The uncertainty quantification of the free boundary G-S plasma equilibrium calculation on experimental advanced superconducting tokamak

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Abstract

The accuracy of plasma equilibrium in a tokamak is a crucial question about fusion plasmas. In the plasma equilibrium uncertainty quantification (UQ) campaign, equilibrium solver input parameters are given a default value interval from experimental data. The input data is then through the process of encoder, decoder, analyzer the calculated equilibrium out put uncertainty and its sensitivity analysis .

1. Introduction

The plasma equilibrium in a tokamak is a critical problem to solve which not only affects the plasma control but also the plasma diagnostic data analysis, plasma physics analysis. The Grad-Shafranov (G-S) equation is the most effective and popular method for calculating plasma equilibrium. FreeGS is an open-source free boundary G-S plasma equilibrium solver in Python [1] and it shows good agreement in benchmarking with EFIT. In the plasma equilibrium uncertainty quantification (UQ) campaign, equilibrium solver input parameters are given a default value from experimental advanced superconducting tokamak (EAST) discharge No. 106915, and an error range within which the inputs are sampled. Data features are extracted and reconstructed from samples by an encoder and a decoder [2]. Then the analyzer analysis the data frame and gives the Sobol analysis (sensitivity analysis) and UQ results. From the UQ campaign, large inputs error (≥5%) will lead to large output deviation in the output results, and even extremely bad integrand occurs or no G-S solution. Specially the plasma shape, it may show an irrational solution. The equilibrium result is reasonable when the error of all inputs is less than 3%. From the Sobol results, the inner midplane location shows a dominant influence (approximate 65%) on this G-S equilibrium solver. In the category of poloidal field currents, the currents of poloidal coil No.10 has a significant influence on equilibrium. For the safety factor (q) profile distribution, toroidal currents and plasma currents affect the most at plasma core area, the major radius of x-point and outer midplane location affect the profile at plasma boundary. For the plasma shape calculation, outer midplane location, outer leg R, x-point location played a more obvious role successively. For the toroidal magnetic field, most of the data distribution shows a good consistency except at the plasma boundary, which is mainly affected by toroidal currents (at plasma core area) and outer midplane location (at plasma boundary). As for the plasma pressure, it is mainly affected by toroidal currents and the Z coordinate of x-point, and the action between them is interrelated. This work can help us improve the accuracy of plasma equilibrium calculation and provide reference for plasma operation.

2. Uncertainty quantification and sensitivity analysis

Once the input parameter samples are chosen, the model is used to compute a system response quantity (SRQ, y-axis) for each sample. This sequence of SRQs is then ordered from smallest to largest, making up the abscissa of the cumulative distribution function (CDF) of the SRQ. Through the analysis from the UQ campaign, probability distribution functions (PDFs) are given. Then the analyzer processing this PDFs and gives the sensitivity (Sobol) analysis for this system [4,5].

From the safety factor *q* profile CDF (Fig. 1), the uncertainty of the *q* profile is very small in the plasma core area, around 2.17%, and the error interval increases gradually with the increase of normalized ψ. The largest error at plasma boundary is around 4.32%. Fig. 2 shows that the toroidal currents affect the profile the most at plasma core (around 60%). The degree of its influence decreases linearly and exponentially when it near the boundary. The plasma currents have the second largest influence on q profile in plasma core area, around 20%, and it has the same trend as toroidal currents. The outer midplane location only has 10% influence on *q* profile at plasma core, but its influence grew to 40% at Γ عي πϐω. It also drop very quickly in the plasma edge. However, the effect of the major radius of x-point increases exponentially in plasma boundary area.

For the plasma shape calculation, it has been divided into two parts to discuss, separatrix R coordinate and Z coordinate, shown in Fig.3, Fig.4 and Fig.5. The parameter which affects the separatrix Z coordinate is much complicated at the area of 1.4m to 1.6m. At inner area (R = 1.4m), the R coordinate of outer leg (outer strike point) and the R coordinate of X-point affect the most. At the area of R = 1.55m, there is a peak of influence by outer midplane location. In the area where the X-point is (R = 1.6m), the plasma shape's Z is mainly affected by the R coordinate of ourter leg (outer strike point). From R = 1.65m to R = 1.8m, the outer midplane show a significant influence on the plasma shape's Z. In the R coorinate area between 1.8m to 2.4m, the plasma shape's Z has been mainly affected by the R coordinate of X-point and the R corrdinate of outer leg (outer strike point) and these two affects peacked at R = 1.95m. The Separatrix R coordinate is mainly affected by the outer midplane location. Secondly, the R coordinate of the outer leg (outer strike point) affects plasma shape's R on the area between Z = -0.6m to -0.3m and 0.05m to 0.3m. Meanwhile, the R coordinate of X-point affects on the plasma shape's R at the area Z = -0.3m to -0.1m and the area Z = 0.3m to 0.8m. At the point Z = 0.0, except the affect from the outer midplane location, the plasma shape's R is also affected by R coordinate of the X-point, toroidal currents and the R coordinate of outer leg (outer strike point).