Quantitative Evaluation of Fatigue Impact on CS and TF Coils in Pulsed Tokamak Power Plant*)

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Fatigue issue of a pulsed operation tokamak is studied for the major radii R_p = 10 m, 11 m and 12 m in this paper. By study of central solenoid coil (CS) fatigue, it is clarified that pulse cycle number of the reference of 10 m throughout 30-year operation period is about 50,000 and its allowable stress amplitude for CS fatigue is about 300 MPa. This constraint has actually no impact on the CS designs of the reference tokamaks. Allowable length of toroidal field coil (TFC) maintenance port of the reference 10 m tokamak is calculated to be 13.3 m, which is corresponding to 92 % of TFC height. Also the minimum width of each cryostat post which supports the overturning force of TFC is found to be 2.3 m to prevent its fracture. This result indicates that fatigue may have impact on rather outer support structure of TFC than TFC itself. This construction cost for strengthening cryostat post could reach a few of hundreds million dollars according to a rough calculation.

Keywords: fatigue life curve, pulsed tokamak reactor, pulse duration, CS, central solenoid coil, TFC, toroidal field coil, equivalent alternating stress, Modified-Goodman Diagram

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1. Introduction

Although the steady state operation will be the best for commercial fusion plants, tokamak reactors with pulsed operation have been discussed as one of candidates of tokamak fusion plants due to some difficulties of non-inductive current drive. On the other hand, several known issues on the pulsed operation have been considered to obstruct its realization crucially. One of the typical issues is "cyclic stress on coils" caused by frequent shutdown, which is generally occurred once a day at least for magnetization of central solenoid coil (CS) [1, 2]. This issue about cyclic stresses on CS and toroidal field coil (TFC) has been focused on in the present study. When cumulative count of operation gets to the order of 10^4 times, which is equivalent to a several ten years operation, fatigue fracture is expected to be incurred. This problem also might be a hindrance even in steady-state operation if load following operation is conducted. As a step to resolve those problems, this study will aim to clarify design impacts of the fatigue problem quantitatively.

This paper consists of sections of defining reference tokamaks to research, calculating allowable stress amplitude from CS fatigue life, TF fatigue and summary.

2. Reference Parameters for Pulsed Tokamak

A parameter set of a 10 m-sized pulsed tokamak is considered for this study referring a concept "Conservative DEMO" which was discussed in Broader Approach (BA) activity under EU/Japan collaboration as an example for benchmark of computer codes [3]. Also 11 m and 12 m plants are arranged in comparison with the reference parameter set of the 10 m tokamak to investigate the effect on the pulse duration and allowable stress amplitude for fatigue. The major parameters are shown in Table 1. All these tokamaks are designed so as to have the net electricity output of about 700 MW_e as well as 10 m tokamak. It is noted that, unlike the normal configuration, the neutral beam (NB) source power is not contained in balance of plant because that power was assumed to be supplied from grid electricity. Almost all other parameters for 11 m and 12 m of the major radius are also set to similar value to

Table 1 Parameter sets of reference pulsed tokamaks.

		Pulsed Tokamak (R_p=10m)	Pulsed Tokamak (R_p=11m)	Pulsed Tokamak (R_p=12m)
Plasma and Reactor Parameters				
Electric output	P_e (MW)	742	753	734
Net electric output	P_{net} (MW)	692	702	684
Balance of plant	P_{BOP} (MW)	50.3	50.9	49.8
NB Source Power	P_{SNB} (MW)	99.8	103	103
Major radius	R_p (m)	10	11	12
Aspect ratio	A	4	4.4	4.8
Elongation at 95% flux surface	κ_{95}	1.66	1.66	1.66
Triangularity at the 95% flux surface	δ_{95}	0.33	0.33	0.33
Troidal field max	B_{tmax} (T)	11.7	11.7	11.7
Troyon coefficient	β_N	2.1	2	1.9
Z-effective	Z_{eff}	1.33	1.33	1.33
Total plasma current	I_p (MA)	18.1	17.2	16.4
Fraction of greenwald limit	f_{nGW}	0.82	0.827	0.82
HH factor	H_{98y2}	0.788	0.769	0.756
CS radius	R_{CS} (m)	3.803	4.617	5.435
Maxmum pulse duration	τ_{op} (hrs)	3.472	6.489	11.04
pulse frequency (including dwell time of 0.5hr, plant	f_{rop} (day^{-1})	4.531	2.575	1.559
Plant availability	f_{av}	0.75	0.75	0.75

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those of the 10 m tokamak. Those shapes are modified so as to enlarge only to radial direction. Their parameters are validated by FUSAC system code developed by T. Yoshida *et al.* [4]. The NB power is optimized using the POPCON diagram because FUSAC cannot calculate the optimized auxiliary heating power for startup and shutdown of pulsed tokamaks.

3. Evaluation of CS Fatigue Life

To find the allowable stress amplitude for CS fatigue, valid design points of CS coil will be scanned. In generally, the allowable stress amplitude can be determined from such as the S-N curve with the total number of cyclic stress. Although this study also follows the method, there is a problem that the allowable number of stress repetition would change by change in CS durability. Namely, if the CS thickness is increased without change of R_p, the hollow area of CS decreases. Consequently the CS flux and the pulse duration decrease, the number of stress repetition increases, and allowable stress amplitude shrinks though CS durability is tried to be strengthened. If R_p is allowed to be increased, also both allowable stress and strengthening CS durability are increased. The CS thickness is limited also by the allowable current density. The determining process of CS allowable stress is complicated. To clarify design window for the CS allowable stress, the numbers of stress repetition and CS durability, which is expressed as maximum allowable stress, are scanned. This parametric scan was performed at multiple maximum allowable stresses in each R_p = 10 m, 11 m and 12 m of the reactor size, where S_m is a allowable static stress, JJ1 steel at 4 K is 800 MPa. The result is shown in Fig. 1, where horizontal-axis is the total number of repetition of stress throughout 30-year tokamak operation, vertical-axis shows maximum allowable stress on CS. Each scanned designs are plotted as square dots. To validate allowable stress amplitude for scanned designs, design S-N curve and failure curves were also plotted. The former one is based on theoretical S-N curve with safety factor of 20 for the life and 2 for the stress [5]. The later one is based on crack growth model for cryogenic JJ1 steel at 4 K [6]. If a square dot is lower than those S-N curve or failure curves, corresponding design is within allowable stress amplitude.

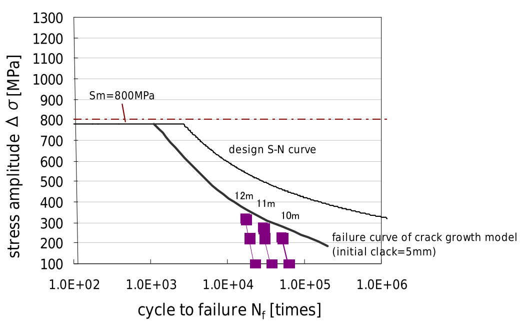

Fig. 1 Fatigue life of reference pulsed tokamaks.

This study found that the constraint of current density condition is rather dominant than stress condition for CS design. Namely, the allowable stress amplitude affects no impact to CS design itself because the CS coil has already been thick enough to endure 30-year cyclic stress by the allowable current density. All the design points have satisfied allowable stress amplitude of both S-N and failure curves. Notably increase of R_p does not contribute raising allowable stress amplitude extremely nor increasing margin of fatigue life as far as this result. Based on this result allowable stress amplitude for the reference tokamak of R_p = 10 m is assumed to be 300 MPa for later discussion.

4. Evaluation of TF Fatigue Life

In assessing the alternating stress on TF, we focused on the stress on its outer leg because the most frequent vibration occurs there in pulsed operation.

All forces and support schematic on outer leg are shown in Fig. 2 [7]. Three forces act on outer leg of TFC as follows: overturning force (expressed as $F_{\theta A}$, $F_{\theta B}$ in the Fig. 2), centering force (F_R) and hoop force (F_h). The overturning force is modeled as the two point loads for simplification in this study. Although the overturning force is the main source of cyclic stress all these forces have to be considered to evaluate cyclic stress. To support mainly the overturning force, a support structure which is named "Shear Panel" is installed on upper and lower shoulder of TFC. The part between the lower and upper shear panels is configured as opening because the space is reserved for the maintenance port. Thus the most intensive stresses of the outer leg is found on the both sides of the opening in analogy to straight beam problem supported at both ends.

The other parameters in Fig. 2 are as follows: the parameter l is the opening height; $F_{\theta A}$ and $F_{\theta B}$ are the overturning forces, which intensities are each 60 MN toward

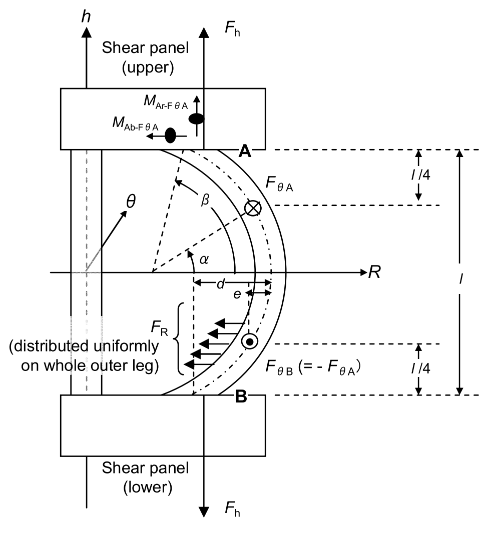

Fig. 2 Analytical schematic of TFC stresses.

opposite direction. Those forces are assumed as point load on the height of $l/4$ and $-l/4$ on the outer leg of TFC. The distances of d and e in radial direction are as follows: the former one is from fixed side of shear panel to TFC vertex of radial direction; and the latter one is from the load point of the overturning force to TFC vertex.

Bending moment and torsion moment on the position A by the overturning force are as follows:

$$M_{\text{Ab-}F_{\theta\text{A}}} = \frac{3}{32} F_{\theta\text{A}} l,$$
$$M_{\text{Ar-}F_{\theta\text{A}}} = R_{\text{A}} d + F_{\theta\text{A}} e,$$

where R_{A} is support resistance from shear panel, whose intensity is $-11/16F_{\theta\text{A}}$. The modulus of section for toroidal and radial direction and polar modulus of section are:

$$Z_{\text{radial}} = \frac{bh^3 - b_1h_1^3}{6h} \quad Z_{\text{troidal}} = \frac{hb^3 - h_1b_1^3}{6b},$$
$$Z_{\text{p}} = \frac{bh^3 - b_1h_1^3}{6h} + \frac{hb^3 - h_1b_1^3}{6b},$$

where b, b_1, h and h_1 are width, width of hollow area, height and height of hollow area of cross-section of TFC can, which is hollow rectangle. Those in the reference tokamak are: $b = 1.9\,\text{m}$, $b_1 = 1.1\,\text{m}$, $h = 1.2\,\text{m}/\cos\alpha$, $h_1 = 0.7\,\text{m}/\cos\alpha$. The coefficient of $1/\cos\alpha$ indicates increase in area of support cross section because of its inclination from vertical section. Also d and e are derived as:

$$d = \begin{cases} R_1(1-\cos\alpha) & (0 \le \alpha < \theta_1) \\ (\because \alpha = \arcsin(l/2R_1)) & \\ R_1(1-\cos\theta_1) + R_2(\cos\theta_1 - \cos\alpha) & (\theta_1 \le \alpha < \theta_2) \\ \left(\because \alpha = \arcsin\left(\dfrac{l - 2(R_1 - R_2)\sin\theta_1}{2R_2}\right)\right), & \end{cases}$$

$$e = \begin{cases} R_1(1-\cos\beta) & (0 \le \alpha < \theta_1) \\ (\because \beta = \arcsin(l/4R_1)) & \\ R_1(1-\cos\theta_1) + R_2(\cos\theta_1 - \cos\beta) & (\theta_1 \le \alpha < \theta_2) \\ \left(\because \beta = \arcsin\left(\dfrac{l - 2(R_1 - R_2)\sin\theta_1}{4R_2}\right)\right), & \end{cases}$$

where R_1, R_2, R_3, θ_1, θ_2, θ_3 are the TFC's shape parameters of 3 arc approximation design method. Its concept is shown in Fig. 3. These shape parameters of TFC of this reference tokamak are as follows: $R_1 = 7.871\,\text{m}$, $\theta_1 = 42.2°$, $R_2 = 6.012\,\text{m}$, $\theta_2 = 63.0°$, $R_3 = 3.591\,\text{m}$, $\theta_3 = 74.9°$. Maximum width and height of TFC are $R_0 = 10.72\,\text{m}$ and $H_0 = 14.52\,\text{m}$.

Bending stresses from the overturning force, centering force, hoop force and torsion stress from the overturning force are as follows:

$$\sigma_{\text{A-}F_{\theta\text{A}}} = M_{\text{Ab-}F_{\theta\text{A}}}/Z_{\text{troidal}},$$
$$\sigma_{\text{A-}F_{\text{R}}} = F_{\text{R}} l/12Z_{\text{radial}},$$
$$\sigma_{\text{A-}F_{\text{Z}}} = F_{\text{Z}}/S,$$
$$\tau_{\text{A-}F_{\theta\text{A}}} = M_{\text{Ar-}F_{\theta\text{A}}}/Z_{\text{p}},$$

where S is cross-sectional area of coil can of $1.51\,\text{m}^2$, F_{R} is the centering force that is assumed to be uniformly-distributed force of 80 MN total on outer leg, F_{Z} is the hoop force whose intensity is 140 MN. $\sigma_{\text{A-}F_{\text{R}}}$ is solved as straight beam problem. Stress tensor in R-θ-h coordinate system is:

$$\sigma = \begin{bmatrix} 0 & \tau_{\text{A-}F_{\theta\text{A}}} & 0 \\ \tau_{\text{A-}F_{\theta\text{A}}} & 0 & 0 \\ 0 & 0 & \sigma_{\text{A-}F_{\theta\text{A}}} + \sigma_{\text{A-}F_{\text{R}}} + \sigma_{\text{A-}F_{\text{Z}}} \end{bmatrix}.$$

Its principal stresses are derived with $\sigma_{\text{A-}F_{\theta\text{A}}} + \sigma_{\text{A-}F_{\text{R}}} + \sigma_{\text{A-}F_{\text{Z}}}$, $\pm\,\tau_{\text{A-}F_{\theta\text{A}}}$, diagonalizing the matrix. To evaluate alternating stress based on Tresca's condition, difference between maximum and minimum principal stress at operation period and at $I_{\text{CS}} = 0$ should be get as follows:

$$\sigma_{\text{d}} = \sigma_{\text{A-}F_{\theta\text{A}}} + \sigma_{\text{A-F}_{\text{R}}} + \sigma_{\text{A-}F_{\text{Z}}} + \tau_{\text{A-}F_{\theta\text{A}}} \quad \text{(operation period)},$$
$$\sigma'_{\text{d}} = \sigma_{\text{A-F}_{\text{R}}} + \sigma_{\text{A-}F_{\text{Z}}} \quad (I_{\text{CS}} = 0, \Phi_{\text{CS}} = 0).$$

Because the overturning force does not appear in the dwell period, the terms of $\sigma_{\text{A-}F_{\theta\text{A}}}$, $\tau_{\text{A-}F_{\theta\text{A}}}$ are not added in σ'_{d}. Then the definition of equivalent alternating stress is:

$$\sigma_{\text{a eq}} = \frac{\sigma_{\text{a}}}{(1 - \sigma_{\text{mm}}/\sigma_{\text{UTS}})},$$

where σ_{a} is alternating stress derived with $\sigma_{\text{a}} = (\sigma_{\text{d}} - \sigma'_{\text{d}})/2$, σ_{mm} is modified mean stress, and σ_{UTS} is the ultimate tensile stress of 1527 MPa for the JJ1 steel [8].

The relationship between the allowable stress amplitude and the opening length based on the previous discussion is shown as Fig. 4, where horizontal-axis is length of

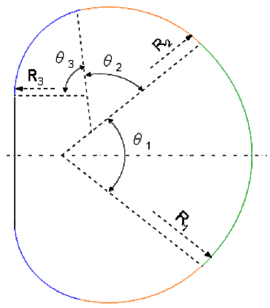

Fig. 3 The concept of TFC shape design by 3 arc approximation method.

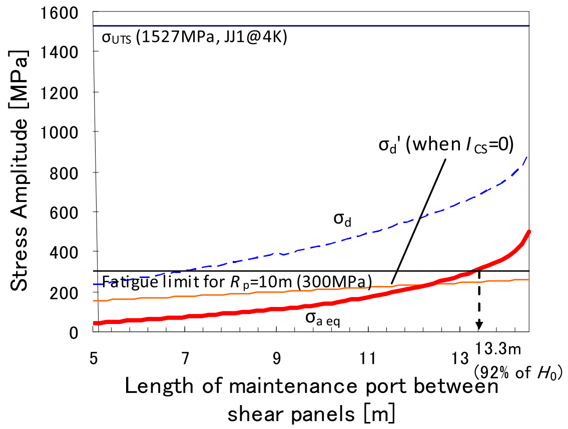

Fig. 4 Stress amplitude on side of maintenance port.

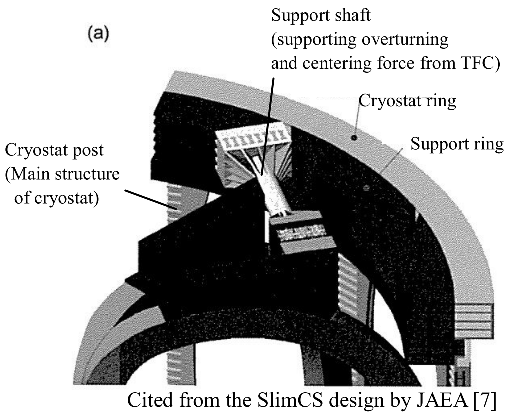

Fig. 5 Schematic view of the TFC support structure attached to the cryostat.

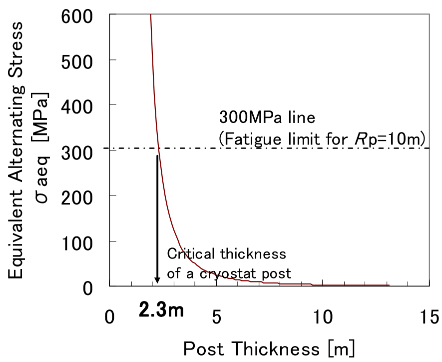

Fig. 6 Stress amplitude of cryostat post.

maintenance port between shear panels on upper and lower side of TFC, shown as l in Fig. 2, vertical-axis is equivalent alternating stress, shown as $\sigma_{\mathrm{a\ eq}}$ in formula above. The stress has been scanned over the opening length from 5 m to 14.52 m, which is maximum height of TFC. The figure indicates that equivalent alternating stress will exceed 300 MPa (which is the allowable stress amplitude to keep 30-year operation as described in Chapter 3) if the opening length is beyond 13.3 m, which is corresponding to 92 % of TFC height. This is enough achievable condition.

In addition, evaluation of cryostat stress was also performed. Here the TFCs are assumed to be supported by the supporting structure attached on the cryostat, as shown in Fig. 5 [7]. The overturning force of the TFC transmitted to the cryostat acts to twist the cryostat in the circumferential direction through the support shaft as shown in Fig. 5. The maximum stress occurs at the upper and lower ends of posts. The stress was evaluated as a cantilever problem, i.e., the upper end and lower end were assumed to be free end and fixed end respectively. Alternating stresses were scanned by post thickness with assumptions as follows:

- Height of the post was fixed 18 m.
- Cross-section was assumed square.
- The number of the posts is as same as that of TFC. (One TFC is supported by one post.)
- Centripetal force is not transmitted to the posts but only to cryostat ring.

The result is shown in Fig. 6, where horizontal-axis shows thickness of post, vertical-axis shows equivalent alternating stress. This figure indicates that thickness of cryostat posts are needed be more than 2.3 m to achieve 30-years operation. This cost could reach a few of hundreds million dollars according to a rough calculation.

5. Summary

Fatigue problems of pulsed operation tokamaks are studied. Pulsed tokamaks of R_{p} = 10 m, 11 m and 12 m are analyzed considering the reference a concept "Conservative DEMO" discussed in BA activity. The design window for CS fatigue is scanned. As a result it is found that the cycle number of stress is about 50,000 throughout 30-year operation and the corresponding allowable stress amplitude is about 300 MPa for the reference tokamak of R_{p} = 10 m. The limitation has almost no impact to the CS design itself including thickness, because other constraints such as allowable current density act in a dominant fashion to determine the thickness of CS. Also the allowable length of maintenance port of TFC with equivalent alternating stress is studied and it is found to be 13.3 m for the reference tokamak. It does not seem to be critical problem. The width of cryostat post, which supports the overturning force of TFC, was also investigated and it should be thickened to 2.3 m or more to endure throughout 30-year plant operation. The cost of such reinforcement of the structure could reach a few hundred million dollars.

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[1] Y. Ogawa, N. Inoue, Z. Yoshida and K. Okano, Fusion Technol. **24**, 188 (1993).
[2] G.T. Sager, D.-K. Sze, C.P.C. Wong *et al.*, Fusion Eng. Des. **29**, 43 (1995).
[3] K. Okano, G. Federici and K. Tobita, "DEMO Design Activities in the Broader Approach under Japana/EU Collaboration" in ISFNT 2013 Barcelona (2013).
[4] T. Yoshida, T. Nanahara, K. Yamaji and T. Takuma, CRIEPI Research Report T94001 (1994) [in Japanese], Central Research Institute of Electric Power Industry, Japan.
[5] K. Hamada *et al.*, Fusion Eng. Des. **75-79**, 87 (2005).
[6] T.N. Todd, R. Clarke, H. Kalsi *et al.*, CCFE Technical Report CCFE-R(12)17 (2012), Culham Centre for Fusion Energy, UK.
[7] K. Tobita, S. Nishio, M. Enoeda *et al.*, JAEA-Research 2010-019 (2010), Japan Atomic Energy Agency, Japan.
[8] K. Hamada, H. Nakajima, K. Kawano *et al.*, Fusion Eng. Des. **82**, 1481 (2007).