RWM Control Code Maturity

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RWM Control Code Maturity

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Outline

• Introduction

• Formulations behind advanced RWM control code
  – Passive stabilisation: drift-kinetic-MHD hybrid
  – Active control: 3D conductors + damping physics

• Examples of recent results
  – Kinetic effects from fast ions (DIII-D)
  – New CarMa implementation: 3D walls + kinetic effects
  – Simulation of RWM feedback in RFX

• Summary
Introduction: RWM code maturity issues

- Significant progress has been made in recent years towards realistic modelling of the RWM

- Two major issues have been attacked in developing RWM control codes
  - Passive control: mode damping physics (plasma rotation, drift-kinetic mode-particle resonances)
  - Active control: 3D structure of walls and feedback coils, realistic (and advanced) control logics

- Eventual goal is to have a code capable of solving above issues simultaneously and consistently

- CarMa code is ready to perform this task.

- There are a few other RWM codes, with one or another advanced features. (AEGIS-K, LIGKA, MISK, MISHKA+HAGIS, VALEN, STARWALL, NMA,KINX,...)
Introduction: MARS-F/K & CarMa codes

- **MARS-F** is single fluid, full MHD, full toroidal eigenvalue code with feedback options, including
  - Toroidal shear flow of plasma
  - Complete thin wall model (2D wall)
  - Continuous description of control coils along toroidal angle

- **MARS-K** adds drift-kinetic terms into MHD in a self-consistent manner, including kinetic contributions from
  - Trapped and passing thermal particles [Liu PoP08]
  - Trapped fast ions (reported here)

- **CarMa** couples MARS-F/K with a 3D eddy current code CARIDDI
  - Coupling strategy is a key issue
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- **Summary**
Self-consistent formulation couples drift kinetic effects with fluid MHD via perturbed kinetic pressure tensors

- MHD-kinetic hybrid formulation

\[(\gamma + in\Omega)\xi = v + (\xi \cdot \nabla \Omega)R^2 \nabla \phi,\]

\[\rho(\gamma + in\Omega)v = -\nabla \cdot p + j \times B + J \times Q - \rho \left[2\Omega \hat{Z} \times v + (v \cdot \nabla \Omega)R^2 \nabla \phi \right],\]

\[(\gamma + in\Omega)Q = \nabla \times (v \times B) + (Q \cdot \nabla \Omega)R^2 \nabla \phi,\]

\[(\gamma + in\Omega)p = -v \cdot \nabla P,\]

\[j = \nabla \times Q,\]

\[p = pI + p_\parallel b\hat{b} + p_\perp (I - b\hat{b}),\]

\[p_\parallel e^{-i\omega t + im\phi} = \sum_{e,i} \int d\Gamma Mv_{\parallel}^2 f_{\parallel}^1((\xi_\perp)) + \int d\Gamma Mv_{\parallel}^2 f_{\parallel}^1((\xi_\perp)),\]

\[p_\perp e^{-i\omega t + im\phi} = \sum_{e,i} \int d\Gamma \frac{1}{2} Mv_{\perp}^2 f_{\perp}^1((\xi_\perp)) + \int d\Gamma \frac{1}{2} Mv_{\perp}^2 f_{\perp}^1((\xi_\perp)).\]
Equilibrium distribution functions of particles

- Assume Maxwellian distribution for thermal particles
  \[ f_{th}^0 = N \left( \frac{M}{2\pi T} \right)^{3/2} e^{-\frac{\varepsilon_k}{T}} \]

- And slowing-down distribution for fast ions
  \[ f_{h}^0 = \begin{cases} \frac{C}{\varepsilon_k^{3/2} + \varepsilon_c^{3/2}} & 0 < \varepsilon_k < \varepsilon_0 \\ 0 & \varepsilon_k > \varepsilon_0 \end{cases} \]

- Same assumptions made in MISK code

- Radial profile of hot ion’s energy distribution determined given hot ion’s density and pressure profiles

\[ \varepsilon_0 = \begin{cases} 3.5 \text{MeV} & \alpha - \text{particles} \\ \varepsilon_h(\psi) & \text{hot ions} \end{cases} \]
Perturbed distribution functions of particles

• Perturbed distribution functions for thermal and fast ions derived by solving linear perturbed drift kinetic equation, following [Antonsen PF82] and [Porcelli PoP94].

• Neglected finite drift orbit width and FLR

• Consider various resonances between mode and particles

- Thermal particles:
  - Bounce resonance of ions
  - Precession drift of ion&electron
  - Trapped and passing particles

- Fast ions:
  - Precession drift of trapped ions

\[ f_{th}^1 \propto \frac{n[\omega_{*N}^{th} + (\hat{\varepsilon}_k - 3/2)\omega_{*T}^{th} + \omega_E]}{n\omega_d^{th} + (\alpha n q + l)\omega_b^{th} - i\nu_{eff} - \omega} - \omega \]

\[ f_{h}^1 \propto \frac{n(f_{h,\psi}^{0}/Zef_{h,\psi}^{0}) - \omega}{n\omega_d^{h} - \omega} \]
MARS-K includes both perturbative & self-consistent approach

- Drift kinetic energy perturbation [Antonsen82, Porcelli94]

\[
\delta W_K = \sum_{e,i} \frac{1}{2} \int d^3x \int d\Gamma (-f_{e0}^i) \sum_l \hat{\lambda}_l \left| e^{-i\omega t} \hat{H}(t) \right|^2
\]

\[
\hat{\lambda}_l = \frac{n[\omega_{*N} + (\epsilon_k - 3/2)\omega_{*T} + \omega_E] - \omega}{n\omega_e + (\alpha n q + l)\omega_p - i\nu_{eff} - \omega}.
\]

\[\hat{H}(t) \propto \xi_\perp\]

- Perturbative
  - Ideal-kink or fluid RWM

- Self-consistent
  - Modified by kinetic effects self-consistently

<table>
<thead>
<tr>
<th>eigen-function $\xi$</th>
<th>perturbative</th>
<th>self-consistent</th>
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<tbody>
<tr>
<td>$\xi_\perp$</td>
<td>ideal-kink or fluid RWM</td>
<td>modified by kinetic effects self-consistently</td>
</tr>
</tbody>
</table>

| eigen-frequency $\omega$ | $\omega = 0$ or $i\gamma_f$ | $\omega = i\gamma$ nonlinear eigenvalue formulation |

| other damping          | shear Alfven damping included a-posteriori | continuum damping included via MHD terms |
MARS-K perturbative approach benchmarked against MISHKA+HAGIS code

- Choose a Soloviev equilibrium with circular-like shape
- Both codes run with perturbative approach

Liu, PoP08

- Validates approximation of neglecting banana width for kinetic RWM
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Formulations behind CarMa code

- CarMa couples MARS-F/K to 3D eddy current code CARIDDI, via two coupling schemes
  - "Forward" coupling scheme
  - "Backward" coupling scheme

- Key ideas of forward coupling [Portone PPCF08]
  - Introduce a coupling surface just outside plasma surface
  - Replace plasma magnetic response by a virtual surface current response at coupling surface
  - Effectively "condense" MHD equations into eddy current equations

- Forward coupling resembles in some aspects VALEN multimode approach. Like VALEN and STARWALL, consider static plasma response, hence no plasma inertia, (fast) rotation, kinetic effects
Formulations behind CarMa code

- Backward coupling scheme "condenses" conductors’ (dynamic) response into MHD equations
  - as a non-trivial boundary condition at coupling surface just outside plasma.

- Key idea is to transform conductors’ dynamic response into a linear BC [Smith PoP08, Guazzotto PoP08, Liu PoP08]
  - Hugely beneficial for linear MHD eigenvalue formulation
  - Allows easy inclusion of all effects beyond ideal MHD in CarMa

\[
\left( \vec{A}_{0N} + \gamma \vec{A}_{1N} \right) b_N + \left( \vec{A}_{0T} + \gamma \vec{A}_{1T} \right) b_T + \left( \vec{A}_{0f} + \gamma \vec{A}_{1f} \right) I_f = 0.
\]

CARIDDI
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Equilibrium profiles from DIII-D 125701
Fast ion density and pressure profiles

- Fast ion contributes nearly half of total pressure

![Density](image1.png)

![Pressure](image2.png)
Computed radial distribution of fast ion energy
Perturbative approach: energy

- Fast ions give minor contribution at slow rotation

\[
\gamma_{W}^{*} = - \frac{\delta W_{\infty} + \delta W_{k}}{\delta W_{b} + \delta W_{k}}
\]
Perturbative approach: eigenvalue

- Fast ions are slightly destabilising at slow rotation, stabilising at faster rotation
- RWM at expt. rotation is stable w/ or w/o fast ions
Self-consistent approach: growth rate

- w/o fast ions, SC approach predicts a narrow window of stabilisation
- w/ fast ions, a second unstable branch appears

Expt.
Self-consistent approach: mode frequency

- Fast ion driven (unstable) branch can have different direction of mode rotation
Self-consistent approach: sensitivity on ion gyroradius

- Fast ions can be stabilising in ITER

\[
\frac{\omega_{ci}}{\omega_A} = \frac{eR\sqrt{\mu_0N}}{\sqrt{M}} \propto R\sqrt{N}
\]
Self-consistent approach: compare eigenmode structure

- Less unstable mode (branch B) more peaked at last rational surface
Self-consistent approach: compare eigenmode structure

- Eigenmodes differ mostly in the outer region of the plasma, outside the $q=2$ surface
Resonance condition for fast ions?

- Fast ion precession drift frequency comparable to experimental rotation frequency
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CarMa capable of solving RWM problems with damping + 3D wall + feedback

- Choose a test equilibrium with circular cross section, and $R/a=5$
CarMa benchmarked for damping models

- Compute passive stability versus plasma rotation
  - Parallel sound wave damping
  - Kinetic damping
- With 2D wall, CarMa results almost identical to MARS-K

![Graphs showing growth rate and frequency](image-url)
Models of 3D wall with holes

Model A

Model B
Wall holes increase both mode growth rate and frequency

- Effect of 3D wall on RWM passive stability, with plasma rotation and strong sound wave damping

Liu PPCF09
Wall holes increase both mode growth rate and frequency

- Effect of 3D wall on the RWM passive stability with plasma rotation and drift-kinetic damping model
Nyquist diagrams show effects of 3D wall on feedback performance

- 3D wall reduces closed loop stability margin
- Synergy between rotation and feedback, in presence of 3D wall
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CarMa used for realistic modelling of RFX feedback experiments

- CarMa computed wall eddy current pattern
- For an unstable mode with $n=3, m=1$

Villone PRL08
CarMa used for realistic modelling of RFX feedback experiments

- A typical RFX plasma equilibrium with shallow field reversal: \( \text{THETA}=1.426, \text{F}=-0.060 \)
Feedback loop in RFX experiments

- CarMa has been used to represent the plant in a full closed loop simulation of the RWM control system, yielding closed loop growth rates, that are directly compared with experiments.

CarMa Model

Marchiori EPS09
RWM feedback modelling in RFX

- Comparing experimental vs. CarMa simulated closed-loop growth rates of RWM

experiment

Amplitude: m=1, n=-6

Time (s)

Marchiori EPS09

experiment vs. modeling

growth rate (1/s)

proportional controller gain [arb]

control gain
Eigenmode structure can also be compared between modeling and expt.

- MARS-F computed amplitude ratio between poloidal harmonics (due to toroidicity) match reasonably well experiments

Experiment

Bolzonella EPS09

Modeling

EQ#4b, RWM

\( n=6 \)

Wall

\( m=-1 \)

\( m=-2 \)

\( m=0 \)

\( m=1 \)

\( m=2 \)
Summary

• Self-consistent approach generally predicts less kinetic stabilisation on RWM compared to perturbative approaches.

• Fast ions contribution, whilst can give additional stabilisation in perturbative approach, can also drive an extra unstable branch in self-consistent approach.

• A new version of CarMa code allows consistent modelling of 3D conductors, kinetic effects and feedback stabilisation all together.

• The RFX feedback experiments well modelled by CarMa.

• Other aspects of RWM code maturity, not discussed here:
  – Capability of treating thick walls and ferromagnetic materials.
  – Multimodal analysis (e.g. n=0+1, n=1+2+3, etc.) …
Discussions

• Are RWM codes mature enough? (No)
  – MARS-K: finite banana orbit effects, FLR, collision?
  – AEGIS-K, LIGKA more advanced in kinetic physics
  – Nonlinear physics (RWM couple to other modes)?
  – CarMa: iron saturation (nonlinear)?

• MARS-K results vs. DIII-D experiment?
  – Finite banana effects? FLR?
  – Collision?
  – Fast particle distribution function? Profiles?
  – Evidence of fast ion driven RWM in other experiments?

• What about prediction for ITER?
  – Seems no complete stabilisation with thermal particles
  – MARS-K modelling with alpha particles in progress
  – Waiting for new reference plasma for steady state scenario…
Backup slides ...
Kinetic effects do modify mode eigenfunction for a test toroidal equilibrium

- Test toroidal Soloviev equilibrium: $R/a=3$, $\kappa = 1.6$
ITER: perturbative

- Radial distribution of drift kinetic energy perturbation with precessional resonances

ITER, $C_β = 0.5$, $\omega_0/\omega_A = 10^{-3}$
Multimodal ITER results /2

- Combined $n=0$ (VDE) + $n=1$ (external kink) plasma evolution

ITER Scenario 4 ($\beta_N=2.7$). Three unstable eigenvalues:

- $\gamma_{1,2} = 10.4 \text{ s}^{-1}$, eigenvectors with a $n=1$ spatial behaviour, shifted of $\pi/2$ toroidally

- $\gamma_3 = 7.66 \text{ s}^{-1}$, eigenvector with a $n=0$ spatial behaviour

Almost identical to those computed with monomodal models: little (open-loop) coupling of $n=0$ and $n=1$ modes due to 3D structures.