ANALYTICAL APPROACH TO CALCULATION OF DISRUPTION-INDUCED VERTICAL FORCE ON THE TOKAMAK WALL

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Abstract. Vertical disruption force acting on the tokamak vacuum vessel wall is the main subject. The force appears due to the currents induced in the wall or 'injected' when the plasma hits the wall. Two main transient phenomena are accounted for: current quench (CQ) and vertical displacement event (VDE), with dynamics similar to the inputs and outputs in the series of computations by the CarMa0NL [1] or JOREK [2] codes. Mostly, the consequences of so-called fast CQs are analyzed. These are known as producing the wall force largely due to the eddy currents [3, 4, 5]. The roles of the halo current and the post-disruption evolution of the force are also considered. The model proposed in [6] is revised. The study is fully analytical.

Impact. In tokamaks with ITER-like current 15 MA, the disruption-induced vertical force is expected on the level of 100 MN (though with some scatter in the predictions: about 120 MN in [7] or 75 MN in [8]). Such marginally tolerable loads can pose serious limitations on the operation. This and the absence of sufficient knowledge make the reduction of the vertical force in large tokamaks an important research area [5]. By showing explicitly the key parameters and their interplay, the analytical study provides a convenient basis for comparison and interpretation of numerical and experimental results, for evaluation of the possible strategies of the force mitigation, and for selecting the directions of future studies.

Novelty. For the first time, the vertical force is examined with emphasis on the post-disruption stage. The newly derived formulas reveal the dependence of the force on the plasma and wall parameters. Comparisons are performed with the results of computations in [1, 2, 9] and measurements in ASDEX Upgrade [10]. The growth of the force after the end of disruption, such as demonstrated in [1, 2, 9, 10], is explained, and its dependence on the wall resistivity is quantified. The new result is illustrated by Fig. 1 showing the vertical force developing after the end of rapid CQ. Zero force at $T = 0$ corresponds to the ideal-wall limit.

Quality. The starting relation for the analysis is a direct consequence of the Maxwell equations. The plasma enters the task as a driver of the wall currents, with both the current quench and VDE included, and the wall is described by the Ohm's law. This is a reliable basis allowing to treat the same evolution and force generation as computed by the codes CarMa0NL in [1], JOREK in [2], and M3D-C1 in [8]. The derivations are transparent, which allows easy cross-checking. The resulting expressions are ready for practical use.

The addressed problems. The first goal is mathematical, the calculation of the integral vertical force on the vacuum vessel wall not only during, but also after both CQ and VDE. For fast enough CQs, the current excitation can be evaluated in the ideal-wall (flux-conserving) approximation, while the subsequent relaxation is a dissipative process. The necessity of the analysis of the latter phase is confirmed by several computations [1, 2, 9] demonstrating the increase of the force after the end of disruption. Accordingly, here the attention is paid to the post-disruption temporal evolution of the force due to the resistivity-affected magnetic energy flow across the wall. This is described with more relevant details compared to the approach in [6] that would give $f = 0$ in Fig. 1 (in contrast to the results in [1, 2, 9].

The model. The force generation is treated as a two-stage process, the disruption itself and the post-disruption evolution of the poloidally distributed current induced in the wall. This combines two dynamic tasks: one with the plasma-wall electromagnetic interaction producing a large current in the toroidal vacuum vessel wall, and another one with redistribution and decay of the currents induced in the wall. The second step is needed because a rapid CQ cannot produce a sizable integral force (it must be zero in the ideal wall limit [11]). However, as it is proved in the study, the force can appear afterwards and reach a high level. To get an integral force, we have to describe the wall as a resistive conductor. Following the standard approach [1, 5, 8, 9, 10], the VDE is treated as an axially symmetric event. The wall is modeled as a large-aspect-ratio magnetically thin shell with a circular cross-section. The CQ is introduced as an exponential decay of the plasma current. After the plasma-wall contact, a halo current is allowed. Then the proposed analytical approach is applicable to analysis of the effects such as observed in advanced computations in [2, 5, 8, 10]. For the wall current description, the results of [12, 13, 14] are used.

Results and conclusions. Our derivations starting from general first-principle equations naturally reveal the key quantities in the task. The advantage of such an approach becomes evident when we compare the results with either estimates introduced semi-qualitatively or computational findings for particular cases, as in [1, 2, 5, 8-10].

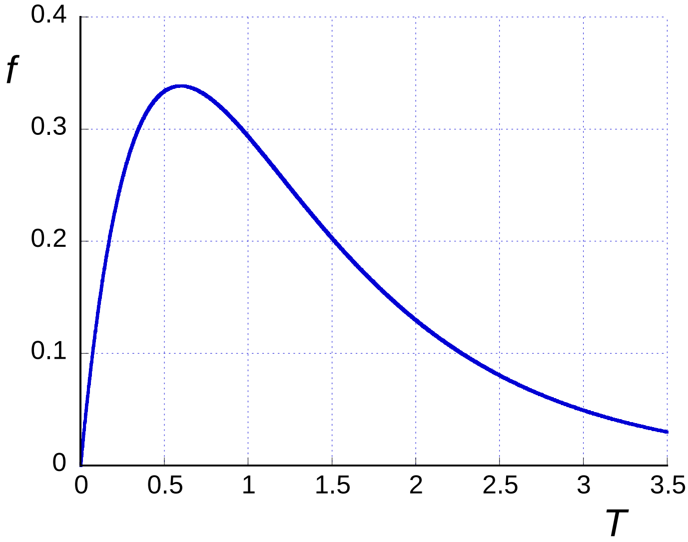

Fig. 1. Function describing the time behavior of the (normalized) post-disruption vertical force developing after the rapid CQ. Here $T \equiv t/\tau_0$ with τ_0 denoting the decay time of the net current in the toroidal resistive wall with aspect ratio 3.4.

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