Control of Resistive Wall Modes in the Spherical Tokamak

Guoliang Xia[1], Yueqiang Liu[2], T.C. Hender[1], K.G. McClements[1] and E. Tholerus[1]

[1]UKAEA, Culham Science Centre, Abingdon, OX14 3DB, United Kingdom of Great Britain and Northern Ireland

[2]General Atomics, PO Box 85608, San Diego, CA 92186-5608, United States of America

E-mails of corresponding authors Guoliang.Xia@ukaea.uk

1. Introduction

The low aspect ratio Spherical Tokamak (ST) is attractive because of its potential to achieve high beta operation. Operations above the no-wall limit, where the Resistive Wall Mode (RWM) must be controlled, can lead to significant gains in future power plant since the fusion power $\sim\beta^2$. Understanding and controlling the RWM is a key issue for the optimization of plasma pressure and improving the economic benefit [1, 2]. The two dominant mechanisms for passive stabilization of the RWM, toroidal plasma flow and kinetic resonances with thermal particles or energetic particles from NBI, are investigated using the MHD-kinetic hybrid code MARS-K [3]. It is also important to study active control of the RWM to supplement passive stabilization. MARS-F [4] is used to model the feedback control scheme to exploit the full high beta potential of the ST. A key aspect in the performance of feedback controller is the presence of system noise.

2. Equilibrium specifications

The equilibrium studied is a case of plasma current I_p=21.2 MA, the major radius R_0=2.5 m, B_0=2.8 T is the toroidal magnetic field at the plasma centre. The case studied has an aspect ratio A=1.65. The safety factor has values of q_0=2.67 on the magnetic axis, q_{min}=2.21, and q_e=6.31 at the plasma edge, the target plasma has the normalized beta value of β_N=5.04. Fig. 1 shows the radial profiles for some key equilibrium quantities. The MARS-F computed no-wall beta limit is $\beta_N^{no-wall}=3.6$, and the ideal-wall beta limit is $\beta_N^{ideal-wall}=5.6$. We choose the pressure scaling factor $C_\beta=(\beta_N-\beta_N^{no-wall})/(\beta_N^{ideal-wall}-\beta_N^{no-wall})=0.73$ for the RWM study. The wall configuration and the assumed set-up for the feedback as shown in Fig. 2.

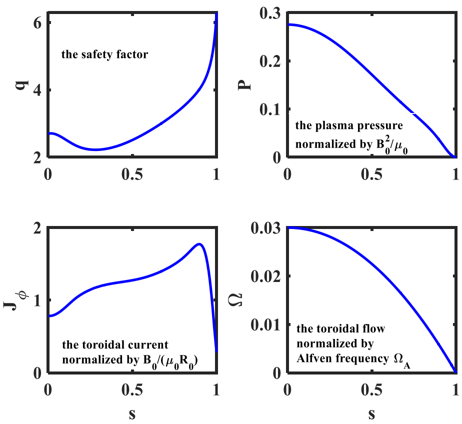

Fig. 1: The safety factor, plasma pressure, toroidal current and toroidal flow profiles versus the magnetic surface label s (the square root of the normalized poloidal flux).

3. Kinetic effects of energetic particles from the NBI

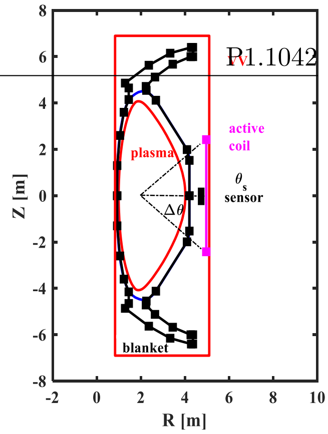

Fig. 2: The RWM passive stability is given by the double wall structure of the assumed simple vacuum vessel (rectangular square in red) and the first wall (in black). The first wall geometry is simplified (blue line) by not including the divertor elements. A midplane active feedback coil (in pink) is assumed along with a coincident sensor coil measuring the poloidal field perturbation. The active coil spans ±18.9 deg.

Neutral Beam Injection (NBI) is a possible heating/current drive scheme for tokamaks. A consideration is whether the energetic particles (EPs) from the NBI have any significant effect on the RWM stability [5, 6]. The assumed NBI parameters are as follows: two deuterium beams are injected, with a 3.0 m tangency radius for an on-axis beam and a 3.5 m tangency radius for an off-axis beam, with both beamlines being horizontal (i.e. not tilted to match the field line pitch). For the on-axis beam the injection energy is 1 MeV, and the power (PNBI) is 11 MW. For the off-axis beam, the injection energy is 500 keV, with PNBI = 71 MW. The particular analytic model for the pitch angle distribution in the MARS-K code assumes a symmetric trapped particle distribution, whereas the numerically computed distribution by ASCOT [7] is not perfectly symmetric due to minor radius averaging and finite orbit effects (Fig. 3). However, this small discrepancy is not thought to be important in terms of the effect on the RWM stability. The resonance strength varies with the plasma rotation from the NBI momentum. For a realistic range of toroidal rotation velocities (central frequency, Ω_0, up to 10% of the toroidal Alfven frequency), there is a limited effect of both thermal and energetic particles on the RWM growth rate (Fig. 4). Note that the EP contribution slightly destabilizes the RWM.

4. Synergetic effects with P controller

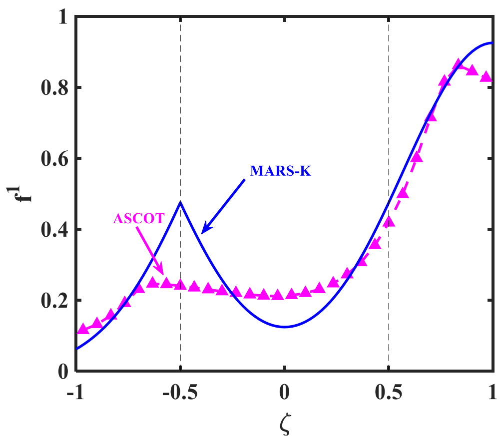

Fig. 3: Comparison of the pitch angle distribution between ASCOT (pink curve) and the MARS-K (blue curve) model fit.

The simulations above revealed that the passive approach cannot fully suppress the RWM for the case studied. Feedback control is necessary in order to operate above the no-wall limit. With a purely Proportional (P) controller (K_p=1, K_d=0), K_p and K_d are dimensionless feedback gain factors, introduced to effectively simulate an ideal Proportional and Derivative (PD) controller [8] it has proven difficult to attain full feedback stabilization, even with high gains (Fig. 5). Note that the abrupt change of the eigenvalue behavior at certain feedback gain

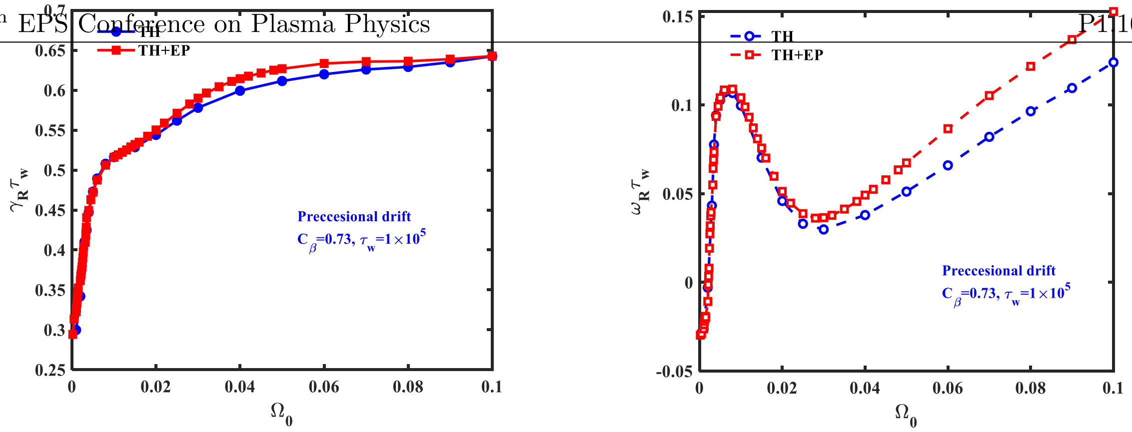

Fig. 4 Left: Growth rate (normalized to the wall time, τ_w) versus the plasma toroidal flow Ω_0;

Right: Real frequency versus Ω_0. Ω_0>0 represents rotation in the co-direction.

value (e.g. at |G|~3.2 with C_β=0.73) is due to the merging of two branches of closed-loop solutions into a complex conjugate pair, resulting in a RWM instability that weakly depends on the feedback gain. The other less unstable branch, before the root-merging occurs, is not shown in Fig. 5. This root-merging process sometimes happens in the RWM feedback modelling, and appears to be robust against variation of the plasma conditions, such as plasma toroidal flow, kinetic effects in Fig. 6, and coil systems (e.g. the poloidal location of the sensor coils, with results not shown here) in ST modelling. Even with a fairly large reduction in normalized β, such that C_β=0.51, marginal stability is just achieved in both eigenvalue and initial value calculations. As a result, a weakly unstable residual (and rotating) closed-loop RWM maintains with P controller alone even at large feedback gain.

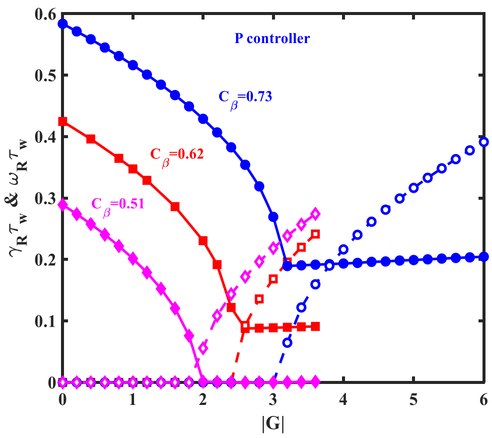

Fig. 5: The calculated n=1 RWM closed-loop eigenvalue, for various values of C_β. The eigenvalues are normalized to the overall wall time, τ_W. The solid curves are the growth rate and the broken curves the mode frequency.

5. Effect of System Noise with PD controller

The difficulties in achieving feedback stabilization with a solely P controller motivates exploring a PD controller. Including toroidal plasma rotation at a realistic level allows feedback stabilization with a relatively smaller derivative term (K_d=0.3) as shown in Fig. 7. A key aspect in the performance of feedback controller is the presence of noise in the detected signal(s) [9]. In the present study, random numbers with normal distribution, zero mean and standard deviation of σ<1 G, are injected into the perturbed magnetic field sensor signal, when the closed-loop system is modelled with the initial value approach. Initial value calculations

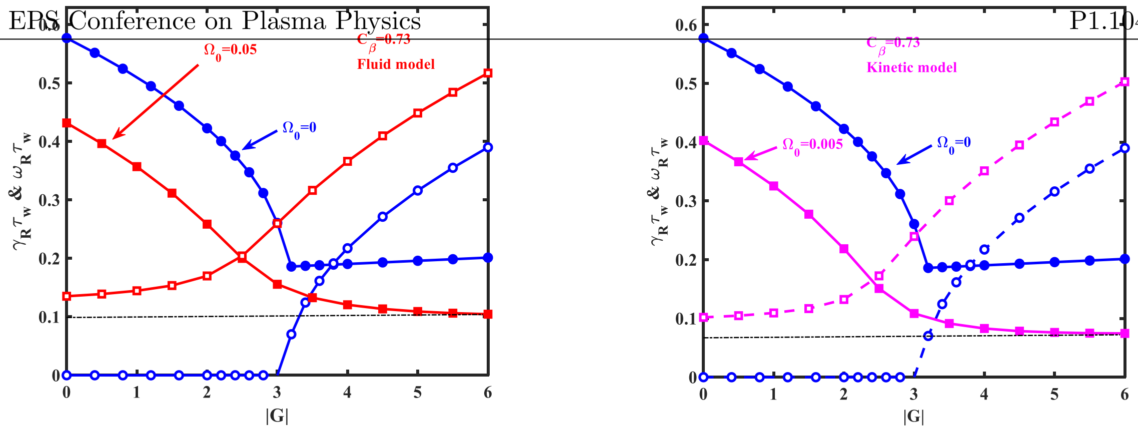

Fig. 6 Left: Feedback control combined with plasma toroidal flow; Right: Feedback control combined with kinetic effects. The solid curves are the growth rate and the broken curves the mode frequency.

show with realistic levels of noise that stabilization rather marginal at K_d =0.3. However increasing to K_d =0.4 gives clear stabilization (Fig. 8). This control with PD controller can be tolerant to a realistic noise level of ~0.1 Gauss in the detection system, and not all cases are successfully stabilized, further studies are in progress to optimize the feedback success rate.

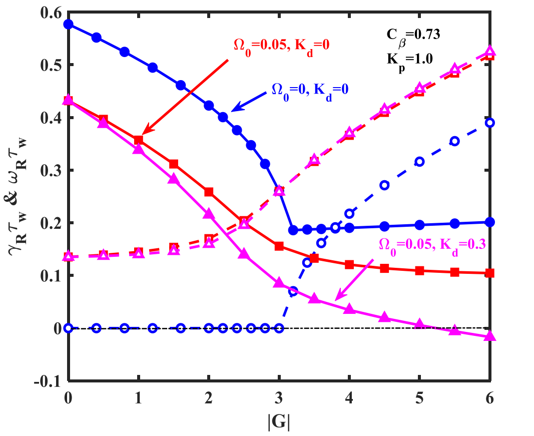

Fig. 7: The calculated n=1 RWM closed-loop eigenvalue, for various control scheme. The solid curves are the growth rate and the broken curves the mode frequency.

6. Summary

The effect of the precessional drift resonance has a very limited effect on the RWM, and the NBI EP contribution slightly destabilizes the RWM. For a plasma with C_β>~0.5, the P controller alone, combined with plasma rotation or kinetic effects, cannot achieve complete feedback stabilization. With the PD controller, the RWM feedback control is achieved. This control can also be tolerant to realistic noise levels in the detection system, and studies are in progress to further optimize its success.

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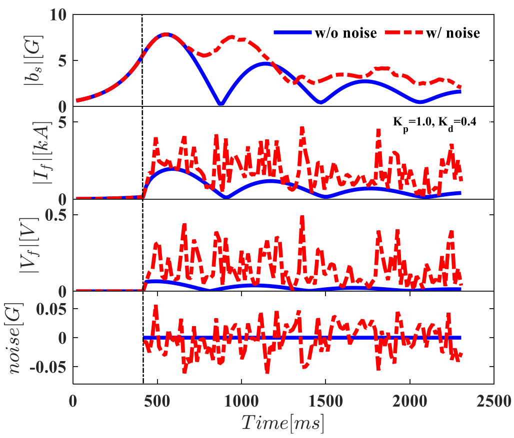

Fig. 8 Initial value simulated time traces for the RWM control, the feedback is activated at 415 ms (vertical dotted line).