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Assessment of electromagnetic loads for EAST magnets using interaction matrix method

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HIGHLIGHTS

- A new technology–interaction matrix method is applied to assess EM loads of EAST magnet system.
- The interaction matrices of EAST magnet system are obtained.
- The application validated the efficiency and accuracy of the method.
- Results indicate that the approach can be conveniently used for multi-scenario EM loads assessment for EAST current-carrying components.

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ABSTRACT

An approach for assessing the electromagnetic (EM) loads of the main current-carrying components in tokamaks has been proposed recently [1,2]. It is mainly based on the interaction matrix and the method is general. This paper explores on the application of the new technology to EAST magnet system. Firstly, the interaction matrices of EAST magnet composed of bilateral interaction forces between separate components at unit current are calculated, then the EM loads are obtained by a linear transform of given currents using the interaction matrix. The application validated the efficiency and accuracy of the method, which is useful for the systematic assessment of Tokamak EM forces. Results indicate that the approach can be conveniently used for multi-scenario EM assessments and parametric studies of the EM loads for EAST current-carrying components, and a specialized force-calculating module for real-time simulating will be developed in the future.

1. Introduction

Experimental Advanced Superconducting Tokamak (EAST) is a fully superconducting tokamak which has been built in ASIPP CAS, aiming at investigating physical issues of steady-state advanced tokamak operation. The core of EAST project consists of the superconducting magnet systems, a non-circular cross-section of the vacuum vessel and actively cooled plasma facing components. There are two superconducting magnet systems in the tokamak machine. Firstly the superconducting toroidal field (TF) magnet system consists of sixteen D-shaped coils which are disposed toroidally and spaced 22.5 apart. Secondly the superconducting poloidal field (PF) magnet system consists of fourteen superconducting coils, including a stack of 6 central solenoid coils (CS) and 8 poloidal coils (PF). The CS and PF systems are supported on the TF magnet assembly [3]. Fig. 1 has shown the main components of EAST magnet system. Tables 1 and 2 have list the design parameters of these coils separately [3,4].

How to calculate the electromagnetic (EM) load on magnets accurately and quickly is one of the key techniques for engineering design of tokamak devices. A new theoretical method was proposed to assess the electromagnetic load on each magnet at various scenarios quickly [1,2]. Considering the linear relationship between the currents and corresponding EM loads, the method firstly calculates the interaction matrices for main Tokamak current-carrying components, which reflects parameters of pair-wise load interactions between separate coils at unit currents. The computed unit current interaction matrices are fundamental scenario-invariant properties of the system. They enable immediate purely-algebraic calculation of all individual interaction forces and torques between the components by given currents. Once the matrices are gained, the full set of loads of the current-carrying components at different scenarios can be simulated in few seconds by simple linear matrix operations [1,2].

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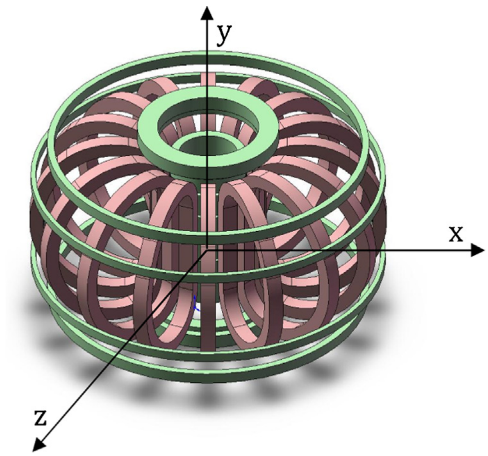


Fig. 1. Main components of EAST magnet system.

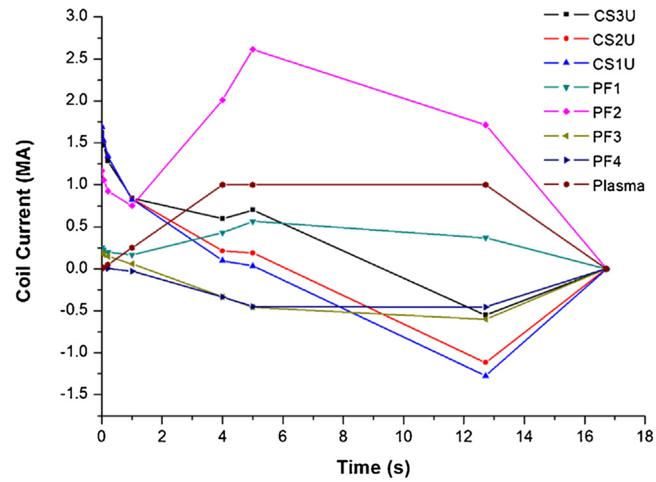


Fig. 2. Currents on toroidal coils with time.

Table 1
Design parameters of EAST TF coils.

Number of Coils	/	16
Number of turns per coil	/	130
Operating current	kA	14.3
Magnetic field at the plasma center(B_t)	T	3.5
Maximum field at the coil(B_{max})	T	5.8
Total stored energy	MJ	300

Table 2
Design parameters of EAST CS and PF coils.

	Position of coil centre		Coil size without ground insulation		
Coils	R(cm)	Z(cm)	dR(cm)	dZ(cm)	Turns
CSU3	62.866	125.66	16.078	45.177	140
CSU2	62.866	75.396	16.078	45.177	140
CSU1	62.866	25.132	16.078	45.177	140
CSL1	62.866	−25.132	16.078	45.177	140
CSL2	62.866	−75.396	16.078	45.177	140
CSL3	62.866	−125.66	16.078	45.177	140
PF1	107.217	175.37	24.694	9.769	44
PF2	113.679	194.09	37.618	27.473	204
PF3	294.558	159.07	12.844	21.256	60
PF4	326.98	90.419	8.896	17.188	32
PF5	326.98	−90.419	8.896	17.188	32
PF6	294.558	−159.07	12.844	21.256	60
PF7	113.679	−194.09	37.618	27.473	204
PF8	107.217	−175.37	24.694	9.769	44

In this paper we apply the method to EAST magnets. The EM load interaction matrices for EAST magnets are calculated in Section 3. Then the loads on each EAST magnet are evaluated at various scenarios for the time-depending multi-point data sequences, corresponding to plasma transient events in Section 4.

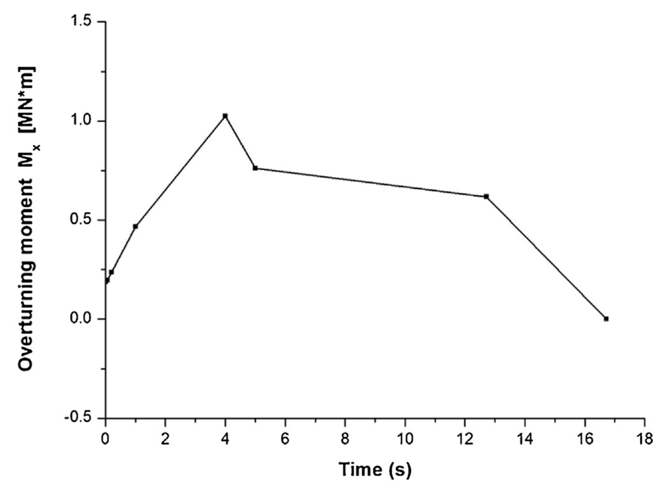


Fig. 3. Overturning moment on a TF from all toroidal coils.

2. Method

2.1. Interaction matrix

According to the method present in [1,2], at the low-frequency domain, the calculation of magnetic field by known currents is substantially a static problem. Then the Lorentz forces, acting on a current-carrying component, are result of interaction of currents in the conductor with the magnetic field, which is the total field of all sources superimposed. So the basic problem can be formulated as a problem of pair-wise interactions between all currents. The two currents: source current I_i and current in the loaded structures I_j consist of a minimum considered system. The Lorentz force acting

Table 3
Specified quantities as parameters of interactions.

Parameter	Description	The load on:	The load from:
$F\ F_R$	Radial force	TF	TF
$F_{tor}^{(1)}$	Out-of-plane force	TF	TF
M_y	Moment of the out-of-plane force about the main axis	TF	TF
$F\ F_{y-hlaf}$	Vertical total force on the upper-half coil	TF	TF
$F_{tor}^{(2)}$	Out-of-plane force	TF	CS/PF/Plasma
M_x	Overturning moment of the out-of-plane force about radial axis	TF	CS/PF/Plasma
${}_v\ F_v$	Vertical total force	CS/PF/Plasma	CS/PF/Plasma
$F\ F_{hoop}$	Hoop force	CS/PF/Plasma	CS/PF/Plasma

on conductor i due to the magnetic field produced by conductor j can be expressed as [5]:

$$\to F_{ij} = \oint_{L_j}\oint_{L_i} \frac{\mu_0}{4\pi}\frac{I_i I_j}{|\to r_{ji}|^3}\left[\to dl_i \times \left[\to dl_j \times \to r_{ji}\right]\right] \quad (1)$$

where $\to dl_i$ and $\to dl_j$ are separately the direction vector, $\to r_{ji}$ is the distance vector from conductor j to i, I_i and I_j are the current amplitude, μ_0 is the permeability in vacuum. ▯

At fixed I_i and I_j, the force can be expressed simply as a function of a certain parameter $\to G_{ij}$:

$$\to F_{ij} = I_i I_j \to G_{ij} \quad (2)$$

$$\to G_{ij} = \oint_{L_j}\oint_{L_i} \frac{\mu_0}{4\pi}\frac{I_i I_j}{r_{ji}^3}\left[\to dl_i \times \left[\to dl_j \times \to r_{ji}\right]\right] \quad (3)$$

Here $\to G_{ij}$ is an element of the interaction matrix which contains the parameters of interactions at unit currents in the two interacting conductors of each pair. So the Lorentz forces acting on any current-carrying component of the system can be calculated as product of the current in loaded structure, source currents and the interaction matrix, of which the currents consolidate the information on magnitudes of currents in the conductors, and the interaction matrix consolidates the information about the geometrical configuration of the current paths:

$$\to F_i = I_i \sum_{j=1}^{n} I_j \to G_{ij} \quad (4)$$

The interaction matrix is by definition a matrix of linear transform between currents and forces. It can be used for the direct calculation of all individual forces in the system and their subtotals by known currents using simple single-step linear matrix operation. Interaction matrix is calculated at unit currents in all element conductors. Therefore, this matrix does not depend on any particular combination of current magnitudes and represents a fundamental attribute of the geometrically non-deformable system of conductors. The simplicity of calculations in the approach permits the use of rather detailed models for assessments.

2.2. EM force calculation

Then the problem turns to how to get the interaction matrix. Suppose all the conductors of the magnet system are loaded with unit currents (1MA) separately. Since the magnetic fields are different everywhere, we can split the conductors into several segments, then the Lorentz force acting on conductor i due to the magnetic field produced by conductor j (all with unit currents) can be calculated by:

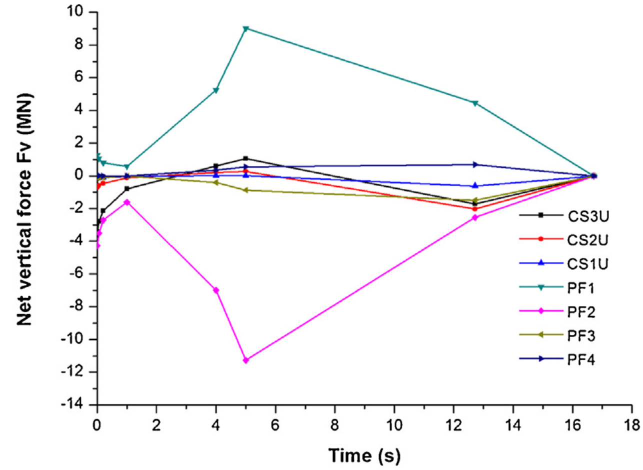
$$\to G_{ij} = \frac{\mu_0}{4\pi}\iiint_{V_j}\iiint_{V_i}\frac{\to j_i dV_i \times (\to j_j dV_j \times \to r_{ji})}{|\to r_{ji}|^3} \quad (5)$$

where $\to j_i$ and $\to j_j$ are separately the current density vector, dV_i and dV_j are the element volume of conductor i and j.

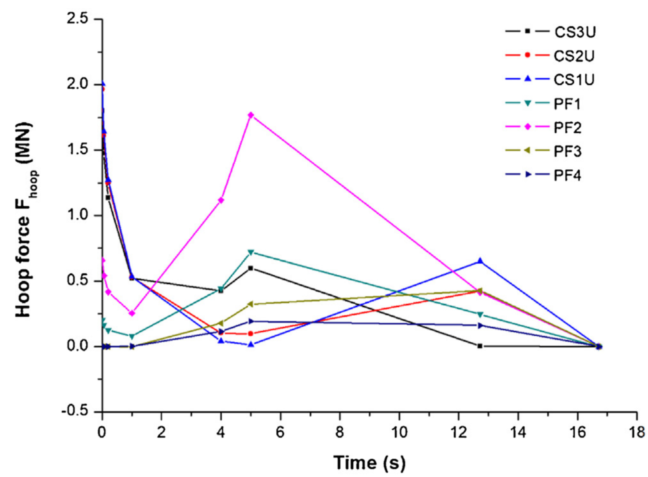
In this paper, the EM force interaction matrix of EAST magnet system is calculated with the above method by Fortran programming. And the EM moments are obtained by integration of the EM forces.

2.3. Specified quantities

According to [1], there are mainly 8 parameters which characterize all principal aspects of the load interaction between Tokamak magnet coils – integral estimates of the corresponding systems of distributed forces, as listed in Table 3. And the study has been split into three parts, concerning different generic configurations: (1) CS/PF-to-CS/PF/Plasma interactions; (2) TF-to-CS/PF/Plasma interactions; (3) TF-to-TF interactions. Additional cases have been run with plasma as “15th toroidal coil”.



(a) Net vertical force



(b) Hoop force

Fig. 4. EM loads on CS/PF coils from all toroidal currents.

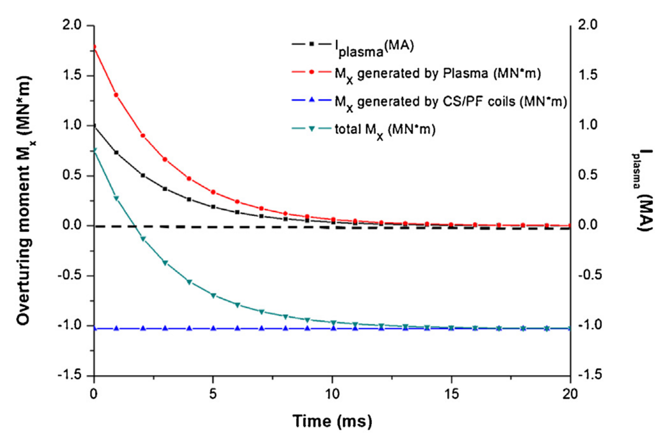


Fig. 5. Overturning moment on a TF from all toroidal currents during MD.

Table 4
Interaction matrices acting on a CS/PF coil from other CS/PF/Plasma coil (all I = 1MA).

	CSU3	CSU2	CSU1	CSL1	CSL2	CSL3	PF1	PF2	PF3	PF4	PF5	PF6	PF7	PF8
Net vertical force F_v ([N])														
CSU3	0	1.31E6	2.93E5	9.68E4	3.88E4	1.80E4	−7.63E5	−6.03E5	−3.17E4	2.43E4	5.90E4	4.98E4	2.15E4	2.26E4
CSU2	−1.31E6	0	1.31E6	2.94E5	9.68E4	3.88E4	−3.78E5	−2.98E5	−6.66E4	−1.06E4	6.40E4	6.31E4	3.76E4	4.08E4
CSU1	−2.93E5	−1.31E6	0	1.31E6	2.94E5	9.68E4	−1.68E5	−1.40E5	−7.93E4	−4.17E4	5.98E4	7.51E4	7.01E4	7.95E4
CSL1	−9.68E4	−2.94E5	−1.31E6	0	1.31E6	2.93E5	−7.86E4	−6.92E4	−7.46E4	−5.95E4	4.17E4	7.93E4	1.40E5	1.68E5
CSL2	−3.88E4	−9.68E4	−2.94E5	−1.31E6	0	1.31E6	−4.05E4	−3.72E4	−6.28E4	−6.38E4	1.06E4	6.66E4	2.98E5	3.78E5
CSL3	−1.80E4	−3.88E4	−9.68E4	−2.93E5	−1.31E6	0	−2.24E4	−2.13E4	−4.96E4	−5.89E4	−2.43E4	3.17E4	6.03E5	7.63E5
PF1	7.63E5	3.78E5	1.68E5	7.86E4	4.05E4	2.24E4	0	−6.46E6	5.67E4	1.67E5	1.46E5	1.08E5	3.39E4	3.43E4
PF2	6.03E5	2.98E5	1.40E5	6.92E4	3.72E4	2.13E4	6.46E6	0	1.45E5	2.26E5	1.61E5	1.16E5	3.39E4	3.39E4
PF3	3.17E4	6.66E4	7.93E4	7.46E4	6.28E4	4.96E4	−5.67E4	−1.45E5	0	4.40E6	1.02E6	6.24E5	1.16E5	1.08E5
PF4	−2.43E4	1.06E4	4.17E4	5.95E4	6.38E4	5.89E4	−1.67E5	−2.26E5	−4.40E6	0	1.81E6	1.02E6	1.61E5	1.46E5
PF5	−5.90E4	−6.40E4	−5.98E4	−4.17E4	−1.06E4	2.43E4	−1.46E5	−1.61E5	−1.02E6	−1.81E6	0	4.40E6	2.26E5	1.67E5
PF6	−4.98E4	−6.31E4	−7.51E4	−7.93E4	−6.66E4	−3.17E4	−1.08E5	−1.16E5	−6.24E5	−1.02E6	−4.40E6	0	1.45E5	5.67E4
PF7	−2.15E4	−3.76E4	−7.01E4	−1.40E5	−2.98E5	−6.03E5	−3.39E4	−3.39E4	−1.16E5	−1.61E5	−2.26E5	−1.45E5	0	−6.46E6
PF8	−2.26E4	−4.08E4	−7.95E4	−1.68E5	−3.78E5	−7.63E5	−3.43E4	−3.39E4	−1.08E+05	−1.46E5	−1.67E5	−5.67E4	6.46E6	0
Hoop force Fhoop ([N])														
Plasma	−1.87E5	−2.15E5	−1.07E5	1.07E5	2.15E5	1.87E5	−3.49E5	−3.44E5	−7.72E+05	−6.64E5	6.64E5	7.72E5	3.44E5	3.49E5
CSU3	2.37E5	1.24E5	5.22E4	2.48E4	1.30E4	7.48E3	−2.10E4	1.16E3	−1.40E+04	−1.13E+04	−4.30E+02	2.50E+03	6.01E+03	6.34E+03
CSU2	1.24E5	2.37E5	1.24E5	5.22E4	2.48E4	1.30E4	2.47E4	2.30E4	−9.99E+03	−1.19E+04	−3.04E+03	1.32E+03	8.72E+03	9.43E+03
CSU1	5.22E4	1.24E5	2.37E5	1.25E5	5.22E4	2.48E4	2.12E4	1.87E4	−5.06E+03	−9.90E+03	−6.47E+03	−1.11E+03	1.29E+04	1.43E+04
CSL1	2.48E4	5.22E4	1.25E5	2.37E5	1.24E5	5.22E4	1.43E4	1.29E4	−1.12E+03	−6.47E+03	−9.90E+03	−5.06E+03	1.87E+04	2.12E+04
CSL2	1.30E4	2.48E4	5.22E4	1.24E5	2.37E5	1.24E5	9.43E3	8.72E3	1.32E+03	−3.04E+03	−1.19E+04	−9.99E+03	2.30E+04	2.47E+04
CSL3	7.48E3	1.30E4	2.48E4	5.22E4	1.24E5	2.37E5	6.34E3	6.01E3	2.51E+03	−4.28 E+02	−1.13E+04	−1.40E+04	1.16E+03	−2.10E+04
PF1	2.52E5	1.11E5	5.63E4	3.15E4	1.90E4	1.21E4	2.90E5	−1.05E4	−4.80E+04	−2.62E+04	4.42E+03	8.96E+03	1.17E+04	1.20E+04
PF2	2.00E5	9.65E4	5.18E4	3.02E4	1.87E4	1.23E4	4.73E5	3.12E5	−5.49E+04	−2.59E+04	6.66E+03	1.08E+04	1.23E+04	1.26E+04
PF3	1.30E5	1.17E5	9.75E4	7.78E4	6.06E4	4.69E4	2.43E5	2.72E5	4.22E+05	−9.59E+04	9.16E+04	8.84E+04	5.97E+04	5.87E+04
PF4	1.17E5	1.19E5	1.12E5	9.84E4	8.24E4	6.69E4	1.90E5	2.03E5	5.93E+05	4.71E+05	1.60E+05	1.46E+05	9.04E+04	8.81E+04
PF5	6.69E4	8.24E4	9.84E4	1.12E5	1.19E5	1.17E5	8.81E4	9.04E4	1.46E+05	1.60E+05	4.71E+05	5.93E+05	2.03E+05	1.90E+05
PF6	4.69E4	6.06E4	7.78E4	9.75E4	1.17E5	1.30E5	5.87E4	5.97E4	8.84E+04	9.16E+04	−9.60E+04	4.22E+05	2.72E+05	2.43E+05
PF7	1.23E4	1.87E4	3.02E4	5.18E4	9.65E4	2.00E5	1.26E4	1.24E4	1.08E+04	6.66E+03	−2.59E+04	−5.49E+04	3.12E+05	4.73E+05
PF8	1.21E4	1.90E4	3.15E4	5.63E4	1.11E5	2.52E5	1.20E4	1.17E4	8.97E+03	4.42E+03	−2.61E+04	−4.80E+04	−1.05E+04	2.90E+05
Plasma	1.10E5	1.65E5	2.16E5	2.16E5	1.65E5	1.10E5	1.04E5	9.72E4	7.90 E+02	−7.25E+04	−7.25E+04	7.89 E+02	9.72E+04	1.04E+05

Table 5
Interaction matrices acting on a TF coil from CS/ PF/Plasma coil (all I=1MA).

	CSU3	CSU2	CSU1	CSL1	CSL2	CSL3	PF1	PF2	PF3	PF4	PF5	PF6	PF7	PF8	Plasma
Out-of-plane forces ([N])															
TF	5.94E4	3.71E4	1.08E4	−1.08E4	−3.71E4	−5.94E4	1.71E5	1.62E5	2.13E5	1.48E4	−1.48E4	−2.13E5	−1.62E5	−1.71E5	0
Overturning moment Mx ([N*m])															
TF	−2.77E4	−7.52E4	-1.26E5	-1.27E5	-7.52E4	-2.77E4	1.26E5	2.04E5	8.39E5	1.03E6	1.03E6	8.39E5	2.04E5	1.26E5	9.62E5

3. Interaction matrix of EAST magnet system

The interaction matrices of the 8 quantities for EAST magnet system are calculated using the method introduced in Section 2. And the results are given in Tables 4–6. All coils are loaded with unit currents (1 MA).

The interaction matrices of the net vertical force and hoop force acting on a toroidal coil from other toroidal coil are given in Table 4. And the matrices for the out-of-plane resultant forces on TF coils from different toroidal coil and their overturning moments about radial axis are given in Table 5.

The interaction matrices acting on a TF coil from other TF coils, expressed in terms of: (1) resultants of the radial (centering) forces; (2) resultants of the out-of-plane forces; (3) moments of the out-of-plane forces about the main axis; (4) vertical total forces on upper half of the TF coil are given in Table 6.

4. EM load assessment of EAST magnet system

4.1. Considered scenario A: normal operation

We have analyzed the EM load of EAST magnet system during normal operation. The currents on CS/PF/Plasma coils at different time are listed in Fig. 2. Since the currents on toroidal coils are up-down symmetrical to the midplane(x-z plane), only the currents on CS/PF coils above the midplane are given. The whole process of a normal plasma discharge includes: discharge start(t = 0.0 s), plasma ignition(t = 0.06 s), plasma ramp to 100 kA(t = 0.2 s), plasma ramps to 420 kA(t = 1.0 s), plasma ramp to 1 MA(t = 4.0 s), beta-p full of 1.6(t = 5.0 s), end of the flat-top(t = 12.72 s), end of discharge(t = 16.72 s). And the current on a TF coil at operating condition remains as 1.859 MA.

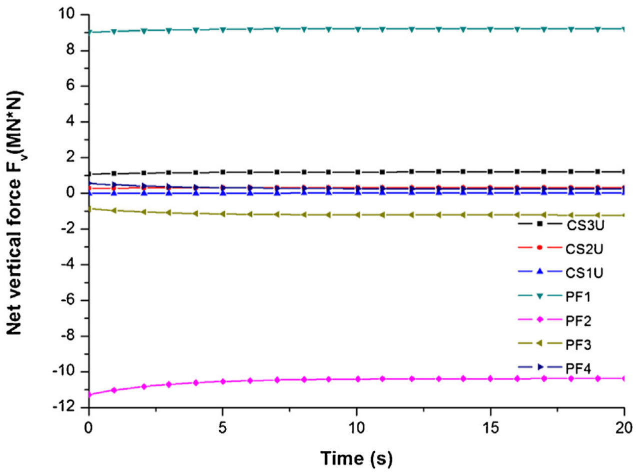
The forces on individual coils from all magnets and plasma are evaluated with pre-computed interaction matrices of constants, supplied in Section 3. The EM load assessment acting on a TF coil from all the 16 TF coils are list in Table 7. The comparison of the results calculated with interaction matrix approach and with ANSYS method [6] demonstrated excellent agreement.

The EM load assessment acting on a TF coil from all the toroidal currents (CS/PF/Plasma) are shown in Fig. 3. Since the currents loading on toroidal coils are up-down symmetrical, the net total out-of-plane force acting on a TF coil is zero at any moment, so only the overturning moment result is given.

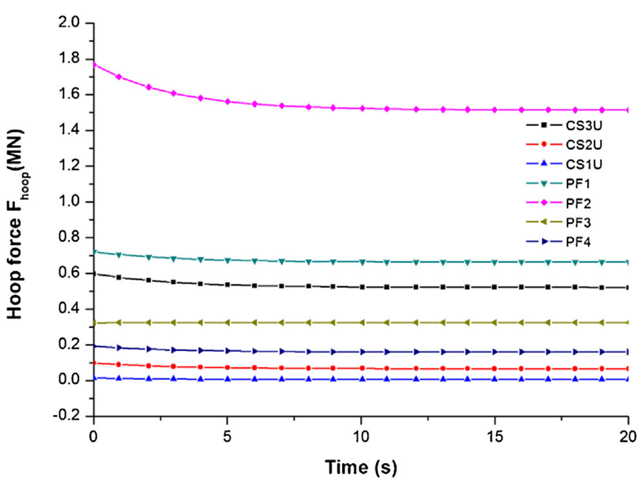
The load assessment on a CS/PF coil from all other toroidal currents is shown in Fig. 4. As shown in this figure, the net vertical force acting on PF1 and PF2 are larger than other toroidal coils. Since these two coils are mechanically bonded as an integral, the resultant vertical force acting on this two-coil-composed magnet is not so large. For the hoop force, the maximum occurs on PF2 at about 5 s while loading current reaches peak at this moment.

Table 6
Interaction matrices acting on a TF coil from other TF coil (all I=1MA).

	TF1	TF2	TF3	TF4	TF5	TF6	TF7	TF8	TF9	TF10	TF11	TF12	TF13	TF14	TF15	TF16
Radial (centering) forces FR ([N])																
TF1	−9.34E3	−4.75E5	−3.19E5	−2.06E5	−1.36E5	−9.52E4	−7.18E4	−6.00E4	−5.63E4	−5.99E4	−7.18E4	−9.51E4	−1.36E5	−2.06E5	−3.19E5	−4.75E5
TF2	−4.75E5	−9.34E3	−4.75E5	−3.19E5	−2.06E5	−1.36E5	−9.52E4	−7.18E4	−6.00E4	−5.63E4	−5.99E4	−7.18E4	−9.51E4	−1.36E5	−2.06E5	−3.19E5
TF3	−3.19E5	−4.75E5	−9.34E3	−4.75E5	−3.19E5	−2.06E5	−1.36E5	−9.52E4	−7.18E4	−6.00E4	−5.63E4	−5.99E4	−7.18E4	−9.51E4	−1.36E5	−2.06E5
TF4	−2.06E5	−3.19E5	−4.75E5	−9.34E3	−4.75E5	−3.19E5	−2.06E5	−1.36E5	−9.52E4	−7.18E4	−6.00E4	−5.63E4	−5.99E4	−7.18E4	−9.51E4	−1.36E5
TF5	−1.36E5	−2.06E5	−3.19E5	−4.75E5	−9.34E3	−4.75E5	−3.19E5	−2.06E5	−1.36E5	−9.52E4	−7.18E4	−6.00E4	−5.63E4	−5.99E4	−7.18E4	−9.51E4
TF6	−9.51E4	−1.36E5	−2.06E5	−3.19E5	−4.75E5	−9.34E3	−4.75E5	−3.19E5	−2.06E5	−1.36E5	−9.52E3	−7.18E4	−6.00E4	−5.63E4	−5.99E4	−7.18E4
TF7	−7.18E4	−9.51E4	−1.36E5	−2.06E5	−3.19E5	−4.75E5	−9.34E3	−4.75E5	−3.19E5	−2.06E5	−1.36E5	−9.52E4	−7.18E4	−6.00E4	−5.63E4	−5.99E4
TF8	−5.99E4	−7.18E4	−9.51E4	−1.36E5	−2.06E5	−3.19E5	−4.75E5	−9.34E3	−4.75E5	−3.19E5	−2.06E5	−1.36E5	−9.52E4	−7.18E4	−6.00E4	−5.63E4
TF9	−5.63E4	−5.99E4	−7.18E4	−9.51E4	−1.36E5	−2.06E5	−3.19E5	−4.75E5	−9.34E3	−4.75E5	−3.19E5	−2.06E5	−1.36E5	−9.52E4	−7.18E4	−6.00E4
TF10	−6.00E4	−5.63E4	−5.99E4	−7.18E4	−9.51E4	−1.36E5	−2.06E5	−3.19E5	−4.75E5	−9.34E3	−4.75E5	−3.19E5	−2.06E5	−1.36E5	−9.52E4	−7.18E4
TF11	−7.18E4	−5.99E4	−5.63E4	−5.99E4	−7.18E4	−9.51E4	−1.36E5	−2.06E5	−3.19E5	−4.75E5	−9.34E3	−4.75E5	−3.19E5	−2.06E5	−1.36E5	−9.52E4
TF12	−9.51E4	−7.18E4	−6.00E4	−5.63E4	−5.99E4	−7.18E4	−9.51E4	−1.36E5	−2.06E5	−3.19E5	−4.75E5	−9.34E3	−4.75E5	−3.19E5	−2.06E5	−1.36E5
TF13	−1.36E5	−9.52E4	−7.18E4	−6.00E4	−5.63E4	−5.99E4	−7.18E4	−9.51E4	−1.36E5	−2.06E5	−3.19E5	−4.75E5	−9.34E3	−4.75E5	−3.19E5	−2.06E5
TF14	−2.06E5	−1.36E5	−9.52E4	−7.18E4	−6.00E4	−5.63E4	−5.99E4	−7.18E4	−9.51E4	−1.36E5	−2.06E5	−3.19E5	−4.75E5	−9.34E3	−4.75E5	−3.19E5
TF15	−3.19E5	−2.06E5	−1.36E5	−9.52E4	−7.18E4	−6.00E4	−5.63E4	−5.99E4	−7.18E4	−9.52E4	−1.36E5	−2.06E5	−3.19E5	−4.75E5	−9.34E3	−4.75E5
TF16	−4.75E5	−3.19E5	−2.06E5	−1.36E5	−9.52E4	−7.18E4	−6.00E4	−5.63E4	−5.99E4	−7.18E4	−9.51E4	−1.36E5	−2.06E5	−3.19E5	−4.75E5	−9.34E3
Out-of-plane forces ([N])																
TF1	0	2.35E6	7.63E5	3.07E5	1.36E5	6.37E4	2.99E4	1.20E4	0	−1.20E4	−2.99E4	−6.37E4	−1.36E5	−3.07E5	−7.63E5	−2.35E6
TF2	−2.35E6	0	2.35E6	7.63E5	3.07E5	1.36E5	6.37E4	2.99E4	1.20E4	0	−1.20E4	−2.99E4	−6.37E4	−1.36E5	−3.07E5	−7.63E5
TF3	−7.63E5	−2.35E6	0	2.35E6	7.63E5	3.07E5	1.36E5	6.37E4	2.99E4	1.20E4	0	−1.20E4	−2.99E4	−6.37E4	−1.36E5	−3.07E5
TF4	−3.07E5	−7.63E5	−2.35E6	0	2.35E6	7.63E5	3.07E5	1.36E5	6.37E4	2.99E4	1.20E4	0	−1.20E4	−2.99E4	−6.37E4	−1.36E5
TF5	−1.36E5	−3.07E5	−7.63E5	−2.35E6	0	2.35E6	7.63E5	3.07E5	1.36E5	6.37E4	2.99E4	1.20E4	0	−1.20E4	−2.99E4	−6.37E4
TF6	−6.37E4	−1.36E5	−3.07E5	−7.63E5	−2.35E6	0	2.35E6	7.63E5	3.07E5	1.36E5	6.37E4	2.99E4	1.20E4	0	−1.20E4	−2.99E4
TF7	−2.99E4	−6.37E4	−1.36E5	−3.07E5	−7.63E5	−2.35E6	0	2.35E6	7.63E5	3.07E5	1.36E5	6.37E4	2.99E4	1.20E4	0	−1.20E4
TF8	−1.20E4	−2.99E4	−6.37E4	−1.36E5	−3.07E5	−7.63E5	−2.35E6	0	2.35E6	7.63E5	3.07E5	1.36E5	6.37E4	2.99E4	1.20E4	0
TF9	0	−1.20E4	−2.98E4	−6.37E4	−1.36E5	−3.07E5	−7.63E5	−2.35E6	0	2.35E6	7.63E5	3.07E5	1.36E5	6.37E4	2.99E4	1.20E4
TF10	1.20E4	0	−1.20E4	−2.99E4	−6.37E4	−1.36E5	−3.07E5	−7.63E5	−2.35E6	0	2.35E6	7.63E5	3.07E5	1.36E5	6.37E4	2.99E4
TF11	2.99E4	1.20E4	0	−1.20E4	−2.99E4	−6.37E4	−1.36E5	−3.07E5	−7.63E5	−2.35E6	0	2.35E6	7.63E5	3.07E5	1.36E5	6.37E4
TF12	6.37E4	2.99E4	1.20E4	0	−1.20E4	−2.99E4	−6.37E4	−1.36E5	−3.07E5	−7.63E5	−2.35E6	0	2.35E6	7.63E5	3.07E5	1.36E5
TF13	1.36E5	6.37E4	2.99E4	1.20E4	0	−1.20E4	−2.99E4	−6.37E4	−1.36E5	−3.07E5	−7.63E5	−2.35E6	0	2.35E6	7.63E5	3.07E5
TF14	3.07E5	1.36E5	6.37E4	2.99E4	1.20E4	0	−1.20E4	−2.99E4	−6.37E4	−1.36E5	−3.07E5	−7.63E5	−2.35E6	0	2.35E6	7.63E5
TF15	7.63E5	3.07E5	1.36E5	6.37E4	2.99E4	1.20E4	0	−1.20E4	−2.99E4	−6.37E4	−1.36E5	−3.07E5	−7.63E5	−2.35E6	0	2.35E6
TF16	2.35E6	7.63E5	3.07E5	1.36E5	6.37E4	2.99E4	1.20E4	0	−1.20E4	−2.99E4	−6.37E4	−1.36E5	−3.07E5	−7.63E5	−2.35E6	0
Moment My of the out-of-plane forces about the main axis ([N m])																
TF1	0	−3.76E6	−1.26E6	−5.37E5	−2.55E5	−1.29E5	−6.49E4	−2.75E4	0	2.75E4	6.49E4	1.29E5	2.55E5	5.37E5	1.26E6	3.76E6
TF2	3.76E6	0	−3.76E6	−1.26E6	−5.37E5	−2.55E5	−1.29E5	−6.49E4	−2.75E4	0	2.75E4	6.49E4	1.29E5	2.55E5	5.37E5	1.26E6
TF3	1.26E6	3.76E6	0	−3.76E6	−1.26E6	−5.37E5	−2.55E5	−1.29E5	−6.49E4	−2.75E4	0	2.75E4	6.49E4	1.29E5	2.55E5	5.37E5
TF4	5.37E5	1.26E6	3.76E6	0	−3.76E6	−1.26E6	−5.37E5	−2.55E5	−1.29E5	−6.49E4	−2.75E4	0	2.75E4	6.49E4	1.29E5	2.55E5
TF5	2.55E5	5.37E5	1.26E6	3.76E6	0	−3.76E6	−1.26E6	−5.37E5	−2.55E5	−1.29E5	−6.49E4	−2.75E4	0	2.75E4	6.49E4	1.29E5
TF6	1.29E5	2.55E5	5.37E5	1.26E6	3.76E6	0	−3.76E6	−1.26E6	−5.37E5	−2.55E5	−1.29E5	−6.49E4	−2.75E4	0	2.75E4	6.49E4
TF7	6.49E4	1.29E5	2.55E5	5.37E5	1.26E6	3.76E6	0	−3.76E6	−1.26E6	−5.37E5	−2.55E5	−1.29E5	−6.49E4	−2.75E4	0	2.75E4
TF8	2.75E4	6.49E4	1.29E5	2.55E5	5.37E5	1.26E6	3.76E6	0	−3.76E6	−1.26E6	−5.37E5	−2.55E5	−1.29E5	−6.49E4	−2.75E4	0
TF9	0	2.75E4	6.49E4	1.29E5	2.55E5	5.37E5	1.26E6	3.76E6	0	−3.76E6	−1.26E6	−5.37E5	−2.55E5	−1.29E5	−6.49E4	−2.75E4
TF10	−2.75E4	0	2.75E4	6.49E4	1.29E5	2.55E5	5.37E5	1.26E6	3.76E6	0	−3.76E6	−1.26E6	−5.37E5	−2.55E5	−1.29E5	−6.49E4
TF11	−6.49E4	−2.75E4	0	2.75E4	6.49E4	1.29E5	2.55E5	5.37E5	1.26E6	3.76E6	0	−3.76E6	−1.26E6	−5.37E5	−2.55E5	−1.29E5
TF12	−1.29E5	−6.49E4	−2.75E4	0	2.75E4	6.49E4	1.29E5	2.55E5	5.37E5	1.26E6	3.76E6	0	−3.76E6	−1.26E6	−5.37E5	−2.55E5
TF13	−2.55E5	−1.29E5	−6.49E4	−2.75E4	0	2.75E4	6.49E4	1.29E5	2.55E5	5.37E5	1.26E6	3.76E6	0	−3.76E6	−1.26E6	−5.37E5
TF14	−5.37E5	−2.55E5	−1.29E5	−6.49E4	−2.75E4	0	2.75E4	6.49E4	1.29E5	2.55E5	5.37E5	1.26E6	3.76E6	0	−3.76E6	−1.26E6
TF15	−1.26E6	−5.37E5	−2.55E5	−1.29E5	−6.49E4	−2.75E4	0	2.75E4	6.49E4	1.29E5	2.55E5	5.37E5	1.26E6	3.76E6	0	−3.76E6
TF16	−3.76E6	−1.26E6	−5.37E5	−2.55E5	−1.29E5	−6.49E4	−2.75E4	0	2.75E4	6.49E4	1.29E5	2.55E5	5.37E5	1.26E6	3.76E6	0
Vertical forces Fy_half on 1/2 (upper half) of the TF coil ([N])																
TF1	5.93E5	2.75E5	1.45E5	8.48E4	5.37E4	3.67E4	2.74E4	2.28E4	2.14E4	2.28E4	2.74E4	3.67E4	5.37E4	8.48E4	1.45E5	2.75E5
TF2	2.75E5	5.93E5	2.75E5	1.45E5	8.48E4	5.37E4	3.67E4	2.74E4	2.28E4	2.14E4	2.28E4	2.74E4	3.67E4	5.37E4	8.48E4	1.45E5
TF3	1.45E5	2.75E5	5.92E5	2.75E5	1.45E5	8.48E4	5.37E4	3.67E4	2.74E4	2.28E4	2.14E4	2.28E4	2.74E4	3.67E4	5.37E4	8.48E4
TF4	8.48E4	1.45E5	2.75E5	5.93E5	2.75E5	1.45E5	8.48E4	5.37E4	3.67E4	2.74E4	2.28E4	2.14E4	2.28E4	2.74E4	3.67E4	5.37E4
TF5	5.37E4	8.48E4	1.45E5	2.75E5	5.93E5	2.75E5	1.45E5	8.48E4	5.37E4	3.67E4	2.74E4	2.28E4	2.14E4	2.28E4	2.74E4	3.67E4
TF6	3.67E4	5.37E4	8.48E4	1.45E5	2.75E5	5.93E5	2.75E5	1.45E5	8.48E4	5.37E4	3.67E4	2.74E4	2.28E4	2.14E4	2.28E4	2.74E4
TF7	2.74E4	3.67E4	5.37E4	8.48E4	1.45E5	2.75E5	5.93E5	2.75E5	1.45E5	8.48E4	5.37E4	3.67E4	2.74E4	2.28E4	2.14E4	2.28E4
TF8	2.28E4	2.74E4	3.67E4	5.37E4	8.48E4	1.45E5	2.75E5	5.93E5	2.75E5	1.45E5	8.48E4	5.37E4	3.67E4	2.74E4	2.28E4	2.14E4
TF9	2.14E4	2.28E4	2.74E4	3.67E4	5.37E4	8.48E4	1.45E5	2.75E5	5.93E5	2.75E5	1.45E5	8.48E4	5.37E4	3.67E4	2.74E4	2.28E4
TF10	2.28E4	2.14E4	2.28E4	2.74E4	3.67E4	5.37E4	8.48E4	1.45E5	2.75E5	5.93E5	2.75E5	1.45E5	8.48E4	5.37E4	3.67E4	2.74E4
TF11	2.74E4	2.28E4	2.17E4	2.28E4	2.74E4	3.67E4	5.37E4	8.48E4	1.45E5	2.75E5	5.93E5	2.75E5	1.45E5	8.48E4	5.37E4	3.67E4
TF12	3.67E4	2.74E4	2.28E4	2.17E4	2.28E4	2.74E4	3.67E4	5.37E4	8.48E4	1.45E5	2.75E5	5.93E5	2.75E5	1.45E5	8.48E4	5.37E4
TF13	5.37E4	3.67E4	2.74E4	2.28E4	2.14E4	2.28E4	2.74E4	3.67E4	5.37E4	8.48E4	1.45E5	2.75E5	5.93E5	2.75E5	1.45E5	8.48E4
TF14	8.48E4	5.37E4	3.67E4	2.74E4	2.28E4	2.14E4	2.28E4	2.74E4	3.67E4	5.37E4	8.48E4	1.45E5	2.75E5	5.93E5	2.75E5	1.45E5
TF15	1.45E5	8.48E4	5.37E4	3.67E4	2.74E4	2.28E4	2.14E4	2.28E4	2.74E4	3.67E4	5.37E4	8.48E4	1.45E5	2.75E5	5.93E5	2.75E5
TF16	2.75E5	1.45E5	84820	5.37E4	3.67E4	2.74E4	2.28E4	2.14E4	2.28E4	2.74E4	3.67E4	5.37E4	8.48E4	1.45E5	2.75E5	5.93E5



(a) Net vertical force



(b) Hoop force

Fig. 6. EM loads on CS/PF coils from all toroidal currents during MD.

Table 7
EM loads acting on a TF from all TF coils.

Parameter	Results by Interaction Matrix Method	Results by ANSYS method [5]
Radial force F_R [MN]	9.65	9.696
Vertical force F_{y_half}, [MN]	6.59	6.873
Net off-plane force $F_{tor}^{(1)}$ [MN]	0	0
Vertical moment M_y [MN*m]	0	0

4.2. Considered scenario B: major disruption

For EAST tokamak, a critical current decay of plasma during major disruption (MD) can be supposed as below:

$$I_{plasma} = I_0 e^{\frac{-t}{\tau}} \quad (6)$$

where $I_0 = 1MA, \tau = 3\ ms$.

Supposed the currents on toroidal coils keep constant of the value at the moment of 5 s in Fig. 2 during the fast disruption process. And the current on every TF coil is 1.859 MA as constant.

The forces on individual coils from all magnets and plasma are evaluated with the interaction matrices supplied in Section 3. The overturning moment acting on a TF coil from all other toroidal currents (CS/PF/Plasma) are shown in Fig. 5. It has shown that the overturning moment acting on a TF produced by plasma current coil has a reversed direction with the moment generated by all the CS/PF coils. So when the moment caused by plasma current changes sharply as plasma current decays, the total overturning moment's direction may reverse, occurring soon after MD begins.

And the load assessment on a CS/PF coil from all toroidal currents is shown in Fig. 6. The results show that the influence of plasma current's decay is not particularly evident.

The EM load assessment performed above does not consider the eddy currents on plasma facing components (vacuum vessel, first wall etc.). Further evaluation need to be continued in the future.

5. Discussion

This paper explores on the application of a new technology – interaction matrix approach for the load assessment of EAST magnet system. This application validated the efficiency and accuracy of the new method, which is useful for the systematic assessment of Tokamak EM forces. The method gets the EM force by a linear transform between the systems of currents and Lorentz forces in a general form. Results indicate that the interaction matrix, as a scenario-invariant property of the system, can be conveniently used for multi-scenario EM assessments and parametric studies of the EM loads for EAST current-carrying components, and a specialized force-calculating module for real-time simulating can be developed in the future.

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