Integrated Design System of Toroidal Field Coil for CFETR*  

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Abstract Integrating engineering software is meaningful but challenging for a system code of a fusion device. This issue is seldom considered by system codes currently. Therefore, to discuss the issue, the Integrated Design System of TF Coil (IDS-TFC) has been worked out, which consists of physical calculation, CAD, and Finite Element Analysis (FEA). Furthermore, an Integrated and Automatically Optimized Method (IAOM) has been created to address the integration and interfaces. The method utilizes a geometry parameter to connect each design submodule and achieve automatic optimization. Double-objectives optimization has been realized, confirming it is feasible to integrate and optimize engineering design and physical calculation. Moreover, IDS-TFC can also serve as a useful reference of integrated design processing for subsequent fusion design.

Keywords: IDS-TFC, IAOM engineering software, integration, TF Coil

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(Some figures may appear in colour only in the online journal)

1 Introduction

The design of a fusion device is quite complicated, regarding the inter-discipline and constraint between physics and engineering. Therefore, it is necessary to work out an integrated design code for fusion devices, which consists of a set of systemic design software. There are several systems codes for fusion devices over the world: Tokamak Systems Code (TSC) [1], Tokamak Plasma power balance calculation Code (TPC) [2], PROCESS [3,4], ARIES [5,6], the code for Broader Approach DEMO design [7]. They facilitate designing processes remarkably. However, these codes are concentrated on physical theoretical calculation and integration, lacking the details of engineering and structural design. For example, TSC mainly calculates tokamak performance and configuration in the field of physics, such as plasma current, torus, and power conversion. Several modules of TSC consider simply the engineering details, for instance the Toroidal Field Coil module calculates bucking cylinder thickness based on centering force and yield stress. But this brief consideration cannot meet the requirement of specific design in the future, it does not consider other supports on TF Coil or include the assessment of structural performance in various scenarios. Therefore, it is quite necessary to integrate engineering modules into design codes.

Furthermore, it is a challenge to integrate different sorts of commercial engineering software, such as FORTRAN, CATIA, ANSYS Classic, GANDALF, FLUENT, because the compatibilities between them are poor. For example, it is difficult for CATIA to import the data from FORTRAN, and a similar situation occurs between ANSYS and CATIA. ANSYS generally consists of Classic and Workbench. Despite Workbench having high compatibility with CATIA, the calculation accuracy is comparatively low and Workbench cannot deal with complex post-processing. ANSYS Classic can meet most requirements of analyses and calculation, but it is almost incompatible with CATIA.

A design code is being developed for China Fusion Engineering Test Reactor (CFETR). Besides physical calculation, the Design Code of CFETR is aimed at introducing a specific engineering design, integrating different sorts of commercial engineering software. As a benchmark of the Design Code of CFETR, the TF Coil module (also called the Integrated Design System of TF Coil, IDS-TFC) would explore a method to integrate engineering software. The final goal is that the IDS-TFC can work out and optimize the design automatically, what the user needs to do is just to set the input parameters and optimization objects. The module should be able to automatically calculate the center line of the TF Coil, build a 3D structural model, and execute electromagnetic (EM) and structural mechanics analyses.

2 A method to integrate engineering software

To realize the final goal, two problems should be solved: first, how to connect different sorts of...
engineering software; second, how to update the data simultaneously between them during iteration. An Integrated and Automatic Optimization Method (IAOM) has been developed to address these two problems. Dealing with the first problem, interface files instead of interface programs can be considered to connect software. It should be determined which kinds of data would pass through interface files, such as dimension parameters, material properties, and structural models. Then different types of interface files can be created based on data types. Parameterized models should be built in order to facilitate the data passing. Regarding the second problem, the engineering software should be executed as batch processing by another exterior program, which can also edit interface files. Then software would be executed and the data would be updated once an iteration.

As above, IAOM mainly consists of the interface files, parameterized models, and exterior program. This paper will expatiate on the method with the description of IDS-TFC, namely how IAOM helps to realize IDS-TFC. Currently, three submodules constitute IDS-TFC: (a) physical calculation by software FORTRAN, (b) structural modeling by software CATIA, (c) finite element analyses by software ANSYS Classic. These three submodules work in series. Fig. 1 shows the workflow of IDS-TFC briefly, the submodules are named after specific software, such as the FORTRAN Module. In Fig. 1, each submodule has been parameterized or directly programed. The dashed lines represent different types of data transmitted between submodules. The exterior program would execute the whole workflow though it does not appear in Fig. 1.

As it is difficult to work out the general solution of this equation, a specific and famous figure named Princeton-D has been worked out. Fig. 2 [9] shows the curve of Princeton-D. The extreme dimensions of radii are given by [8]:

\[ r_1 = r_0 e^{-k}, \]
\[ r_2 = r_0 e^{+k}. \]

Therefore,

\[ r_0 = (r_1 r_2)^{\frac{1}{2}}, \]
\[ k = \frac{1}{2} \ln\left(\frac{r_2}{r_1}\right). \]

The curve of the magnet winding is determined by \( k, r_0, r_1, r_2 \).

Fig.1  The workflow of IDS-TFC

3 FORTRAN module

FORTRAN Module leads the workflow, it determines the center line of TF Coil. Theoretically, the goal is to find a constant-tension, momentless shape for TF Coil’s center line, which will ease the serious force load induced by the highest field. The constant-tension curve’s equation is [8,9]:

\[ r d^2 z \over dr^2 = \pm \frac{1}{k} [1 + \left( {dz \over dr} \right)^2]^{3/2}, \]

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However, the exponential figure of Princeton-D is difficult to manufacture and process. Hence, the program in FORTRAN Module designs three tangential circular arcs to fit Princeton-D, the configuration of three-arc curve is shown in Fig. 3. The relations between radii and the coordinates of arcs are given [10]:

\[ h_2 = \frac{\sqrt{3}}{2(\sqrt{3} - 1)} \left( 2h_M - \frac{1}{\sqrt{3}} h_L - r_2 + r_1 \right), \]
\[ \rho_3 = \frac{2}{\sqrt{3}} h_2 + \rho_2, \]
\[ \rho_2 = h_M - h_2, \]
\[ \rho_1 = \frac{2}{\sqrt{3}} (h_2 - h_L) + \rho_2. \]

Here, \( h_L \) is the height of the starting point of the first arc, \( \rho_i \) is the radius of the i-th arc, \( \theta_i \) is the central angle of the i-th arc, \( h_M \) is the height of the coil, \( h_2 \) is the height of the second arc center.
First, $r_1$, $r_2$ are given to determine the Princeton-D curve. Then regrading the three-arc curve, three central angles ($\theta_1, \theta_2, \theta_3$) are set to 60 degrees as initial values. In addition, $h_L$, $h_M$ are given based on the Princeton-D curve. As a result, the initial values of central coordinates would be calculated by these known values and Eqs. (6) to (9). Then the central angles are changed while centers are all fixed, to make the arcs fit the Princeton-D curve. Consequently, the initial values of central coordinates would be calculated by these known equations.

To interact with FORTRAN Module, it is necessary to determine a dimension link for the center line of TF Coil in CATIA Module. There are 14 parameters of the center line in FORTRAN module, including input and output: $r_1$, $r_2$, $Arc_1(\rho_1, h_1)$, $Arc_2(\rho_2, h_2)$, $Arc_3(\rho_3, h_3)$, $\rho_1$, $\rho_2$, $\rho_3$, $\theta_1$, $\theta_2$, $\theta_3$. However, it is unnecessary to transfer all 14 parameters to CATIA Module because there are several relationships between these parameters. For instance, the sum of three central angles is 180$^\circ$, therefore $\theta_3$ can be established by (180$^\circ$ – $\theta_1$ – $\theta_2$). Moreover, it is more convenient to apply central coordinates than central angles in ANSYS software, thereby central angles would be expressed by other parameters. The equations are given below:

$$O_{r_1} = r_1 - \rho_1,$$  \hspace{1cm} (10)

$$O_{z_2} = 0,$$  \hspace{1cm} (11)

$$O_{z_1} = h_L,$$  \hspace{1cm} (12)

$$\rho_1 < \rho_2 < \rho_3,$$  \hspace{1cm} (13)

$$(r - O_{r_1})^2 + (z - O_{z_1})^2 = \rho_1^2,$$  \hspace{1cm} (14)

$$(r - O_{r_2})^2 + (z - O_{z_2})^2 = \rho_2^2,$$  \hspace{1cm} (15)

$$(r - O_{r_3})^2 + (z - O_{z_3})^2 = \rho_3^2,$$  \hspace{1cm} (16)

$$\theta_1 + \theta_2 + \theta_3 = \pi.$$  \hspace{1cm} (17)

4 CATIA module

Based on the center line calculated by FORTRAN Module, CATIA Module builds a 3D parameterized model of the TF Coil with structural details, shown in Fig. 4. The 3D model mainly consists of Coil, Coil Case, Support, and Outer Intercoile Structure (OIS) [11].

As an intermediate portion in the workflow, CATIA Module and its 3D model should be carefully modified to interact with FORTRAN Module and with ANSYS Module.

The 3D model has been simplified properly to be compatible with ANSYS Module, shown in Fig. 4. First, the winding details of the Coil are replaced by solid structure. Furthermore, the ground insulation between the Coil and the Coil Case is simplified into TF Coil Case. In addition, the bolt holes in OIS and support are omitted. However, the center line and the dimension of the Coil and the Coil Case are not simplified.

![Fig.3 The configuration of three-arc curve](image)

![Fig.4 3D parameterized CATIA model](image)
Obviously, equations from (14) to (16) are analytic geometry equations of circles. They can also be expressed as:
\[
\begin{align*}
\begin{cases}
  r = O_1 + p_1 \cos \theta_1 \\
  z = O_1 + p_1 \sin \theta_1
\end{cases},
\end{align*}
\]
(18)
\[
\begin{align*}
\begin{cases}
  r = O_2 + p_2 \cos \theta_2 \\
  z = O_2 + p_2 \sin \theta_2
\end{cases},
\end{align*}
\]
(19)
\[
\begin{align*}
\begin{cases}
  r = O_3 + p_3 \cos \theta_3 \\
  z = O_3 + p_3 \sin \theta_3
\end{cases}.
\end{align*}
\]
(20)
Based on the tangent point between Arc1 and Arc2, Eqs. (18), (19) and (17) are combined to yield:
\[
\begin{align*}
\begin{cases}
  O_1 + p_1 \cos(\pi - \theta_3) = O_2 + p_2 \cos(\pi - \theta_3) \\
  O_1 + p_1 \sin(\pi - \theta_3) = O_2 + p_2 \sin(\pi - \theta_3)
\end{cases}.
\end{align*}
\]
(21)
Combining Eq. (21) with the trigonometric function:
\[
(\sin \alpha)^2 + (\cos \alpha)^2 = 1,
\]
(22)
here \(\alpha\) is an arbitrary angle, results in:
\[
\frac{(O_1 - O_2)^2}{p_1 - p_2} + \frac{(O_1 - O_2)^2}{p_1 - p_2} = 1.
\]
(23)
Similarly, combining Eqs. (19), (20), (17) and (22) gives:
\[
\frac{(O_3 - O_2)^2}{p_3 - p_2} + \frac{(O_3 - O_2)^2}{p_3 - p_2} = 1.
\]
(24)
Eqs. (23) and (24) actually describe the distance between two centers. Considering that the parameterization of CATIA model has difficulty in describing quadratic equations, it is assumed that:
\[
O_2 > O_1 \text{ and } O_2 > O_3.
\]
(25)
Therefore, \(O_2\) and \(O_3\) could be calculated by Eqs. (23)–(25) and (13):
\[
O_2 = \sqrt{(p_1 - p_2)^2 - (O_1 - O_2)^2} + O_1.
\]
(26)
\[
O_3 = -\sqrt{(p_3 - p_2)^2 - (O_3 - O_2)^2} + \sqrt{(p_1 - p_2)^2 - (O_1 - O_2)^2} + O_1.
\]
(27)
Combining Eq. (21) with (26) and (27) results in:
\[
\theta_3 = \sin^{-1}\left(\frac{O_3 - O_2}{p_3 - p_2}\right).
\]
(28)
Similarly, \(\theta_1\) can be calculated by Eqs. (19), (20), (17), (26), (27):
\[
\theta_1 = \sin^{-1}\left(\frac{O_2 - O_3}{p_3 - p_2}\right).
\]
(29)
Therefore,
\[
\theta_2 = \pi - \sin^{-1}\left(\frac{O_2 - O_3}{p_3 - p_2}\right) - \sin^{-1}\left(\frac{O_1 - O_2}{p_1 - p_2}\right).
\]
(30)
As above, there are six independent variables left after the calculation: \(p_1, p_2, p_3, O_2, h_1, r_1\). The other eight parameters can be expressed by these independent variables or be directly constant, based on eight equations from Eqs. (10) to (12) and from Eqs. (26) to (30). As a result, these six independent variables and eight equations constitute the dimension link of the center line in CATIA Module.

As for the other dimension links of structural details, they are mainly relative to cross-section dimensions, shown in Fig. 5. The cross-section of bucking cylinder (or defined as Inner Leg Segment) is shown at the left side in Fig. 5, and the cross-section of arsegment (or defined as Outer Leg Segment) is shown at the right side in Fig. 5. The independent variables are: the length and width of coil \(l_{\text{coil}}\) and \(w_{\text{coil}}\), the thickness of Coil Case \(t_{\text{case,inner}}\) and \(t_{\text{case,outer}}\), and the number of TF Coil \(n_{\text{TF}}\). Furthermore, the relationships between structural parameters are given as:
\[
w_1 = 2 \cdot \tan(\text{angle}_{\text{TF}}) \cdot (r_1 - l_{\text{coil}}/2 - t_{\text{case,inner}}),
\]
(31)
\[
w_2 = 2 \cdot \tan(\text{angle}_{\text{TF}}) \cdot (r_1 + l_{\text{coil}}/2 + t_{\text{case,outer}}),
\]
(32)
\[
\text{angle}_{\text{TF}} = \frac{360^\circ}{2n_{\text{TF}}},
\]
(33)
\[
t_{\text{case,lateral}} = \frac{1}{2} \left(\frac{2\pi l_{\text{x}}}{n_{\text{TF}}} - w_{\text{coil}}\right),
\]
(34)
here, \(w_1\) and \(w_2\) are the widths of the inner leg of Coil Case, \(\text{angle}_{\text{TF}}\) is the angle of each sector of TF Coils, \(t_{\text{case,lateral}}\) is the lateral thickness of the outer leg Coil Case.

Also, there are many other parameters in support and OIS, which are not described in this paper for avoiding verbosity.

![Fig.5 The cross section of TF Coil](image-url)
5 ANSYS module

Following CATIA Module, ANSYS Module calculates the electromagnetic (EM) and mechanical performance by Finite Element Method. Actually ANSYS software is the main tool to accomplish the engineering and mechanics analyses in various scenarios for TF Coils \[^{[11]}\]. The scenario discussed here is the equilibrium status where the currents of coils and plasma are unchanged.

The finite element model of TF Coil is shown in Fig. 6. For facilitating the process, only one TF Coil is defined as analysis object, which is built by SOLID5 Element, shown on the right side of Fig. 6. Other TF Coils, as well as Poloidal Field Coils, Central Solenoid Coils, and plasma are built by SOURC36 Element and offer currents in the analyses. The current directions are also described in Fig. 6.

![Finite element model of TF Coil](image)

As a result, the magnetic flux density \( B \) of TF Coil is shown in Fig. 7. The maximum magnetic field \( B_{\text{max}} \) is 9.6551 T, occurring at the middle of the Inner Leg Segment, shown in A-A cross section. The vector plot of A-A cross section indicates that the magnetic flux runs in a toroidal direction and that the flux density increases as the coordinate increases in radius direction.

Moreover, ripple is calculated in ANSYS Module, using another finite element model. Toroidal field ripple \( \delta_{\text{TF}} \) describes the extent to which toroidal field reduces in the inter-coil gaps, which is defined as \[^{[12]}\] :

\[
\delta_{\text{TF}}(r,z) = \frac{B_{\text{max}}(r,z) - B_{\text{min}}(r,z)}{B_{\text{max}}(r,z) + B_{\text{min}}(r,z)}.
\]  

(35)

Here, \( \varphi \) is the angle in toroidal direction. Since there are 16 TF Coils in total, the maximum \( \delta_{\text{TF}} \) occurs when \( \varphi = 22.5^\circ \). Consequently, the ripple is displayed in Fig. 8. The \( \delta_{\text{TF}} \) is distributed parabolically in the radius direction and the maximum \( \delta_{\text{TF}} \) is 0.229%.

![The magnetic flux density \( B \) of TF Coil](image)

![The toroidal field ripple in cross-section direction when \( \varphi = 22.5^\circ \)](image)

Regarding IAOM, the commands method APDL is applied in ANSYS Module. APDL directly reads the interface files to introduce the 3D model and the independent parameters of center line and structure details. All relationship equations in CATIA Module are repeated in APDL too. In addition, APDL also creates output files to store objective parameters, such as \( B_{\text{max}} \) and \( \delta_{\text{TF}} \). Finally, the APDL commands are stored in a text file.

6 Realization of the IDS-TFC

After the parameterized models and interface files are established, it is ready to integrate the IDS-TFC. The exterior program is applied to connect interface files and software in each submodule. There are several ways to realize the exterior, such as using programming language (VB, Java, C++, Matlab) and commercial software (Optimus, iSIGHT). Here, Optimus has been applied in our research, considering the convenience and operating efficiency.

The specific workflow of IDS-TFC is shown in Fig. 9, demonstrating one step during optimization iteration. The green cylinder icons are interface files which store parameters. The software in submodules is marked by red dashed lines and caption. Particularly, ANSYS Module carries on two analyses, which are parallel.

![Specific workflow of IDS-TFC](image)
A double-object optimization experiment has been worked out to test the integration. The objects are the minimum $B_{\text{max}}$ and the minimum $\delta_{\text{TF}}$, which are also the final outputs in ANSYS Module. Furthermore, for expediting the calculation, several less important parameters have been defined as constant. Corresponding to Fig. 1, the iteration and data participating in the optimization experiment are shown in Fig. 10. Through the parameter transferring, the original input parameters in FORTRAN Module have been cut to $r_2$, and the parameters of structural details in CATIA Module have been cut to $t_{\text{case},\text{inner}}$ and $t_{\text{case},\text{outer}}$. Other parameters remain unchanged. Since the preliminary value of $r_2$ is around 10 m, the range of $r_2$ is set as [6 m, 15 m], for covering all physical solutions during the calculating iterations.

Regarding optimization method, there are roughly two ways to achieve optimum result. The first way is applying workflow directly during optimization, namely running the whole workflow one time in every iteration step. It is credible but time-consuming. The other way is Design of Experiment (DOE). The purpose of DOE is to find the relationships between input and output to facilitate the optimization. Furthermore, Super Latin Hypercube Sampling (SLHS) has been applied in DOE because it needs much smaller quantity of experiments than other methods. That is, a DOE will be made by running the workflow certain times before optimization. Then after gaining the input-output relationships, the optimization can be executed among input and output parameters instead of running the whole workflow. It is efficient to apply this method for subsequent design code, especially when the code system is too large and time-consuming.

As results of the first optimizing method, Fig. 11 describes the parallel-line figure of optimization results. The physical feasible range of $r_2$ is about [1.6 m, 1.8 m]. There is linear relationship between $r_2$ and $B_{\text{max}}$, $r_2$ and $\delta_{\text{TF}}$, $\rho_1$, $\rho_2$, $\rho_3$, $Oz_2$, $h_L$, verifying the equations in FORTRAN Module. It should be noted that the physical feasible ranges of $r_2$, $\rho_1$, $\rho_2$, $\rho_3$, and $h_L$ all contain intermediate blank regions, however, $Oz_2$ has a continuous physical feasible range. It indicates that when other parameters are set to the values in the blank regions, for example, $r_2$ is set to 11.3 m, there is no corresponding solution for $Oz_2$. The range of $Oz_2$ to some extent impacts the blank regions of other parameters.

Moreover, Fig. 11 also demonstrates that the minimum $B_{\text{max}}$ and the minimum $\delta_{\text{TF}}$ cannot both be realized. There is a positive correlation between $r_2$ and $B_{\text{max}}$, but negative between $r_2$ and $\delta_{\text{TF}}$. Therefore, the optimum solution of $B_{\text{max}}$ and $\delta_{\text{TF}}$ is a range rather than a specific one, shown in the parallel lines and the color legend in Fig. 11. In practical design, the optimum solution could be selected based on specific requirement.
As for the second optimizing method, Fig. 12 describes the input-output relationship. The Pearson factors among $r_2$, $p_1$, and $O_{22}$ are correspondingly high in Fig. 12, confirming the linear relationship in Fig. 11. Particularly, Fig. 12 also gives the correlations between $t_{\text{case, inner}}$, $t_{\text{case, outer}}$ and other parameters. The scatter plots of $t_{\text{case, inner}}$ are disorderly, indicating that $t_{\text{case, inner}}$ impacts little on center line dimension, $B_{\text{max}}$ and $\delta_{\text{TF}}$. The reason is that $t_{\text{case, inner}}$ represents the structural details, which contributes to structural strength and stress rather than center line dimension and electromagnetic (EM) properties. A similar situation occurs for $t_{\text{case, outer}}$.

7 Conclusion

Based on IAOM, the Integrated Design System of TF Coil has been operated successfully to optimize the design automatically. Namely, it indicates that the engineering software such as FORTRAN, CATIA, and ANSYS has been integrated successfully. Parameterized models and interface files have been created in each submodule, with the exterior program connecting them. FORTRAN Module establishes the center line dimensions. CATIA Module creates a 3D model, introduces center line dimensions from FORTRAN Module, and builds new dimension links. ANSYS Module directly reads interface files and executes analyses for $B_{\text{max}}$ and $\delta_{\text{TF}}$. The optimization experiment has been finally carried on and the optimum solution of double objects has been acquired.

Moreover, serving as a design process for CFETR, IDS-TFC would participate CFETR formally and facilitate the design process remarkably. Also, IDS-TFC is an example and reference for other device component modules, such as PF module, divertor module, vacuum vessel module.

Regarding future work, more scenarios would be added such as verifying stress and strain of TF Support in structural simulation, calculating heat transfer of TF Coil. As a result, multiple objectives optimization would be executed depending on specific scenarios. Also, comparison of different optimizing methods or even algorithms would be worked out to find the suitable ways for design code system.

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