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COUPLING BETWEEN ANGULAR DEFLECTION AND EDDY CURRENTS IN THE FELIX PLATE EXPERIMENT

by

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COUPLING BETWEEN ANGULAR DEFLECTION AND EDDY CURRENTS IN THE FELIX PLATE EXPERIMENT

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ABSTRACT

For a conducting body experiencing superimposed changing and steady magnetic field, for example a limiter in a tokamak during plasma quench, the induced eddy currents and the deflections resulting from those eddy currents are coupled. Experimental study of these coupled deflections and currents can be performed with the FELIX (Fusion ELectromagnetic Induction eXperiment) facility nearing completion at ANL. Predictions of the coupling are described, as computed with the code EDDYNET, which has been modified for this purpose. Effects of the coupling will be readily observable experimentally.

In the FELIX plate experiment, the coupling between deflection and eddy currents was readily calculated because the rigid-body rotation of the plate is equivalent to a contrarotation of the applied magnetic fields. For a geometry such as a plasma limiter, in which the eddy currents would cause a deformation of the conducting body, an analysis of the coupling between eddy currents and deformation would require a structural-analysis code and an eddy current code to be simultaneously computing from the same mesh.

I. INTRODUCTION

In a tokamak changes in magnetic fields produce changing magnetic fluxes through conducting materials within the fields. Thus eddy currents are induced in components such as the plasma limiter and the first wall. These currents are typically large and can produce effects such as electrical arcing and, through the interaction of their magnetic moments with the magnetic fields, large mechanical forces, potentially damaging to the reactor.

The Fusion ELectromagnetic Induction eXperiment (FELIX) facility is being built at Argonne National Laboratory for the study of such electromagnetic effects in the first wall, blanket, and shield (FWBS) of fusion reactors. One of the goals of this experimental program is the validation of computer codes which can predict electromagnetic effects in FWBS systems, the predictions of which can be verified with data from FELIX.

The first FELIX experiments are to study eddy current effects in flat plates, the simplest geometry to simulate with computer codes and the simplest to provide diagnostic instrumentation. The first test object will be a 1-cm thick rectangular aluminum plate, 1.0 m by 0.8 m in size. For these first experiments the FELIX facility will be able to provide a steady solenoidal field of up to 1.0 T and a pulsed dipole field of 0.5 T.

II. MODELING THE FELIX PLATE EXPERIMENT

The effort to model the eddy current effects in the FELIX plate experiment began with the application of the computer code EDDYNET, which solves eddy current problems by approximating the conducting surface with a mesh of conducting lines. The currents, fields, temperature distributions, forces, and torque to be expected in the plate have been computed with EDDYNET, under the assumption that the plate would remain stationary within the fields.[1] The torques which act on the plate are caused by the interaction of the magnetic moments from the induced eddy currents with the solenoid field. These torques are significant and are expected to cause angular deflection of the plate within the magnetic fields.

The angular deflection of the plate within the fields will cause the conducting surface to cut the field lines of the solenoidal field, and the plate's motion will thus add another changing flux to that of the decaying dipole field. Because the eddy currents and the angular deflection of the plate interact in this way, they must be analyzed together. This paper describes an analysis of their interaction. Cecchi[2] has pointed out that this coupling between eddy currents and deflection can significantly modify the eddy current forces expected on a tokamak limiter.

III. THE EDDYNET CODE

As mentioned above, the EDDYNET code solves eddy current problems by a network approach, modeling the conductor with a quadrilateral wire mesh (only the two-dimensional version is considered here).[3] The currents around each loop of the mesh are treated as the independent variables. The sum of the four resistive voltage drops around the sides of one quadrilateral loop must equal the emf around the loop. The emf is due to the change in applied magnetic flux through the loop and the changes in flux due to all of the other loop currents. Because the equation for the current in each loop involves the current in all of the other loops, the method of solution is considered as an integral method. The equation which must be solved for each loop i at each time step Δt can be written

$$\sum_j (G_{ij} + R_{ij}\,\Delta t)\Delta I_j = -\Delta\phi_{app,i} - \sum_j (R_{ij}\Delta t)I_j \ , \qquad (1)$$

where I_j is the current in loop j at the beginning of the time step, ΔI_j is the unknown change in the loop current during Δt, $\Delta\phi_{app,i}$ is the change in applied flux through the loop, and G_{ij} is the mutual inductance of loops i and j. R_{ij} is the matrix of resistances. When $i = j$, R_{ij} is the sum of the resistances of the lines making up the four sides of the loop, but because each line current is the difference of two loop currents there will be other nonzero elements in R corresponding to the four neighboring loops.

EDDYNET consists of four separate programs. The first is a standard quadrilateral mesh generator program. Symmetry may be used here to reduce the number of unknown loop currents. For the FELIX plate experiment, reflection symmetry about the x and y axes is permitted. The second program calculates the matrices R_{ij} and G_{ij} for each loop and adds them to obtain the left-hand side of Eq. (1). The left-hand side matrix is then inverted by the third program, and the results of these three programs are stored in temporary files.

The fourth program, called MOVIRECT, reads these files and for specified applied fields as a function of time calculates at each time increment the flux changes $\Delta\phi$ through all the loops and the resulting changes in the loop currents ΔI of Eq. (1). Only this fourth part of the code needed to be modified in order to compute the angular deflection of the plate and the eddy currents simultaneously.

IV. INTERACTION OF CURRENT AND DEFLECTION

The angular deflection of the plate to be expected in the FELIX experiment and the eddy currents circulating in the plate are mutually coupled.

The deflection θ of the plate affects the currents through the change in applied magnetic flux. In the EDDYNET model for the plate experiment

$$\Delta\phi_{app,i} = A_i \Delta\left(B_y \cos\theta - B_x \sin\theta\right) ,$$

where A_i is the area enclosed by the loop.

The current in the loop affects the deflection θ through its magnetic moment $\mu_i = I_i A_i$. Since the direction of the magnetic moment vector is in all cases perpendicular to the plate, the magnetic moment for the entire plate can be found from

$$\mu = \sum_i I_i A_i .$$

The magnetic moment interacts with the magnetic fields to produce a magnetic torque on the plate given by

$$N_z = -\mu\left(B_x \cos\theta + B_y \sin\theta\right) .$$

The plate also experiences a mechanical restoring torque of $-K\theta$ due to its mounting, where K is the torsion constant of the mounting. The angular deflection thus obeys the equation

$$I_m d^2\theta/dt^2 = -K\theta - \mu\left(B_y \sin\theta + B_x \cos\theta\right) , \qquad (2)$$

where I_m is the moment of inertia of the plate (and its mounting).

V. MODELING CURRENT AND DEFLECTION

The simultaneous computer modeling of both eddy currents and angular deflection in the FELIX plate experiment was first done with a separate computer program written specifically for that purpose. This program modeled the flat plate with a hollow toroid with a single circulating current path. The program used both analytical approximations and a numerical method to solve the differential equations describing the current and the deflection. Values input to the program allowed for modeling of different L/R time constants for the current and different values of the torsion constant for the plate's angular motion. This program's results gave an approximation of the magnitudes of the currents and angular motion to be expected and of the time scale of their rise and decay.

To allow EDDYNET to simultaneously model both current and deflection, the MOVIRECT portion of the code had to be modified to calculate the deflection θ at each time interval and to represent its interaction with the eddy currents in the various loops. The first necessary modification was to have the program read in values for variables with which it had not previously been concerned, including the intensity of the solenoidal field and the torsion constant. The program was also modified to read in the values of the initial intensity of the dipole field and its time decay constant as input, rather than defining them within the program. A run of the first three parts of the EDDYNET code creates the necessary files for modeling a plate with a particular L/R time determined by the values input to the program. Thereafter, only the MOVIRECT portion of the code need be run for modeling different field strengths and torsion constants.

It was decided to interleave the θ time steps and the current time steps, and to consider θ constant for the calculation of current changes and the currents constant for the calculation of changes in θ, a good approximation for small enough time steps.

The only important change to the current calculation portion of the program was in the function which gives the magnetic field passing through the loops of the mesh. The value of this function had to be changed from simply $B_y(t)$ to $B_y(t) \cos \theta - B_x \sin \theta$ to account for the angular position of the plate.

To allow for the computation of θ, it was necessary to calculate the magnetic moment μ of the plate for each current time step. This was done simply by adding together all of the magnetic moments of the individual loops and multiplying the total by four, to account for the fact that the loops represent only one fourth of the surface of the plate because of the reflection symmetry being utilized.

For the computation of θ, an attempt was first made to solve Eq. (2) analytically over a time step. This approach, however, yielded unphysical results, through accumulating round-off error. Thus the computation of θ was performed instead using a numerical "predictor-corrector" method, which had been successful in the simple toroid model.

This method entailed calculating $d^2\theta/dt^2$ at the beginning of each time step from Eq. (2). This value and the value of $d\theta/dt$ at the beginning of the interval were then used to predict the values of θ and $d\theta/dt$ for the end of the time step. The mean of the old value of $d\theta/dt$ and its predicted new value were used to calculate θ, and the value of $d^2\theta/dt^2$ was predicted for the end of the time step, with the mean of its beginning and end values used to compute $d\theta/dt$.

The program outputs the value of θ for each time step, along with the current which, running along the plate's perimeter, would give a magnetic moment equivalent to that due to the eddy currents.

VI. RESULTS AND CONCLUSIONS

The modified EDDYNET code was able to provide a reasonable and realistic model of the development with time of both eddy currents and the angular motion of the plate. The program predicts that eddy currents and angular motion arise and decay as expected, and that the deflection and currents are coupled. Figures 1 to 4 are graphs of the output of the adapted EDDYNET program for four different cases.

The program predicts that torques acting on the plate will be large, and thus the torsion constant provided by the plate's mounting must be large in order to keep the deflections reasonably small. The value of the torsion constant used in all four cases shown, 116.08 kN m/rad, is the value predicted to give a nominal deflection of 5 deg for the simple toroid model with L/R time constant 48 ms and solenoid field 0.1 T.

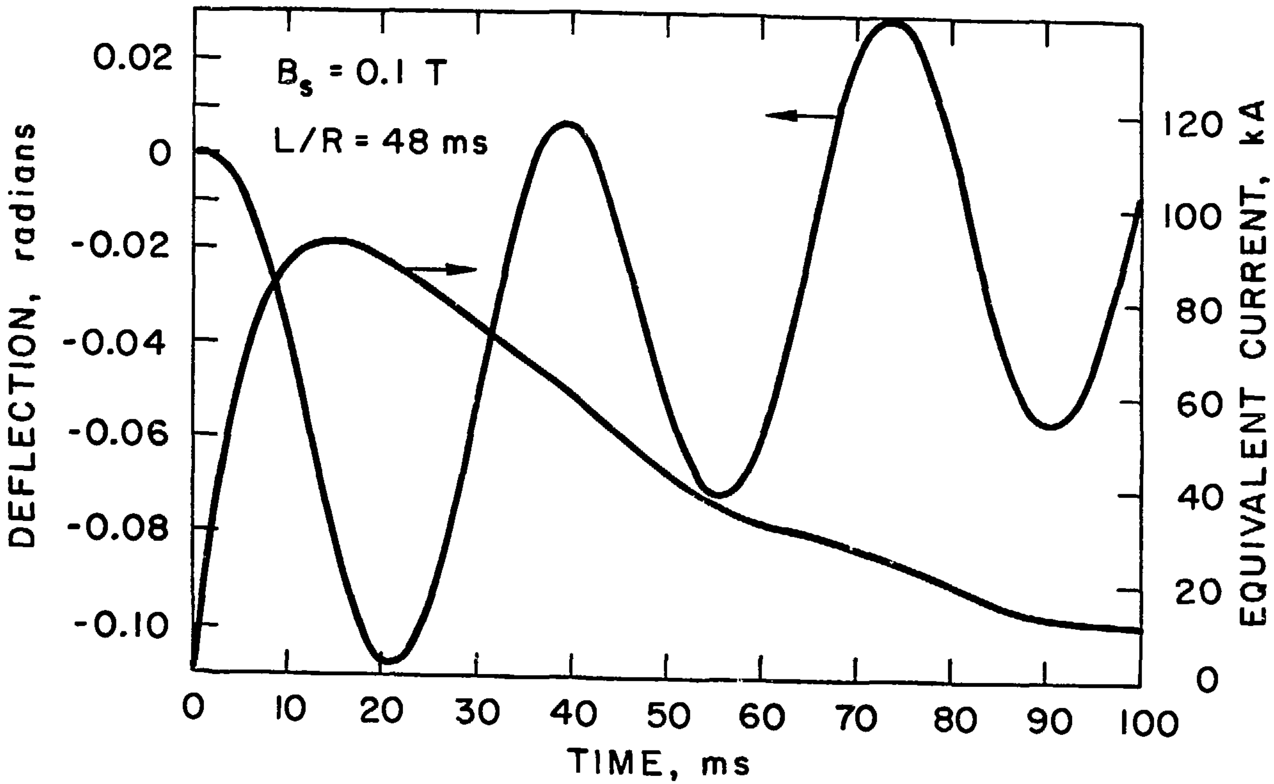

Fig. 1. Deflection and equivalent eddy current in the FELIX plate experiment for a dipole field of 0.5 T decaying in 10 ms, a steady solenoidal field of 0.1 T, a plate L/R time of 48 ms, and a restoring torsional constant of 116.08 kN·m/rad. The plate oscillates about a time varying equilibrium angle which returns to zero as the current decays. Ripple in the current due to the plate oscillations is small but noticeable.

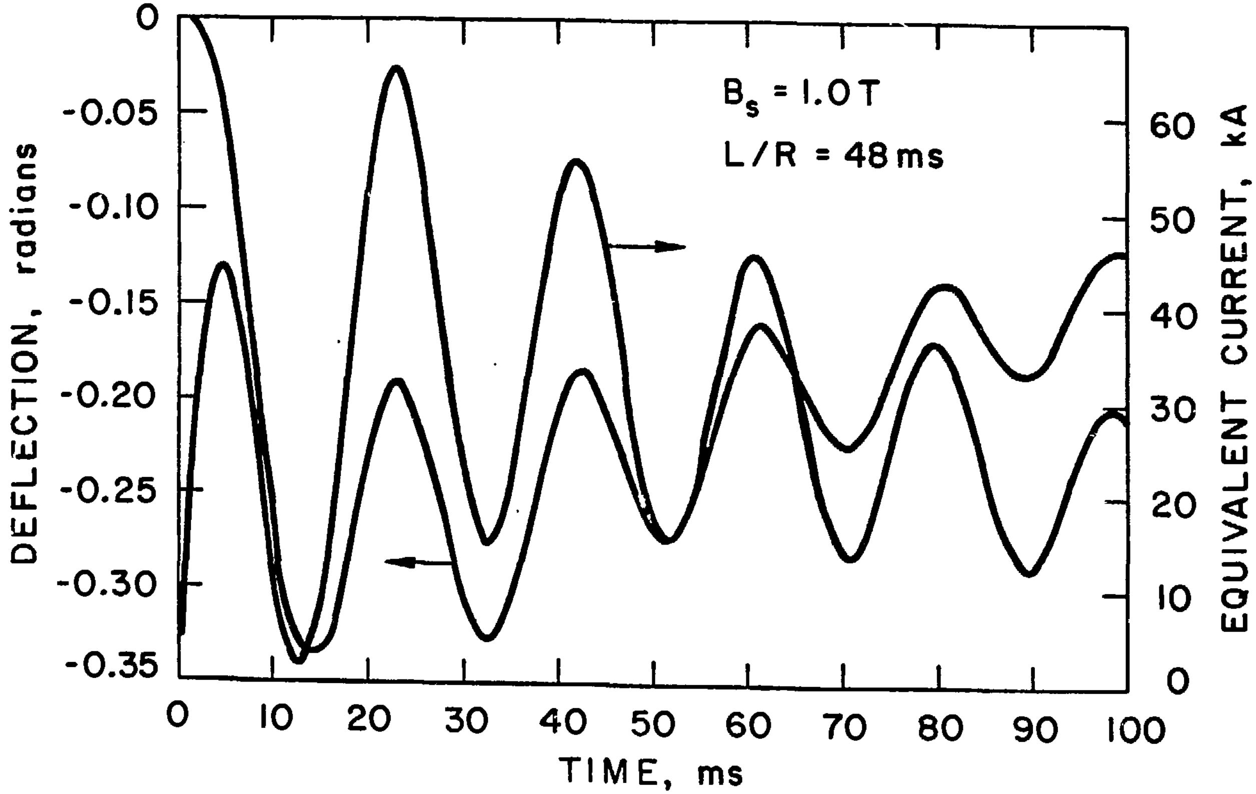

Fig. 2. Deflection and equivalent eddy current in the FELIX plate experiment for a solenoid field of 1.0 T and all other parameters the same as in Fig. 1. Peak current is much reduced; current ripple is large, and the peak deflection is increased by a factor of only 3.1 for a solenoid field increase by a factor of 10.

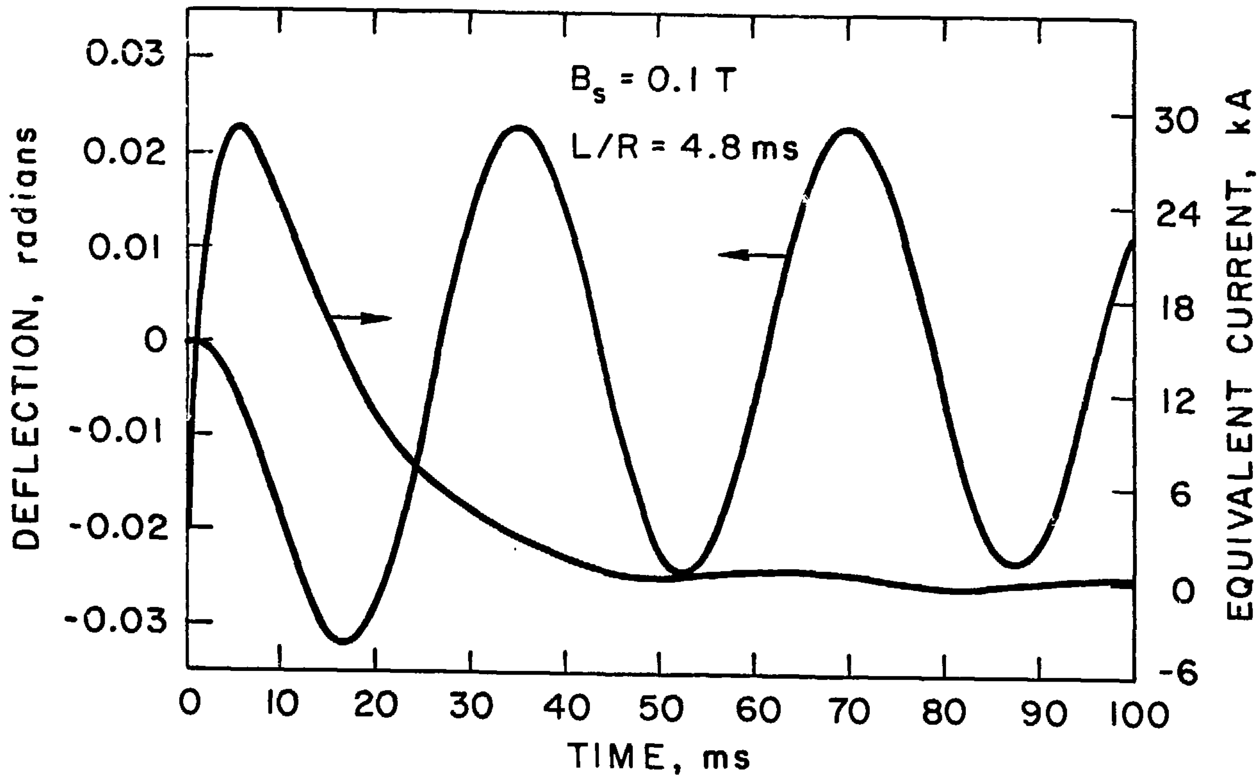

Fig. 3. Deflection and equivalent eddy current in the FELIX plate experiment for a dipole field of 0.5 T decaying in 10 ms, a steady solenoid field of 0.1 T, a plate L/R time of 4.8 ms, and a restoring torsional constant of 116.08 kN•m/rad.

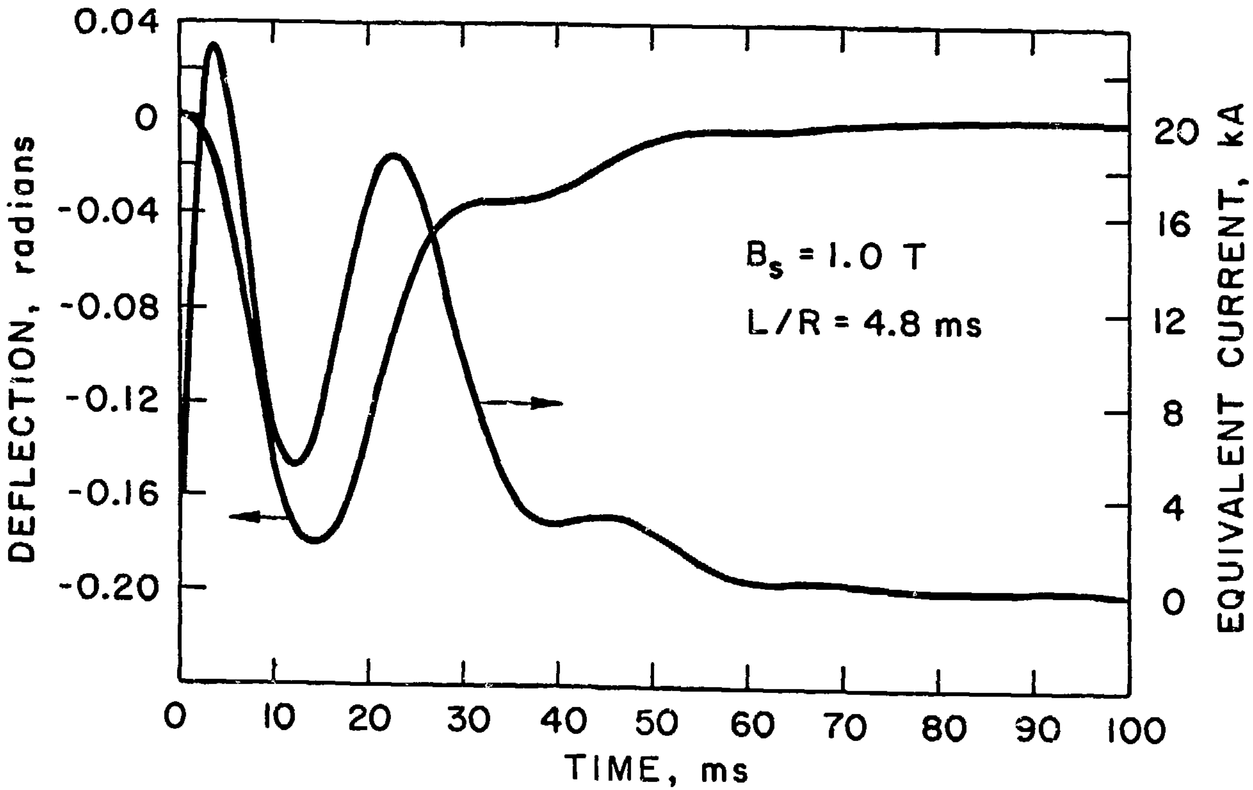

Fig. 4. Deflection and equivalent eddy current in the FELIX plate experiment for a solenoid field of 1.0 T and all other parameters the same as in Fig. 3. Oscillations are rapidly damped out.

The four figures show the results for an initial field B_y of 0.5 T decaying exponentially with a time constant of 10 ms, with steady solenoidal fields of 0.1 T and 1.0 T for each of two L/R times. Figures 1 and 2 represent the initial FELIX test plate, with an L/R time of 48 ms, as predicted by EDDYNET, while Figs. 3 and 4 represent a plate with a time constant of 4.8 ms.

The interaction of the currents and the deflection of the plate is clearly evident from the graphs. If there were no interaction the equivalent current would decay smoothly from its peak value to zero, without the oscillations which appear in the graphs. Another effect of this interaction, which the graphs do not show, is a slightly higher frequency in the angular motion of the plate than would be found were there no interaction. This is because the eddy currents themselves provide some additional "stiffness" to the motion of the plate.

The four graphs show predictions for the effects of different L/R times and solenoidal field strengths on the behavior of the plate. The cases with the longer L/R time show a much higher current peak and, of course, a much longer time for the currents to decay. The longer L/R time also gives a significantly greater peak deflection of the plate, and a much longer time for the decay of the angular motion (a more pronounced effect for the higher field in Figs. 2 and 4).

The difference shown between the cases with a 1.0 T solenoidal field and the 0.1 T cases include a much greater peak deflection for the higher field. Here again the effects of the current-deflection interaction appear, as the peak deflection would be expected to be ten times as great for ten times the field intensity if there were no interaction. However, in the cases shown the increase in peak deflection is by a factor of only 5.7 for the shorter L/R time and only 3.2 for the longer. The higher field strength also gives a much shorter time for the decay of the plate's angular motion (more pronounced for the short L/R time of Figs. 3 and 4) and a greater frequency of oscillation, again due to the greater magnetic "stiffness" provided. Finally, the cases with the higher field also show a lower peak current, but a longer time for the currents' decay, consistent with the fact that the same amount of magnetic energy is dissipated in the plate in each case.

In conclusion, the predictions of the adapted EDDYNET code show that the interaction of the angular motion of the plate and the induced eddy currents is significant, and will be observed in the actual performance of the FELIX plate experiments. Results of the these experiments will prove useful in predicting the eddy current forces on a tokamak limiter which can deflect in response to the forces.

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