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REPORT

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Tearing Modes in Tokamaks

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NIMROD and FAR Comparison for Tearing Modes in Tokamaks

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(October 20, 1998)

A comparison of linear growth rates and eigenfunctions for tearing modes resonant at the $q=2$ surface is made for simulations based on the initial value codes NIMROD and FAR for $S = 1.35(10^3)$, $S = 1.35(10^4)$, and $S = 1.35(10^5)$. Very good agreement for both growth rates and eigenfunctions between the two codes is indicated.

I. INTRODUCTION

NIMROD and FAR [1,2] are two large numerical initial value codes that can be used to solve the MHD equations. FAR uses a potential representation for both fields and velocities with field projections relative to a straight field line metric representation, uses a Fourier decomposition in both the poloidal and toroidal directions, and also uses central differences in the radial/flux direction. In contrast, NIMROD uses the actual magnetic fields and velocities with field projections (at least for this comparison) in the cylindrical directions (R, Z, ϕ) , uses a finite element representation in the R-Z plane with a grid aligned to flux surfaces and a fourier decomposition in the toroidal direction. The linear solver in FAR is implicit with groupings of harmonics with the same toroidal number coupled. In NIMROD, the time advance is semi-implicit with coupling across the R-Z plane. While both codes solve the MHD equations, each code handles viscosity slightly differently. In the case of FAR, the viscosity terms are (as near as I can tell) a large-aspect ratio, tokamak ordering of the ∇^2 acting on the appropriate projection of the vorticity, e.g, the toroidal or poloidal projections of the vorticity. The viscosity does not act on the compressibility. In the case of NIMROD, the viscosity is $\nabla^2 \vec{v}$. In both cases the resistivity and viscosity are constant across the entire plasma extent. Also the NIMROD simulations are based on the magnetic field formulation of the semi-implicit operator.

The particular equilibrium that will be considered is illustrated in Figure 1. The input file for the rsteq equilibrium code is supplied in Appendix A. Both NIMROD and FAR can read output from this equilibrium code. The equilibrium is based on another validation study [3] between FAR and AELOUS [4] and parameterizes the profiles as

$$P(r) = (1 - (r/a)^2)^2, \tag{1}$$

$$q(r) = 1.38(1 + (r/0.6)^8)^{1/4}, \tag{2}$$

with a geometric major radius of $R_0 = 5m$, a minor radius of $0.5m$, and a value of poloidal beta of $\beta_p = 1$. Rsteq computes a magnetic axis of $R_m = 5.026m$ and an inverse aspect

ratio of $\epsilon = 9.925(10^{-2})$. Note that this value is not the geometric inverse aspect ratio and is required for the FAR normalizations.

When doing comparisons the issue of normalizations often makes the comparison difficult. NIMROD is based on SI units (see Appendix B for a typical input file), while FAR uses dimensionless numbers (see Appendix C for a typical input file). For the purposes of this comparison, the dimensionless quantities relevant for FAR are defined in terms of NIMROD quantities. The resistive time is defined as

$$\tau_R = \frac{a^2}{elec d}, \quad (3)$$

where $a = \epsilon R_0 = 0.4988$ and $elec d = \eta/\mu_0$ is the electrical diffusivity. The Alfven time is defined as

$$\tau_A^{-2} = \frac{F_0^2}{\rho_D \mu_0 R_0^4} \quad (4)$$

where the magnetic field at the magnetic axis is given by F_0/R_0 , $\rho_D = (m_e + m_i)ndens = 3.1(10^{-9})kgm^{-3}$ is the mass density, and $ndens$ is the particle density ($\#/m^{-3}$). Here, $\tau_A = 7.18(10^{-8})s$. The Lunquist number as used by FAR is defined as

$$S = \tau_R/\tau_A, \quad (5)$$

and the viscosity (vis) or magnetic Prandtl number as used by FAR is given by

$$vis = kin_visc/elec d. \quad (6)$$

In this case the comparison was also complicated because of a bug indentified in the calculation of the toroidal current profile in the routine *delstar* associated with FAR. Eventually this routine was deleted and replaced with Eq. (2.50) of Reference [5]. The original routine produced growth rates that were approximately a factor of two greater than the updated version.

NIMROD simulations are based on Version 2.2, 8/21/98.

II. RESULTS

In Table I-III, various growth rates are presented that indicate the convergence of a particular NIMROD run with respect to both time step (dtm) and spatial decomposition (mx/my). The time step is literally in seconds and is typically a fraction of Alfven time. The quantity mx refers to the total number of radial cells and the quantity my refers to the total number of poloidal cells. The viscosity is held fixed at $kin_visc = 252.6 m^2 s^{-1}$ for each simulation, while the resistivity varies from $elec d = 2526.0$ for Table I, $elec d = 252.6$ for Table II, and $elec d = 25.26$ for Table III. NIMROD growth rates were computed by plotting the slope of $\log E$ and dividing this slope by 2. (The procedure is to convert the *energy.bin* file with the xlog program.) Also provided in each table is the "Start" point for each simulation. The notation used in this column indicates which "Run" followed by underscore followed by a timestep from that run that was used to initiate the new simulation. In some cases this represents a regridding of a coarse simulation onto a finer grid. When such a regridding takes place the dump file has been reset to zero. The "End" category represents the time step at which the growth rate was measured and the "CPU s" column reflects on the total number of CPU seconds required to complete that simulation on the T3E. The rblock heading reflects the parallel decomposition (nxbl/nybl), where nxbl is the number of rblocks in the radial direction and nybl is the number of rblocks in the polodial direction. The total number of processors used in the simulation is the product nxbl times nybl.

Further simulations could probably be added to Tables I-III to better gauge convergence with respect to time-step. Also very little convergence work has been completed for $S = 1.35(10^5)$ simply because of the long time required to complete the simulations.

In Table IV, the growth rates as determined by FAR are presented for variations both in the viscosity and the resistivity. The growth rate is based on running FAR as an initial value simulation (versus eigenvalue mode) and waiting until "gampsi" has converged. The reported value of the growth rate is from "gampsi" and is in units of $\gamma\tau_R$. For too large of a timestep, FAR has the propensity of converging to the wrong growing instability, hence a

timestep had to be chosen that was again less than an Alfvén time. At the highest value of S , the FAR simulations tend to converge very slowly and are subject to oscillations in the growth rate/decay.

TABLE I. Growth rates from NIMROD simulation for $S = 1.35(10^3)$ and $vis = 0.1$.

Run	mx/my	dtm	$\gamma\tau_A$	Start	End	rblock	CPU s
10c	200/99	12e-08	3.33e-02	10a_1700	2000	4/2	4.4(10 ⁴)
10b	200/99	6e-08	3.39e-02	10a_1700	2000	4/2	1.2(10 ⁴)
10a	200/99	3e-08	3.44e-02	6a_1400	2300	4/2	2.6(10 ⁴)
10d	200/99	1e-08	3.37e-02	10a_1700	2900	4/2	3.9(10 ⁴)
10f	300/149	1e-08	3.37e-02	10d_2900	400	8/4	2.3(10 ⁴)
10e	400/199	1e-08	3.37e-02	10d_2900	400	8/4	6.2(10 ⁴)

TABLE II. Growth rates from NIMROD simulation for $S = 1.35(10^4)$ and $vis = 1.0$.

Run	mx/my	dtm	$\gamma\tau_A$	Start	End	rblock	CPU s
6c	200/99	12e-08	numerical	6a_1400	1625	4/2	-
6b	200/99	6e-08	1.05e-02	6a_1400	2500	4/2	7.3(10 ⁴)
6a	200/99	3e-08	1.03e-02	0000	1400	4/2	7.2(10 ⁴)
6d	200/99	1e-08	9.46e-03	6a_1400	2400	4/2	5.9(10 ⁴)
6f	300/149	1e-08	9.41e-03	6d_2400	900	8/4	3.9(10 ⁴)
6e	400/199	1e-08	9.53e-03	6d_2400	500	8/4	2.0(10 ⁴)

TABLE III. Growth rates from NIMROD simulation for $S = 1.35(10^5)$ and $vis = 1.0$. The results are not well converged in time advance as indicated by a discrepancy in the growth rate of magnetic and kinetic energy.

Run	mx/my	dtm	$\gamma\tau_A$	Start	End	rblock	CPU s
8b	200/99	6e-08	numerical	8a_2900	3454	4/2	-
8a	200/99	3e-08	1.94e-03	6a_1400	5000	4/2	2.3(10 ⁵)
8d	200/99	1e-08	-	6a_1400	2400	4/2	-
8e	400/199	5e-08	1.97e-03	8d_5000	1800	8/4	2.8(10 ⁵)

TABLE IV. Linear growth rates from FAR simulations for 400 radial cells and 5 equilibrium harmonics. The perturbed harmonics are $n=1$ and $m=1$ through 8. For $S = 1.35(10^5)$ the growth rates are based on FAR in eigenvalue mode.

S	vis	$\gamma\tau_R$
1.35(10^3)	0.0	51.7
1.35(10^3)	0.01	50.8
1.35(10^3)	0.10	44.6
1.35(10^3)	1.00	25.0
1.35(10^3)	10.0	9.65
1.35(10^4)	0.0	170
1.35(10^4)	0.01	167
1.35(10^4)	0.1	155
1.35(10^4)	1.0	118
1.35(10^4)	10.	67.9
1.35(10^5)	0.0	669
1.35(10^5)	0.01	460
1.35(10^5)	0.1	406
1.35(10^5)	1.0	300
1.35(10^5)	10.	203

III. DISCUSSION

The validation results of the previous section are summarized in Table V. In general, the NIMROD results are uniformly larger than the FAR results. Since these particular modes are in a regime where viscous effects are important, the difference could perhaps be attributed to the alternate viscosity formulations for the two codes. In addition to comparing the growth rates, the radial projection of the perturbed magnetic field is compared in Figs. 2-4. The particular choice of this projection was based on the ease with which it could be computed within the two codes, e.g., poloidal projections are complicated by the choice of what angle one uses. The eigenfunctions show very good agreement between NIMROD and FAR.

TABLE V. Comparison of NIMROD and FAR growth rates

S	vis	$(\gamma\tau_R)_{FAR}$	$(\gamma\tau_R)_{NIMROD}$
$1.35(10^3)$	0.10	44.6	46.2
$1.35(10^4)$	1.0	118	129
$1.35(10^5)$	10.	203	~ 269

IV. ACKNOWLEDGMENT

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- [1] L.A. Charlton, J.A. Holmes, H.R. Hicks, V.E. Lynch, B.A. Carreras. *J. of Comp. Physics* **63** (1986), 107.
- [2] V.E. Lynch, B.A. Carreras, H.R. Hicks, J.A. Holmes, L. Garcia. *Computer Physics Communications* **24** (1981), 465.
- [3] J.G. Leboeuf G.I. Kurita. *Finite beta and compressibility effects on stability of resistive modes in toroidal geometry*. Report No. JAERI-M 98-010, Japan Atomic Energy Research Institute (JAERI) , 1998.
- [4] G.I. Kurita, M. Azumi, T. Takeda. *AELOUS-IT MHD simulation code based on a toroidally incompressible plasma model*. Report No. JAERI-M 93-004, Japan Atomic Energy Research Institute (JAERI), 1993.
- [5] T.A. Gianakon. *Computational Modeling of Neoclassical and Resistive MHD Tearing Modes in Tokamaks*. PhD dissertation, University of Wisconsin-Madison, 1996. (T.A. Gianakon, UW-CPTC 96-1).

APPENDIX A: RSTEQ INPUT FILE

```

&namin
numrun=7000,
rbore=50.00,ellipt=1.0,deity=0.,fwall=39.00,nqprof=20,ieq=6
,ndat=61
,xr=
0.00000E+00, 0.16667E-01, 0.33333E-01, 0.50000E-01, 0.66667E-01, 0.83333E-01,
0.10000E+00, 0.11667E+00, 0.13333E+00, 0.15000E+00, 0.16667E+00, 0.18333E+00,
0.20000E+00, 0.21667E+00, 0.23333E+00, 0.25000E+00, 0.26667E+00, 0.28333E+00,
0.30000E+00, 0.31667E+00, 0.33333E+00, 0.35000E+00, 0.36667E+00, 0.38333E+00,
0.40000E+00, 0.41667E+00, 0.43333E+00, 0.45000E+00, 0.46667E+00, 0.48333E+00,
0.50000E+00, 0.51667E+00, 0.53333E+00, 0.55000E+00, 0.56667E+00, 0.58333E+00,
0.60000E+00, 0.61667E+00, 0.63333E+00, 0.65000E+00, 0.66667E+00, 0.68333E+00,
0.70000E+00, 0.71667E+00, 0.73333E+00, 0.75000E+00, 0.76667E+00, 0.78333E+00,
0.80000E+00, 0.81667E+00, 0.83333E+00, 0.85000E+00, 0.86667E+00, 0.88333E+00,
0.90000E+00, 0.91667E+00, 0.93333E+00, 0.95000E+00, 0.96667E+00, 0.98333E+00,
0.10000E+01,
pdat=
0.10000E+01, 0.99944E+00, 0.99778E+00, 0.99501E+00, 0.99113E+00, 0.98616E+00,
0.98010E+00, 0.97296E+00, 0.96476E+00, 0.95551E+00, 0.94522E+00, 0.93391E+00,
0.92160E+00, 0.90831E+00, 0.89408E+00, 0.87891E+00, 0.86283E+00, 0.84589E+00,
0.82810E+00, 0.80950E+00, 0.79012E+00, 0.77001E+00, 0.74919E+00, 0.72770E+00,
0.70560E+00, 0.68292E+00, 0.65970E+00, 0.63601E+00, 0.61187E+00, 0.58735E+00,
0.56250E+00, 0.53737E+00, 0.51202E+00, 0.48651E+00, 0.46089E+00, 0.43523E+00,
0.40960E+00, 0.38406E+00, 0.35867E+00, 0.33351E+00, 0.30864E+00, 0.28415E+00,
0.26010E+00, 0.23657E+00, 0.21365E+00, 0.19141E+00, 0.16993E+00, 0.14930E+00,
0.12960E+00, 0.11093E+00, 0.93364E-01, 0.77006E-01, 0.61946E-01, 0.48278E-01,
0.36100E-01, 0.25511E-01, 0.16612E-01, 0.95063E-02, 0.42975E-02, 0.10927E-02,
0.50487E-28,
xdat=
0.13800E+01, 0.13800E+01, 0.13800E+01, 0.13800E+01, 0.13800E+01, 0.13800E+01,
0.13800E+01, 0.13800E+01, 0.13800E+01, 0.13800E+01, 0.13800E+01, 0.13800E+01,
0.13801E+01, 0.13801E+01, 0.13802E+01, 0.13803E+01, 0.13805E+01, 0.13809E+01,
0.13813E+01, 0.13821E+01, 0.13831E+01, 0.13846E+01, 0.13867E+01, 0.13895E+01,
0.13933E+01, 0.13983E+01, 0.14049E+01, 0.14133E+01, 0.14240E+01, 0.14375E+01,
0.14541E+01, 0.14742E+01, 0.14983E+01, 0.15268E+01, 0.15600E+01, 0.15980E+01,
0.16411E+01, 0.16892E+01, 0.17424E+01, 0.18004E+01, 0.18632E+01, 0.19306E+01,
0.20023E+01, 0.20782E+01, 0.21580E+01, 0.22415E+01, 0.23285E+01, 0.24189E+01,
0.25126E+01, 0.26092E+01, 0.27089E+01, 0.28113E+01, 0.29165E+01, 0.30244E+01,
0.31349E+01, 0.32479E+01, 0.33633E+01, 0.34813E+01, 0.36016E+01, 0.37243E+01,
0.38493E+01,
psipow=1.25
&end

```

APPENDIX B: NIMROD INPUT FILE

```
&grid_input
gridshape = 'flux'
eqfile = 'fluxgrid.dat'
xmin = 0.E+0
xmax = 1.
ymin = 0.E+0
ymax = 1.
skew = 0.E+0
firstx = 0.E+0
firsty = 0.E+0
periodicity = 'none'
geom = 'tor'
per_length = 1.
xo = 2.
yo = 0.E+0
mx = 200
my = 99
mxpie = 1
lphi = 2
lin_nmodes = 1
lin_nmax = 1
nxb1 = 4
nyb1 = 2
nlayers = 1
decompflag = 0
pieflag = 'rblock'
rimflag = 'none'
nbl_rim = 2
/

&physics_input
nonlinear = .false.
ohms = 'mhd'
elecd = 2526.0
kin_visc = 252.6
dvac = 1.
dexp = 20.
ds_use = 'both'
ndens = 9.4E+17
be0 = 1.
thetab = 0.E+0
phib = 0.5
beta = 2.00000000000000004E-3
lamprof = 'mbfm'
```

```

lam0 = 0.E+0
rbreak = 0.200000000000000001
alpha = 3.
pit_0 = 1.
pit_2 = 0.E+0
pit_4 = 0.E+0
pres_2 = 0.E+0
pres_4 = 0.E+0
advect = 'none'
eq_flow = 'none'
ve0 = 0.E+0
thetav = 0.E+0
phiv = 0.5
eqflow_width = 0.5
loop_volt = 0.E+0
tloopv0 = -1.
tloopv1 = 0.E+0
init_type = 'shear alf'
reset_file = 'none'
nx = 1
ny = 4
bamp = 1.00000000000000008E-5
/
&neoclassical_input
neo_flag = 'none' neo_debug = .false.
mu_e = 0.E+0 mu_i = 0.E+0 ng_ft = 10
/
&numerical_input
dtm = 1.0E-8
dt_stop = 1.00000000000000005E-4
dt_incr = 10.
tmax = 12.
nstep = 300
npc = 1
conform = .true.
met_spl = 'cubic'
lump_b = .false.
ngr = 2
fom = 1.
feta = 1.
fvsc = 1.
fb_vxb = 1.
fv_vdgv = 1.
fp_vdgp = 1.
v_cfl = 0.5

```



```

nl_cfl_lim = 10000000000.
si_in_v = .false.
si_fac_mhd = 1.
si_fac_hall = 1.
si_fac_pres = 1.
mhd_si_iso = 0.E+0
split_resist = .true.
split_visc = .false.
divbd = 3000.
fdivb = 1.
split_divb = .true.
ndivb = 1
kdivb_2_limit = 3.
dt_change_frac = 0.25
ave_change_limit = 2.50000000000000014E-2

```

```

/solver_input
solver = 'bl_ilu_0'
off_diag_fac = 0.90000000000000002
extrap_order = 2
maxit = 1000
tol = 9.9999999999999995E-8

```

```

/output_input
dump_file = 'dump.02900'
dump_name = 'dump'
dump_dir = '.'
ndump = 100
dump_over = 0
nhist = 1
hist_binary = .true.
ihist = 20
jhist = 1
xdraw_dir = '.'
xy_stride = 0
xt_stride = 0
yt_stride = 0
xOfac = 0.5
yOfac = 0.25
ndxout = 0
dx_dir = '.'
detflag = .false.
itflag = .false.

```

APPENDIX C: FAR INPUT FILE.

```
0 t402 fs### 9989 001103 a50
&nam
maxstp=2000, nonlin=0, mj=400, lmax=13, leqmax=5,
ical=2, nonlin=0, ietaeq=3, etascl=1.0, ngeneq=1, iexp=0, mOdy=0,
stdifa=0.0, vis=1.0, stdifp=0.00,
mm=1,2,3,4,5,6,7,8,
    0,1,2,3,4,
nn= 8*1,
    5*0,
mmeq=0,1,2,3,4,
nneq=5*0,
widthi(1)=1.e-60,
widthi(2)=1.e-60,
widthi(3)=1.e-60,
widthi(4)=1.e-60,
widthi(5)=1.e-60,
widthi(6)=1.e-60,
widthi(7)=1.e-60,
widthi(8)=1.e-60,
gamma=1.66666, ipert=0,
lplots=3, nprint=100, ndump=10000,
s=1.35e4, dt0=1.0, itime=2, ieq=7,
&end
```

FIG. 1. Equilibrium profiles from rsteq based on input in Appendix A.

FIG. 2. Contours of the radial prjection of the perturbed magnetic field for NIMROD (colored) and FAR (black) for $S = 1.35(10^3)$ and $vis = 0.1$.

FIG. 3. Contours of the radial prjection of the perturbed magnetic field for NIMROD (colored) and FAR (black) for $S = 1.35(10^4)$ and $vis = 1.0$.

FIG. 4. Contours of the radial prjection of the perturbed magnetic field for NIMROD (colored) and FAR (black) for $S = 1.35(10^5)$ and $vis = 10.0$.