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EDDY CURRENTS IN A NONPERIODIC VACUUM VESSEL INDUCED BY
AXISYMMETRIC PLASMA MOTION

By

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ABSTRACT

A method is described for calculating the two-dimensional trajectory of a vertically or horizontally unstable axisymmetric tokamak plasma in the presence of a resistive vacuum vessel. The vessel is not assumed to have toroidal symmetry. The plasma is represented by a current-filament loop that is free to move vertically and to change its major radius. Its position is evolved in time self-consistently with the vacuum vessel eddy currents. The plasma current, internal inductance, and poloidal beta can be specified functions of time so that eddy currents resulting from a disruption can be modeled. The vacuum vessel is represented by a set of current-filaments whose positions and orientations are chosen to model the dominant eddy current paths. Although the specific application is to TFTR, the present model is of general applicability.

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I. INTRODUCTION

Noncircular tokamak plasmas can be unstable to ideal-MHD axisymmetric instabilities. A closely fitting vacuum vessel will slow down the growth of this mode to the inductive/resistive (L/R) time of the vessel. However, the resulting eddy currents produce potentially damaging mechanical forces at the vessel surface. In addition, currents induced on the vessel during a plasma disruption may produce substantial forces. It becomes important to know the amplitude and spatial structure of eddy currents induced by plasma motion so that peak forces on the vessel can be estimated.

Sophisticated electrical engineering codes exist which accurately calculate eddy currents on conducting surfaces in three dimensions.¹ However, many elements are needed to model the important aspects of the vacuum vessel. It is therefore impractical to couple these codes self-consistently to a plasma dynamics model.

This paper describes a nonperiodic, *resistive vacuum vessel model* and its self-consistent coupling to the axisymmetric motion of a plasma filament whose horizontal and vertical position changes on the L/R time of the vacuum vessel. A similar model was used to estimate the effects of the mutual inductance between the plasma and vacuum vessel during adiabatic compression in TFTR.²

The vacuum vessel model used here is described in Sec. II. The plasma dynamics model and the self-consistent coupling between the plasma and vacuum vessel are described in Sec. III. This model is then applied to calculate the plasma trajectory and peak eddy current amplitudes which result during the evolution of a vertically unstable plasma in TFTR. Such a configuration will occur during the early stages of the discharge in a mode of operation being studied for TFTR. These results are presented in Sec. IV. Summary and conclusions are given in Sec. V.

II. VACUUM VESSEL MODEL

A current-filament model of the TFTR vacuum vessel was introduced in Ref. 2 for estimating the amplitude of magnetic field perturbations, in the plasma vicinity, due to eddy currents induced during adiabatic compression. It consisted of twenty-six electrically insulated triple-loop stainless-steel structures each with a size and orientation chosen to represent the true nonperiodic structure of the TFTR vacuum vessel. The high-resistance bellows regions were treated as perfect insulators so that current could not flow between adjacent low-resistance sections. This was a good approximation on the time scale of adiabatic compression. The top half of the vessel consisted of thirteen triple-loop structures and the bottom half was the mirror image of the top. Since all sections were electrically insulated, the assumption that the plasma was constrained to move in the midplane was built into the vessel model.

The vacuum vessel model used in Ref. 2 is adopted here with two generalizations. First, since this work is concerned with predominantly vertical plasma motion, the assumption that current cannot flow from the upper to the lower half of the vessel has been removed. The top structures are electrically connected to the corresponding bottom structures, so that the present vessel model consists of thirteen conducting loop structures insulated from each other at the bellows regions only. Second, the number of loops per structure has been changed from a fixed number (three), with the possibility of toroidally directed branches being unequally spaced in the poloidal angle θ , to an arbitrary number, with toroidal branches being equally spaced in θ . Also, the widths of the toroidal branches is left arbitrary so that both thin and thick loops can be used.

These aspects of the present vacuum vessel model are illustrated in Fig. 1 (top view). The dark regions represent conducting bars. Figure 1 (a) shows eight loops per conducting structure, four loops in the upper half-plane and four in the lower. Figures 1 (b) and 1 (c) show sixteen loops per section. In Figs. 1 (a) and 1 (b) the toroidal branches are thin as compared to the thicker branches in Fig. 1 (c).

III. PLASMA AND VACUUM VESSEL EQUATIONS

This section describes a set of ordinary differential equations which are integrated to give the time histories of the vacuum vessel Maxwellian-loop currents (see Ref. 2 for their definition) and of the horizontal and vertical plasma positions. The notation used in Ref. 2, generalized from six loops to an arbitrary number of loops per vacuum vessel section, is adopted here and will now be briefly reviewed.

Two indices (k,j) are used to indicate a single vacuum vessel loop where k identifies a particular low-resistance section and j identifies a loop within section k . In general $k = 1, 2, \dots, K_v$ and $j = 1, 2, \dots, J_v$. The current flowing in loop (k,j) is $I^v(k,j)$ and the loop voltage is $V(k,j)$. The mutual inductance between vessel loops (k,j) and (k',j') is denoted $M^{vv}(k,j|k',j')$.

Loop voltages are given in terms of loop currents by

$$V(k,j) = \sum_{j'=1}^{J_v} S(k|j,j') I^v(k,j') \quad .$$

Here $S(k|j,j')$ are elements of the resistance matrix. When $j = j'$, $S(k|j,j')$ is total resistance of loop (k,j) . When $j \neq j'$, but is such that loops (k,j) and (k,j') have a common branch, then $S(k|j,j')$ is the negative of the resistance of that branch. Otherwise $S(k|j,j')$ is zero.

External axisymmetric conducting coils are also identified by two indices (k, j) where k indicates a group of coils connected in series and j identifies a particular coil in group k . In general, $k = 1, 2, \dots, K_x$ and $j = 1, 2, \dots, J_x(k)$. Application of indices (k, j) to either the vacuum vessel loops or the external coils will be clear from the context of their usage. The current flowing in external coil group k is $I^x(k)$ and is prescribed as a function of time. The mutual inductance between vacuum vessel loop (k, j) and external coil group k' is denoted $M^{vx}(k, j|k')$.

The horizontal and vertical plasma positions are given in standard cylindrical coordinates $\vec{R}_p = \hat{R}R_p(t) + \hat{Z}Z_p(t)$. The magnetic flux through vacuum vessel loop (k, j) due to the plasma is given by $\psi(k, j) = M^{vp}(k, j|\vec{R}_p)I_p$. Here M^{vp} is the mutual inductance between vessel loop (k, j) and the axisymmetric plasma filament, and I_p is the plasma current. In general, I_p is a prescribed function of time so that eddy currents arising from a plasma disruption can be modeled.

All of the above defined quantities are elements of a corresponding vector or matrix, i.e.,

$$\{\underline{I}^v\}_j \equiv I^v(k, j) \quad , \quad (1a)$$

$$\{\underline{V}\}_j \equiv V(k, j) \quad , \quad (1b)$$

$$\{\underline{M}^{vv}\}_{j, j'} \equiv M^{vv}(k, j|k', j') \quad , \quad (1c)$$

$$\{\underline{S}\}_{j, j'} = \delta_{kk'} S(k|j, j') \quad , \quad (1d)$$

$$\{\underline{I}^x\}_k \equiv I^x(k) \quad , \quad (1e)$$

$$(\underline{M}^{vx})_{l,k} \equiv M^{vx}(k,j|k') \quad , \quad (1f)$$

$$(\underline{\psi})_l \equiv \psi(k,j) \quad , \quad (1g)$$

and

$$[\underline{M}^{vp}(\underline{\hat{R}}_p)]_l \equiv M^{vp}(k,j|\underline{\hat{R}}_p) \quad , \quad (1h)$$

where the vacuum vessel index "l" is defined to be

$$l(k,j) \equiv (k-1)J_v + j \quad ,$$

$$\text{i.e., } l = 1, 2, \dots, K_v J_v \equiv L_v \quad .$$

The method of calculating the mutual inductances $\underline{M}^{vv}$, $\underline{M}^{vx}$, and $\underline{M}^{vp}$ is described in Ref. 2.

A mixed vector product notation is employed from here on in order to distinguish vector products between matrices and vectors defined in Eqs. (1) from vector products between $\underline{\hat{R}}_p$ and gradients of scalar fields written in the (R,ϕ,z) cylindrical coordinate system. When referring to the three dimensional (R,ϕ,z) vector space the familiar dot (" $\cdot$ ") notation is used, i.e.,

$$\underline{\hat{R}}_p \cdot \nabla f(R,Z) = R_p \frac{\partial f}{\partial R} + Z_p \frac{\partial f}{\partial z} \quad .$$

When referring to the L_v and K_x dimensional spaces used in Eqs. (1), an asterisk ("*") is employed, i.e.,

$$\underline{v} * \underline{I}^v \equiv \sum_{\ell=1}^{L_v} (\underline{v})_{\ell} (\underline{I}^v)_{\ell} ,$$

and

$$(\underline{M}^{vv} * \underline{I}^v)_{\ell} \equiv \sum_{\ell'=1}^{L_v} (\underline{M}^{vv})_{\ell\ell'} (\underline{I}^v)_{\ell'} ,$$

for $\ell = 1, 2, \dots, L_v$.

Using the above notation, the circuit equations for the vessel eddy currents become

$$\underline{M}^{vv} * \frac{d}{dt} \underline{I}^v + \underline{S} * \underline{I}^v = -\underline{M}^{vx} * \frac{d}{dt} \underline{I}^x - \frac{d}{dt} \underline{\Psi} ,$$

where

$$\frac{d}{dt} \underline{\Psi} = \underline{I}_p \underline{v} \underline{M}^{vp} \cdot \frac{d}{dt} \underline{\tilde{R}}_p + \underline{M}^{vp} \frac{d}{dt} \underline{I}_p .$$

Solving the above equation for $d\underline{I}^v/dt$ gives:

$$\frac{d}{dt} \underline{I}^v = -\underline{Q} * \underline{I}^v - \underline{P} * \frac{d}{dt} \underline{I}^x - \underline{I}_p \underline{v} \underline{W} \cdot \frac{d}{dt} \underline{\tilde{R}}_p - \underline{W} \frac{d}{dt} \underline{I}_p , \quad (2)$$

where

$$\underline{Q} \equiv (\underline{M}^{vv})^{-1} \cdot \underline{S} ,$$

$$\underline{p} \equiv (\underline{M}^{vv})^{-1} \cdot \underline{M}^{vx} ,$$

and

$$\underline{w} \equiv (\underline{M}^{vv})^{-1} \cdot \underline{M}^{vp} .$$

At this point the dynamical equations for $\vec{R}_p(t)$ must be specified.

This work assumes that the vacuum vessel fits the plasma close enough to slow down the growth rate of the axisymmetric instability from the poloidal Alfvén time $\tau_A = (\mu_0 \rho_0)^{1/2} a/B_p$, which is on the order of μsec for typical tokamak parameters, to the inductive resistive decay time of the vacuum vessel, $\tau_R = L/R$, which is on the order of msec in TFTR. It has been shown³ under this condition that, to lowest order in $\tau_A/\tau_R \sim 10^{-3}$, the plasma evolves through a sequence of equilibrium configurations.

The equilibrium equations consistent with the large-aspect-ratio plasma filament approximation used here are the following:

$$B_R(\vec{R}_p, t) = -\frac{\mu_0 I}{4\pi R_p} \left[\ln\left(\frac{8R}{a_p}\right) - \frac{3}{2} + \frac{\kappa_i}{2} + \beta_\theta \right] , \quad (3a)$$

and

$$B_z(\vec{R}_p, t) = 0 , \quad (3b)$$

where $\vec{B} \equiv B_R \hat{R} + B_z \hat{z}$ is the toroidally averaged poloidal magnetic field at the plasma position $\vec{R}_p$, due to vacuum vessel eddy currents and external axisymmetric currents. Equation (3a) is the familiar Shafranov formula.⁴

The field $\vec{B}$ is given in terms of the currents by the following expressions:

$$\vec{B}(\vec{R}_p, t) = \vec{G}^V(\vec{R}_p) * \vec{I}^V + \vec{G}^X(\vec{R}_p) * \vec{I}^X, \quad (4a)$$

where

$$\vec{G}^V(x) \equiv \vec{A}^{V(x)} \hat{R} + \vec{B}^{V(x)} \hat{Z}, \quad (4b)$$

The value of $\vec{G}$ for a given loop (k, j) , either vessel or external coil path, is given by the toroidal average of the appropriate vector line integral around path (k, j) ⁵ (see Fig. 2), i.e.,

$$\vec{G}(\vec{R}_p) = \frac{\mu_0}{8\pi^2} \int_0^{2\pi} d\phi \left\{ \oint \frac{d\vec{L} \times (\vec{x}_p - \vec{x})}{|\vec{x}_p - \vec{x}|^3} \right\}, \quad (5)$$

where $\vec{x}_p$ represents a point on the plasma axis and $\vec{x}$ is a point on current path (k, j) .

The plasma equation of motion is obtained by taking the total time derivative of Eqs. (3), using Eqs. (4) to express the magnetic field in terms of external and vacuum vessel currents, and using the circuit equation (2) to express $d\vec{I}^V/dt$ in terms of $d\vec{R}_p/dt$. The resulting equation is:

$$\frac{d}{dt} \vec{R}_p = \frac{\hat{\phi}}{\Delta} \times \{ \omega \vec{a} - \lambda \vec{B} \}, \quad (6)$$

where

$$\Delta \equiv (\hat{R} \cdot \hat{a})(\hat{Z} \cdot \hat{B}) - (\hat{Z} \cdot \hat{a})(\hat{R} \cdot \hat{B}).$$

The quantities $\vec{\alpha}$, $\vec{\beta}$, λ , and ω are explicit functions of $\vec{R}_p$, I^V and t . They are defined as follows:

$$\vec{\alpha} \equiv I_p \vec{\Lambda}^V * \nabla \vec{W} - \vec{I}^V * \nabla \vec{\Lambda}^V - \vec{I}^X * \nabla \vec{\Lambda}^X, \quad ,$$

$$\vec{\beta} \equiv I_p \vec{\Omega}^V * \nabla \vec{W} - \vec{I}^V * \nabla \vec{\Omega}^V - \vec{I}^X * \nabla \vec{\Omega}^X - \frac{\partial h}{\partial R} \Big|_{R_p} \hat{R}, \quad ,$$

$$\lambda \equiv (\vec{\Lambda}^V * \vec{Q}) * \vec{I}^V + (\vec{\Lambda}^V * \vec{P} - \vec{\Lambda}^X) * \frac{d}{dt} \vec{I}^X + \vec{\Lambda}^V * \vec{W} \frac{d}{dt} I_p, \quad ,$$

$$\omega \equiv (\vec{\Omega}^V * \vec{Q}) * \vec{I}^V + (\vec{\Omega}^V * \vec{P} - \vec{\Omega}^X) * \frac{d}{dt} \vec{I}^X + \vec{\Omega}^V * \vec{W} \frac{d}{dt} I_p - \frac{\partial h}{\partial t}. \quad .$$

Here $h(R,t) \equiv (\mu_0 I_p / 4\pi R) [\ln(8R/a) - (3/2) + (\lambda_i/2) + \beta_\theta]$ with the plasma current I_p , self-inductance λ_i , and poloidal beta β_θ all prescribed as functions of time so that plasma disruption effect can be modeled.

Inserting Eq. (6) into Eq. (2) gives the appropriate equation for the vacuum vessel eddy currents, i.e.,

$$\frac{d}{dt} \vec{I}^V = -\vec{Q} * \vec{I}^V + \frac{I_p}{\delta} \hat{\phi} * \nabla \vec{W} * (\omega \vec{\sigma} - \lambda \vec{\beta}) - \vec{P} * \frac{d}{dt} \vec{I}^X - \vec{W} \frac{d}{dt} I_p. \quad (7)$$

Given initial values of $\vec{I}^V$ and $\vec{R}_p$ consistent with Eqs. (3), Eqs. (6) and (7) are integrated in time using the Shampine-Gordon algorithm.⁶

IV. APPLICATION

Two possible variations of the present TFTR magnetic field configuration have been analyzed,⁷ one of which will be discussed below to demonstrate the utility of the present model. The first variation is to reconfigure the

existing poloidal field coils to increase the maximum number of volt-seconds. This configuration has been denoted Mode-D and has the disadvantage that during the start-up phase when I_p is only 0.1 to 0.2 MA, the plasma is elongated and hence is potentially vertically unstable. In the second variation, more extensive coil reconfiguration would be to form a bean-shaped plasma by making use of a new pusher coil which would be mounted inside of the vacuum vessel.

This section presents results from a study of the Mode-D configuration. A particular point in the discharge is chosen which is shown to be vertically unstable on the ideal-MHD time scale when no conducting walls are present, but stable on the ideal-MHD time scale in the presence of the model TFTR vacuum vessel discussed in Sec. II. As discussed in Sec. I, a residual resistive instability persists on the L/R time scale of the vacuum vessel. The resulting vacuum vessel eddy current and plasma trajectory are calculated here.

The plasma current is 0.2 MA, the ohmic-heating current is 24 kA/turn, and the equilibrium-field current is 2.93 kA/turn (see Table I for Mode-D external coil positions and turns). Flux surfaces, obtained by solving the Grad-Shafranov equation using standard techniques, are seen in Fig. 3. The plasma is seen here to have non-circular-shaped cross section with x points nearby. The magnetic axis position is $R_p = 2.76$ meters.

The plasma position and value for $[(\ell_i/2) + (\beta_\theta)]$ obtained from the MHD equilibrium calculation are used in Eq. (6). The minor radius a_p , also used in Eq. (6), is chosen to be consistent with the radial position obtained from the MHD equilibrium calculation. In the result presented here, ℓ_i , β_θ , and I_p are all held constant in time.

The plasma filament is displaced a fraction of a centimeter off the midplane and the vacuum vessel eddy currents are initialized in the eigenstate of the fastest growing mode. This is done by first solving the eigenvalue problem obtained by linearizing Eqs. (6) and (7).

Holding the equilibrium field and ohmic-heating currents fixed in time and integrating Eqs. (6) and (7) gives the resulting plasma positions seen in Fig. 4. Figure 4(a) shows the major radius, $R_p(t)$, staying nearly constant up to about 30 msec. After this point the plasma begins to move inward toward the x point. The time history of the vertical plasma position, $Z_p(t)$, is seen in Fig. 4(b). A calculation of $Z_p^{-1} dZ_p/dt$ reveals that the plasma vertical position is initially increasing exponentially with a growth rate given by the solution to the eigenvalue problem, i.e., $\gamma \approx 85 \text{ sec}^{-1}$. After 30 msec, the value of $Z_p^{-1} dZ_p/dt$ begins increasing with time. This is due to the fact that as the plasma moves toward the x point the external magnetic field curvature is becoming more unfavorable. The plasma trajectory, Z_p vs R_p , is shown in Fig. 4(c) at intervals of $\Delta t = 2.4 \text{ msec}$. The plasma moves up approximately 18 cm in 50 msec.

The particular vacuum vessel model used in this simulation is the one pictured in Fig. 1(a), i.e., eight thin loops per section. Loop currents were seen to increase in proportion to the plasma vertical displacement, i.e., being smallest at $t = 0$ and increasing monotonically until the simulation was halted at $t = 50 \text{ msec}$. Peak branch and loop currents for all eight branches and loops in three of the thirteen stainless-steel sections are listed in Table II.

Branch currents are defined to be the current flowing in a given toroidally directed path and are given by the difference between adjacent loop currents. The currents flowing through the rib sections, i.e., the poloidally

directed paths adjacent to the bellows sections, are given by the loop currents. Branch #1 is the toroidally directed path on the midplane, on the inboard side of the vacuum vessel. Subsequent branches are numbered in order across the top of the vessel, moving from the inboard to the outboard side, and then returning across the bottom of the vessel, from the outboard to the inboard side. Loop currents are indexed in a similar manner.

Stainless-steel Section #1 corresponds to the largest section seen in Fig. 1. Subsequent sections are numbered in order with increasing toroidal angle, i.e., counterclockwise in Fig. 1. Section #4 is seen to be one of the smaller sections and Section 8 is one of the intermediate-sized sections.

Peak eddy current amplitudes are seen to be proportional to the size of the section. Eddy currents in the toroidally directed paths are largest at the top of the vacuum vessel, i.e., the point on the vessel toward which the plasma is moving. Eddy current amplitudes in the poloidally directed rib sections are maximum on the inboard and outboard sides, i.e., where the vacuum vessel crosses the midplane.

The currents given in Table II can be used by a code which calculates the total horizontal and vertical forces and which calculates the torque on the vacuum vessel, given the eddy currents and externally applied magnetic field.

The above simulation was repeated with the 16-loop model pictured in Fig. 1 (b). Neither the growth rate γ , the plasma trajectory, or the peak vacuum vessel eddy current density changed significantly from the results presented for the 8-loop model.

V. SUMMARY AND CONCLUSIONS

A method has been described for calculating TFTR vacuum vessel eddy currents self-consistently with the two-dimensional trajectory of a plasma filament moving on the inductive/resistive time scale of the vessel. The

vacuum vessel model is in general nonperiodic and consists of a set of closed filamentary loops whose positions, orientations, and resistivity are chosen to represent the dominant eddy current paths which form in response to axisymmetric plasma instabilities and plasma disruptions. Equations of motion for the horizontal and vertical position of the plasma magnetic axis are obtained by taking the total time derivative of the equilibrium equation for a large-aspect-ratio plasma filament. This gives an excellent approximation to the plasma motion when the vacuum vessel is close enough to slow down the growth rate of axisymmetric modes from the poloidal Alfvén time to the L/R time of the vessel.

This model has been designed to give an estimate of the peak forces on a nonperiodic vacuum vessel which would occur in a tokamak if the plasma disrupts or if the external magnetic field curvature is unfavorable by design and active feedback control is somehow lost. It has been applied in Sec. IV to calculate eddy currents and the plasma motion for a mode of operation which is being analyzed for TFTR. Peak eddy currents calculated here can be used by a magnetics force code to obtain local forces on the vessel.

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TABLE I.
MODE-D COIL SYSTEM

	<u>R (meters)</u>	<u>Z (meters)</u>	<u>Turns</u>
Equilibrium Field	2.480	± 2.169	~ 9
	3.879	± 1.947	~ 14
	4.881	± 0.809	~ 26
<hr/>			
Ohmic-heating	0.667	± 0.245	100
	0.670	± 0.769	40
	0.780	± 0.802	7
	0.816	± 0.835	2
	0.755	± 1.013	71
	0.911	± 0.986	4
	0.925	± 1.067	11
	0.982	± 1.094	2
	1.198	± 1.586	26
	1.604	± 1.842	18
	3.880	± 2.086	6
	5.000	± 0.710	2
	0.717	± 1.465	27
	1.605	± 2.020	15
	2.333	± 2.296	4
	5.000	± 0.875	3
	1.604	± 2.189	17

TABLE II.

PEAK VESSEL CURRENTS (kA).

		SECTION #		
		1	4	8
BRANCH #	1	0.0	0.1	0.0
	2	-2.1	-0.9	-1.6
	3	-3.6	-2.2	-3.0
	4	-1.2	-0.8	-1.0
	5	1.5	1.1	1.4
	6	2.3	1.4	2.0
	7	2.0	0.9	1.5
	8	1.1	0.4	0.8
LOOP #	1	-3.2	-1.6	-2.5
	2	-1.1	-0.7	-0.9
	3	2.5	1.5	2.1
	4	3.7	2.3	3.2
	5	2.1	1.2	1.8
	6	-0.9	-0.2	-0.2
	7	-2.2	-1.2	-1.7
	8	-3.3	-1.5	-2.5

FIGURE CAPTIONS

FIG. 1. Top view of nonperiodic vacuum vessel models with 8 thin loops per section in (a), 16 thin loops in (b), and 16 thick loops in (c).

FIG. 2. Geometry used for magnetic field calculation.

FIG. 3. Flux surfaces for $I_p = 0.2$ MA in TFTR Mode-D operation.

FIG. 4. Plasma filament trajectories.

#85T0254

Fig. 1

#85T0328

Fig. 2

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Fig. 3

Fig. 4

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