfaces. Since the Az DOF is the integral on the edge from the lower corner node number to the higher corner node number [5], the CEs should take the Az integral direction into account (see the explanation in Fig. 1).

b). If the conducting component crosses the cyclic boundary, the cyclic BC of Volt DOF should also be applied on the conducting component sections.

c). Coupling the Az DOF on axial line with CEs (taking into account the Az integral directions) to avoid the insufficient constrained model. One could also apply flux parallel BC (Az=0) on axial line except the two mid-side nodes close to the external surfaces to avoid rapid flux change at the corner, see Fig. 1.

Besides, for both sector EM model and the expanded 360° EM model, the magnetic flux parallel BC (Az=0) should be specified on external air surfaces which are far from excitation currents, and one node with fixed Volt DOF for each isolated conducting component to avoid floating of the entire Volt DOFs. The BCs for sector EM model are fully verified by comparing the results with the expanded 360° EM model without the above cyclic BCs.

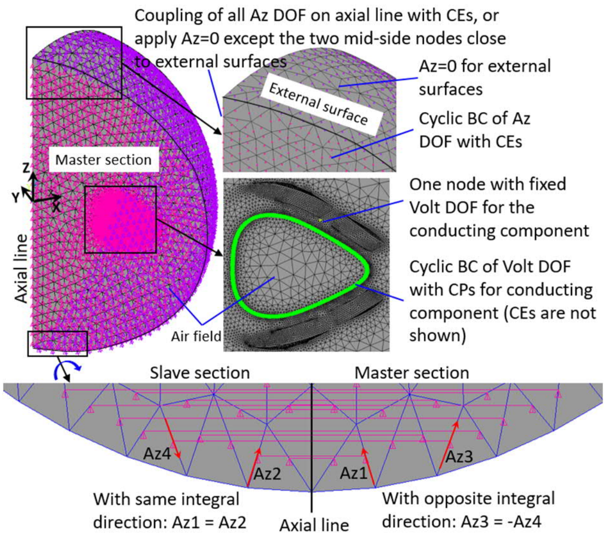

Fig. 1. Specific boundary conditions for sector EM model and the explanation of cyclic BC with CEs.

3. Excitation currents application

In case the excitation coil current is closed in the domain, the 'solenoidal condition' ($\boldsymbol{\nabla} \cdot \boldsymbol{J} = \boldsymbol{0}$) of the applied current densities need to be satisfied (it is not necessary for SOLID97 elements) [5]. For the coil with simple shape, this condition could be fulfilled by modelling the coil with regular hexahedral elements that well orientated with local coordinates systems (LCS). However, for the coils with complex shapes, such as the non-planar coils of W7-X [4], this condition cannot be fulfilled easily. Therefore, the steady-state current conduction analysis (using SOLID231 elements) is to be performed prior to the EM analysis to obtain the current densities, which intrinsically satisfy the 'solenoidal condition'. However, if the coil is modelled with smeared structure (without consideration of the individual conductor turns), the calculated current density tends to be concentrated at curved region and results in its unevenly distribution over the cross section. This issue could be solved by detaching the regular hexahedral mesh of the coil in cross section direction to form 'multi-filament' structure. In this case, the applied current is forced to flow only in circumference direction, as illustrated in Fig. 2.

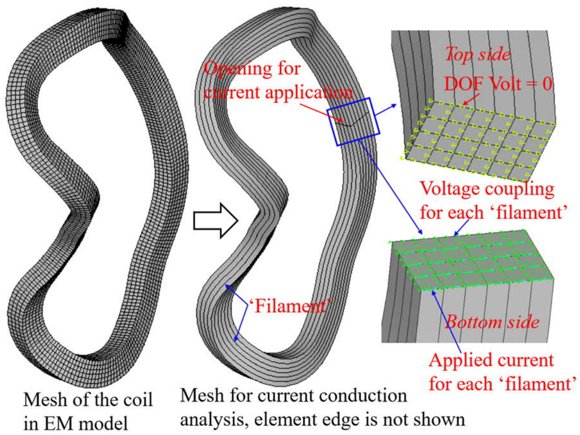

Fig. 2. Modelling and BC for current conduction analysis of W7-X non-planar coil (NPC) type 1 (close to the middle of one W7-X sector).

4. Studies on some technical issues

4.1 Field and eddy current accuracy

One important reason of abandoning the SOLID97 element by ANSYS® is the requirement of special treatment to enforce the magnetic field boundary conditions on the material interfaces. The issue is especially crucial for ferromagnetic materials. The SOLID236 / 237 element on the contrast shows full advantage in this case. In addition, as it has been studied, the SOLID236 / 237 produces more accurate results of fields and eddy currents. As shown in Fig. 3, with the same mesh (Tetrahedral shape) of the conducting component, the eddy currents solved with SOLID97 have significant out-of-plane components, while SOLID236 / 237 yields much better results. Although the eddy current accuracy of SOLID97 could be improved by refine the mesh or with hexahedral elements, it is not as practical as using SOLID237 tetrahedral elements for the complex shape components.

However, it is necessary to emphasize that the field accuracy of SOLID236 / 237 is highly depending on the element shapes. The degraded elements of SOLID236, especially the pyramid elements, are necessary to be excluded in the interested components. Actually, for the conducting component close to the excitation current, it is suggested to use SOLID237 (tetrahedral elements) to avoid the connected pyramid elements (between air field and conducting components) in the region with high field gradient, since the air field is usually predominantly meshed with tetrahedral elements (SOLID237). The fact could be considered as an advantage of SOLID236 / 237 elements, since it is much easier to mesh the components with tetrahedral elements. For the case when the conducting component is relatively far from excitation current, other element shapes (except the pyramid elements) produce accurate results. According to the studied cases, if the component of interest is close to the excitation current (e.g. inboard part of the PV near NPC type 1) the model with SOLID237 elements gives the field accuracy improvements by ~2 % in comparison with the same mesh constructed from SOLID97 elements, as listed in Table 1 from our studies. The fields from EFFI code [6] and / or SOLID5 coupled field elements are taken as a reference field calculation for the above mentioned comparison due to the consideration of much accurate Biot-Savart's law. The summed maximum EM force and moment in conducting component from SOLID97 and SOLID237 are also compared in Table 1. The moment summation point is at the center of the conducting component.

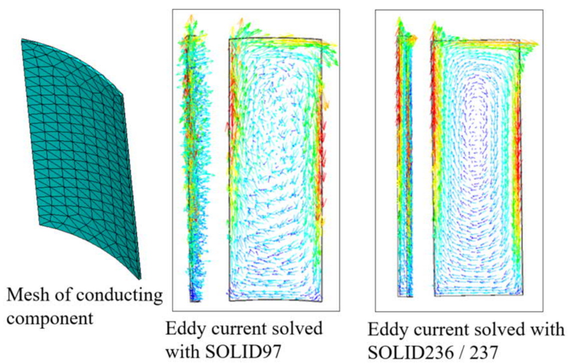

Fig. 3. Comparison of the eddy currents calculated with SOLID97 and SOLID236 / 237.

Table 1. Studied field deviations between different methods

Comparisons of field	Deviations	
	In T	In %
EFFI vs SOLID5	0.03 ~ -0.07	0.73 ~ -1.83
SOLID97 vs EFFI	0.18 ~ -0.22	4.57 ~ -6.5
SOLID97 vs SOLID5	0.16 ~ -0.192	4.0 ~ -5.83
SOLID237 vs EFFI	0.13 ~ -0.151	3.2 ~ -4.0
SOLID237 vs SOLID5	0.124 ~ -0.1	3.35 ~ -2.7
Comparison of the EM force and moment	Force, %	Moment, %
SOLID237 vs SOLID97	6.2	1.5

4.2 Skin effect and shielding effect

When the excitation current changes rapidly, e.g. with decay time constant of less than 1 ms, the eddy current tends to concentrate on the edge / surface of conducting components due to the skin effect [7]. Both SOLID97 and SOLID236 / 237 elements are able to consider the skin effect. For the comparative study, the conducting component is meshed with hexahedral elements and is located far from the excitation current. As shown in Fig. 4, the relative difference of skin effect between SOLID236 / 237 and SOLID97 is only 1 %.

The shielding effect due to an intermediate massive component, such as the PV in W7-X, is remarkable. The intermediate component absorbs part of the magnetic energy and reduce the coupling between varying excitation plasma currents and critical conducting components. As a result, the induced eddy currents in the components are partially mitigated. The possibility to consider the shielding effect is available in both SOLID97 and SOLID236 / 237 elements. It was shown that the result difference between corresponding models is less than 0.1 %, which is negligible.

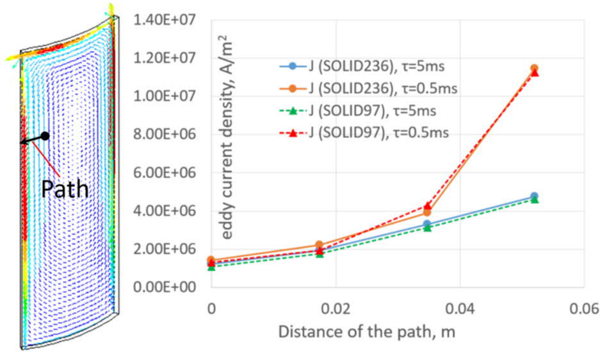

Fig. 4. Comparison of the skin effect considered by different element types (τ is the excitation current decay time constant).

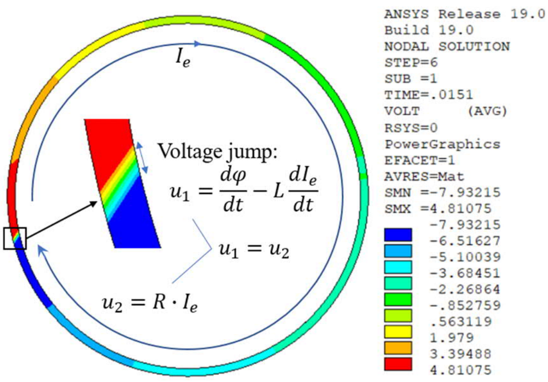

Fig. 5. Explanation of the voltage drop along the eddy current loop solved by SOLID236 / 237, φ is the magnetic flux, I_e is the eddy current, L is the self-inductance of the eddy current loop, R is the resistance of eddy current loop.

4.3 Voltage in conducting component

The additional VOLT DOF of SOLID97 elements used for the conducting component is always time integrated, while the VOLT DOF of SOLID236 / 237 elements could be directly formulated as voltage drop during solution if the KEYOPT 2 is set to 0. The resulting voltage drop is very important for the estimation of ohmic current sharing with minor conducting components (e.g. copper tubes attached to the W7-X PV for the protection of in-vessel cables). These multiple tubes are excluded from the EM analysis because the induced eddy current in them is negligible in comparison with the current sharing effect. In particular, it is also useful for the calculation of the induced voltage on sc coil terminals during plasma currents discharge events in order to evaluate the influences on the sc coil quench detection system. It is necessary to highlight that the voltage jump peculiar to the analysis of a closed loop of eddy current is to be avoid in the current sharing estimation. As explained in Fig. 5, the voltage jump represents the derivative of flux linkages, and the voltage drop along the eddy current follows the Ohm's law. Moreover, the accuracy of the calculated voltage also depends on element shapes, and the SOLID237 element (Tetrahedral shape) is recommended for the conducting components to avoid the inaccuracies due to the attached pyramid elements.

4.4 Other studied issues

The following important issues on using of SOLID236 / 237 and SOLID97 are also studied and summarized:

1). Since the INFIN111 element used for far-field decay simulations is not compatible with SOLID236 / 237 elements, the external surface of the air field (applied with the flux parallel condition, Az=0) is suggested to be away from the coil external surfaces with a distance of ~12 times of the coil radius to assure that the field inaccuracy in air field is less than ~1 %.

2). For the EM analysis with SOLID236 / 237 elements, the iterative solver (JCG solver) is very time consuming and not accurate enough in comparison with the direct solver (SPARSE solver). However, the direct solver requires more memories and time for SOLID236 / 237 elements than SOLID97 elements.

3). In order to achieve accurate results with SOLID236 / 237 elements, the weak coupling between magnetic and Volt DOF (KEYOPT 2 = 1) should be avoided during the eddy current analysis.

4). With SOLID97 elements, the results of excitation current are always to be saved (with command 'OUTRES'), otherwise, the result of eddy current is misleading, especially for the rapid change of excitation currents.

5). In case of calculating the voltage drop in conducting components using SOLID236 / 237 elements, all items of results (command 'OUTRES, ALL') need to be saved during the solution.

5. Experiences from the eddy currents analyses for W7-X

Some important experiences are gained and learned from the eddy currents analysis of W7-X complex components during fast plasma currents discharge:

1). The time constant of the eddy current loop in PV varies from place to place due to its complex 3D (three dimensional) shape, therefore, the EM responses, in terms of maximum eddy current and corresponding time instant, are different in different areas depending on the local time constants.

2). The large eddy current in the PV, especially during toroidal plasma current decay, becomes an additional source that inducing secondary eddy currents in nearby component superimposed on the eddy currents induced by plasma currents. The secondary eddy currents have considerable effect on the total eddy currents when the time constant of the components is close to the PV one.

3). For the 360° EM model expanded from sector EM model, as shown in Fig. 6, the transient EM analysis result indicates that the symmetry of field and eddy current could be broken in the regions close to symmetric section if there is a coil with excitation current close to it. The cyclic behavior can be improved a lot if the mesh of the coil is refined in current direction. However, the issue is less pronounced for the sector EM model with cyclic BC where the cyclic behavior is enforced.

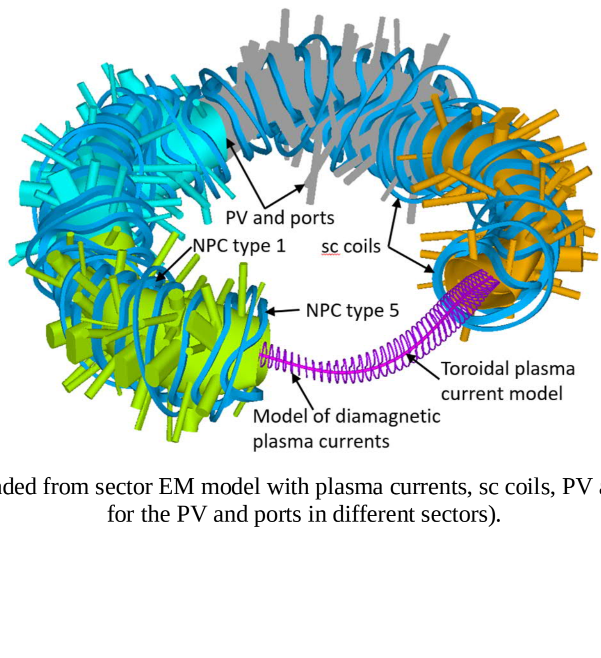

Fig. 6. The 360° EM model expanded from sector EM model with plasma currents, sc coils, PV and multiple ports (different colors for the PV and ports in different sectors).

6. Conclusion

The specific features and experiences of using SOLID 236 / 237 element for eddy current analysis are studied in details and the following conclusion can be drawn ("+" for pros of SOLID236 / 237 and "–" for cons in comparison with SOLID97):

+ It is not necessary to apply the magnetic field boundary conditions on the material interfaces,

+ Similar model produces much accurate results of magnetic field and eddy currents,

+ Voltage drop in conducting components could be directly formulated during solution,

+ It is convenient to apply the velocity as body loads when the velocity effect is considered.

– The application of cyclic BC and excitation currents is not convenient,

– Sub-modelling of the interested region with the BC of vector potential is not possible, but alternatively the corresponding Az DOF could be specified as BC,

– Requires more computational resources and time.

The fact that the abandoned SOLID97 element is not supported properly in new versions of ANSYS® forces to consider in the EM analysis strategy the extensive use of SOLID236 / 237 elements. The presented study shows that in-spite of the issues to be considered in the EM analysis the modern elements are fully capable to deliver accurate results for critical components of fusion devices with magnetic field confined plasma.

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References

[1] H. S. Bosch et al., Engineering challenges in W7-X: Lessons learned and status for the second operation phase, IEEE Trans. Plasma Sci., 46(2018), 1131-1140.

[2] D. Naujoks, Plasma currents decay times / ECCD operation, W7-X project document, PLM: 1-NBF-Y0065.

[3] V. Bykov, J. Zhu et al., An overview of EM analysis of W7-X components behavior during fast plasma current decay event, to be presented in TOFE 2021 conference.

[4] T. Rummel, K. Riße, et al., The Superconducting Magnet System of the Stellarator Wendelstein 7-X, IEEE Transactions on plasma science, 40 (2012) 769-776.

[5] ANSYS® Help Documentation.

[6] Steven J. Sackett, Calculation of electromagnetic fields and forces in coil system of arbitrary geometry, Sixth symposium on engineering problems of fusion research, (1975) 935-939.

[7] H. A. Wheeler, Formulas for the skin effect, *Proceedings of the IRE*, 30(1942), 412-424.