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EXPERIMENTAL STUDY OF COUPLING BETWEEN EDDY CURRENTS AND DEFLECTIONS IN CANTILEVERED BEAMS AS MODELS OF TOKAMAK LIMITERS*

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The coupling between eddy current and motion in a cantilevered beam is examined. The beam, which provides a simple model for the limiter blades of a tokamak fusion reactor, was subjected to simultaneous orthogonal time-varying and constant magnetic fields. The dynamic deformation of the beam includes two different modes: a bending mode and a torsional mode. Interaction of current with each mode and with the combined modes of vibration is described. Experimental verification for the case without torsional motion was performed with the FELIX facility at ANL. The peak deflection and stresses are much less than those predicted without consideration given to the coupling.

1. INTRODUCTION

During plasma disruptions in a tokamak reactor, eddy currents are induced in the limiters and other conducting structures surrounding the plasma. The eddy currents, through interaction with the applied toroidal and poloidal magnetic fields, produce large mechanical torques and forces that deflect the structural components. Such undesired deformations and the resulting electromagnetic stress may compromise the integrity of the structures.

Fortunately, an important coupling effect between deflection and eddy currents can mitigate the potential damages to the structure. This coupling occurs when, as it deflects, the component intercepts additional magnetic flux. The structural motion in strong magnetic fields induces additional eddy currents opposing the initial eddy current and modifying subsequent structural dynamics. Experiments [1] on the magnetic coupling in rigid body rotation were performed by a team of investigators from Princeton Plasma Physics Laboratory and Argonne National Laboratory (ANL) with the FELIX (Fusion ELectromagnetic Induction eXperiment) facility [2,3] at ANL. Analyses [4,5] and experiments [5] on the coupling between current and lateral deflection (beam bending) in a cantilevered beam have been performed previously. The results of these experiments [5,6] showed that the coupling between deflection and eddy current could reduce the peak current, deflection and other electromagnetic effects to a level for less severe than would be predicted if coupling is disregarded.

In this study the analysis for a cantilevered beam is extended to include torsional motion. In general, the beam vibrates faster in torsional mode than in bending mode, coupling between current with torsional motion may affect lateral deflection. This paper also presents the experimental results for the case without torsional motion. The beam was clamped rigidly at one end and subjected to simultaneous time-varying and constant magnetic fields. The time-varying field simulates the decaying field during a plasma disruption and the constant field models the toroidal field. The constant to time-varying field ratios were kept in a range of 10:1 to 20:1 as would be appropriate to tokamak limiters.

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2. ANALYSIS

The basic configuration of the problem is illustrated in Figure 1. The time-varying field, B_y, is perpendicular to the beam. The constant field, B_s, is in the xz plane, at an angle θ_0 with the x-axis (i.e., with the beam direction). The time-varying field induces eddy current in the beam. Current in paths parallel to the z direction interacts with the field B_x, the x component of B_s, and produces a Lorentz force that causes lateral beam deflection in the y direction. Meanwhile current in paths parallel to the x direction interacts with the field B_z, the z component of B_s, and produces a torque that causes torsional motion about the x-axis.

For the purpose of analysis, the current induced in the beam is characterized by a single current loop. The beam has two perpendicular axes of symmetry and consequently the equations of free lateral and torsional motion are uncoupled. However, both equations are coupled to the current making them indirectly coupled to each other.

The governing equations for the lateral deflection $W(x,t)$, the angle of twist $\Psi(x,t)$ and the current I can be formulated as follows:

$$EI_y \frac{\partial^4 W(x,t)}{\partial x^4} = p(x,t) - m \frac{\partial^2 W}{\partial t^2} - c \frac{\partial W}{\partial t} \tag{1}$$

$$\frac{\partial}{\partial x} \left(KJG \frac{\partial \Psi(x,t)}{\partial x} \right) - \rho J \frac{\partial \Psi}{\partial t} = q(x,t) \tag{2}$$

$$L \frac{dI}{dt} + RI = - \frac{d\phi}{dt} \, . \tag{3}$$

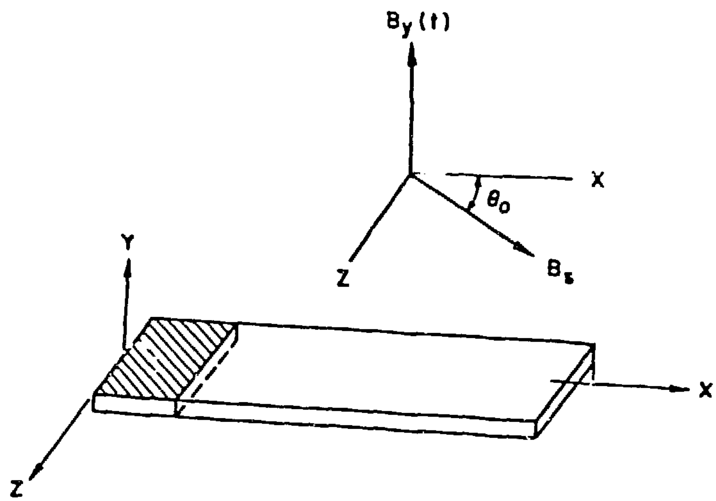

Fig. 1. Schematic of cantilevered beam and magnetic fields direction. The solenoid field is at an angle with the beam axis

where E is the Young's modulus, G is the modulus of rigidity, I_y and J are the rectangular and polar moment of inertia, KJ [7] is the torsional constant, ρ is the mass density, m is the mass per unit length and c is the mechanical damping constant.

The flux ϕ intercepted by the beam has three contributions: one from the decaying field B_y, the other two from the constant fields B_x and B_z. Assuming small deflection and small angle of twist for a beam of length ℓ, we have:

$$\phi = - A_t B_y + \frac{AB_x}{\ell} \int_0^\ell \frac{\partial W}{\partial x} dx + \frac{AB_z}{\ell} \int_0^\ell \Psi dx \quad (4)$$

A_t and A are the effective total area and unclamped area of the beam. The effective loop resistance R, inductance L, and area of a rectangular plate were determined empirically [8] using the SPARK [9] code to match the decay time constant, total current and net torque.

The distributed Lorentz force p(x,t) and the distributed torque per unit length q(x,t) are given by

$$p(x,t) = - \frac{A\ B_x}{\ell} I(t)\ \delta(x-\ell) \quad (5)$$

$$q(x,t) = - \frac{A\ B_z}{\ell} I(t) \quad (6)$$

In this model, B_y decays exponentially from some initial value B_0 with decay time constant τ_d.

3. EXPERIMENT

Experiments were performed for the case $\theta_0 = 0°$ (i.e., $B_z = 0$, no torsional motion). In the experiment, B_y is called the dipole field and B_x is called the solenoid field. The test beams were made of copper, 6061-aluminum, phosphor bronze, and brass. They were 48.7 cm long, 10 cm wide and 2.4 to 4.6 mm thick. Dipole field strengths of 34 mT and 55 mT were used, with decay time constants of 6.6 ms, 11.6 ms, and 21.0 ms. The solenoid fields were 0 T, 0.2 T, 0.5 T, 0.7 T, and 0.9 T.

Several parameters were measured as functions of time at a data sampling rate of 1000 Hz. Beam deflection was measured at the free end and near mid-beam using a non-contact electro-optical device. Strains were measured near the clamped end and at mid-beam using strain gauges. A Rogowski coil linked through a central hole 2.54 cm in diameter to measure the eddy current. Magnetic fields were monitored by Hall probes.

4. ANALYTICAL AND EXPERIMENTAL RESULTS

The results presented here are for an aluminum beam. Its length, width, and thickness are 48.7 cm, 10 cm, and 3.175 mm, respectively. The beam was clamped at 7.6 cm from one end to form a cantilever. The property parameters are $E = 6.89 \times 10^{10}$ N/m, $G = 2.6 \times 10^{10}$ N/m, $\rho_e = 3.95 \times 10^{-8}$ Ω·m, $\rho_m = 2713$ kg/m^3.

4.1 Purely Bending Mode, $\theta_0 = 0°$

When $\theta_0 = 0$, $B_x = B_s$ and $B_z = 0$. Deflection at the end of the beam and total current are shown in Figs. 2 and 3 for $B_x = 0.2$ T and 0.9 T, respectively. The dipole field was initially 55 mT, and decayed exponentially with a time constant of 6.6 ms. Experimental results are shown in dots, analytical results are shown in solid lines.

In Fig. 2 the coupling between current and deflection was weak. The beam oscillated at its natural frequency, and the current decayed smoothly with only small perturbation due to deflection. In Fig. 3 the coupling effect was pronounced because of the higher solenoid field. The total current decayed faster, and a second peak in current was observed. After a first swing, the beam slowly returned to rest at the equilibrium position. Note from Figs. 2 and 3 that the peak deflection increased by a factor of 2.1 when the solenoid field increased 4.5 times. Without current-deflection coupling, the peak deflection would be expected to increase linearly with field intensity, and the current would decay smoothly to zero after reaching a peak value.

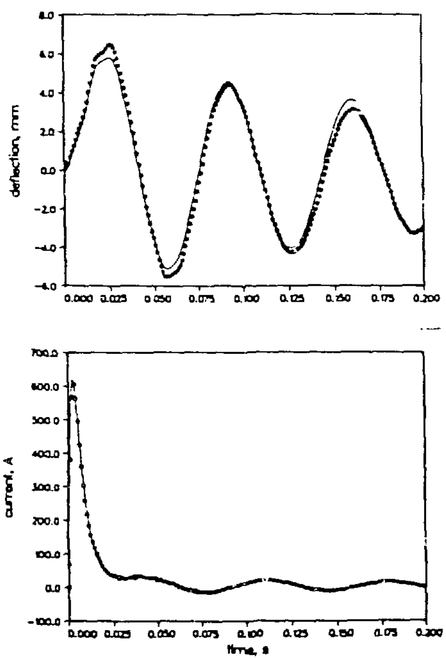

FIGURE 2.
End deflection (top), current (bottom), in an aluminum beam. $B_x = 0.2$ T, $B_0 = 0.055$ T, $\tau_d = 6.6$ ms. Solid lines are analytical results.

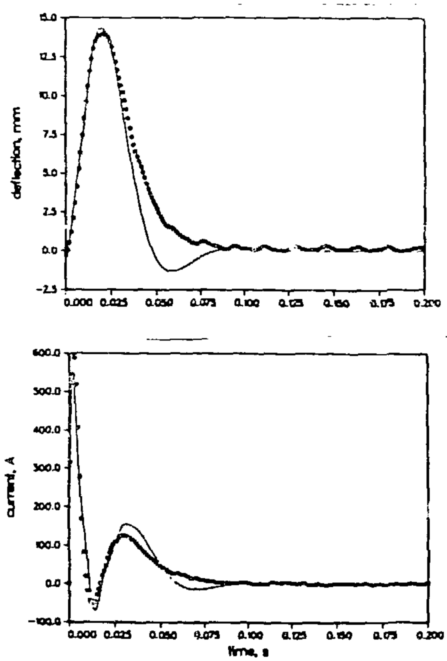

FIGURE 3.
End deflection (top), current (bottom), in an aluminum beam. $B_x = 0.9$ T, $B_0 = 0.055$ T, $\tau_d = 6.6$ ms. Solid lines are analytical results.

4.2 Purely Torsional and Combined Modes; $\theta_0 > 0$

In general the torsional vibration period is several times smaller than the lateral deflection period (9.4 ms and 65.4 ms, respectively for the beam studied), therefore the interaction between current with torsional motion will occur more rapidly than with lateral deflection. As a result, for a same range of the field B_s, coupling is more intense with the purely torsional mode. In the combined modes if B_z is large enough to produce strong coupling, the current could be quickly damped out, consequently reducing the magnitude of the force that causes lateral deflection. Shown in Fig. 4 is an example for B_s = 0.9 T and θ_0 = 60° (B_x = 0.45 T, B_z = 0.78 T). The peak deflection (10 mm) is substantially less than the peak (14.5 mm) calculated for the same value of B_x when B_z is zero.

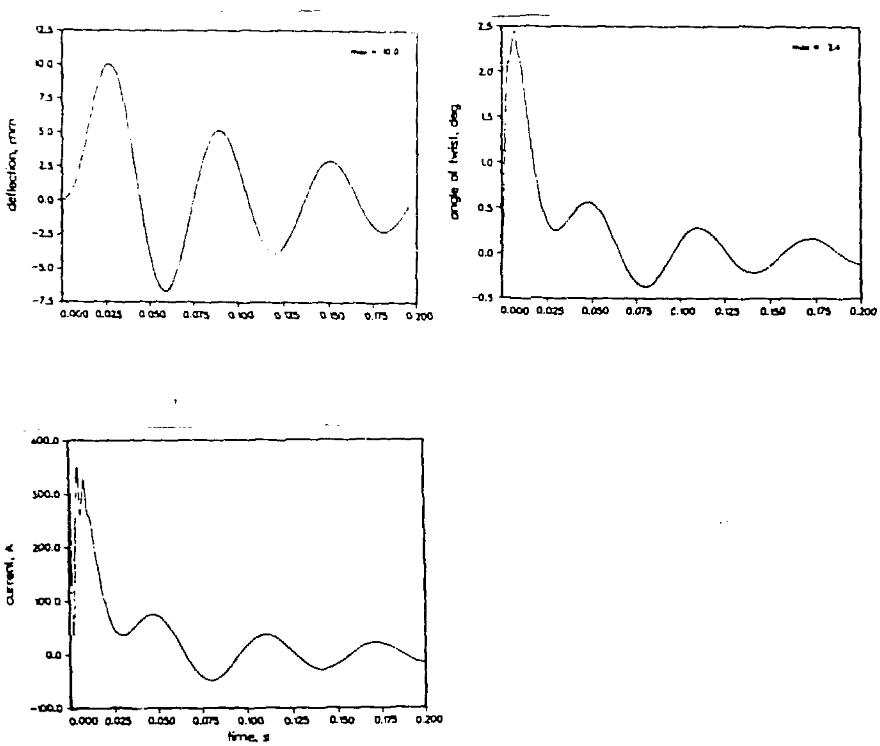

FIG. 4. Deflection (top left) and angle of twist (top right) at the end of the beam, and current (bottom left) in combined modes of motion for θ_0 = 60°, B_s = 0.9 T, B_0 = 0.055 T, and τ_d = 6.6 ms.

5. CONCLUSIONS

Analysis and experiments have shown that the coupling between current and deflection in a cantilevered beam is an important effect. Results showed that the coupling effect could reduce current, deflection and therefore stresses below the levels which were calculated without considering the coupling. In general, coupling with the combined lateral and torsional mode of motion could further reduce lateral deflection more than coupling with lateral motion alone. In a fusion reactor with large magnetic fields a limiter designed with consideration given to coupling will be decidedly less costly.

REFERENCES

[1] Weissenburger, D. W., et al., "Experimental Observations of the Coupling Between Induced Currents and Mechanical Motion in Torsionally Supported Square Loops and Plates," Princeton Plasma Physics Laboratory, PPPL-2158 and PPPL-2159 or Argonne National Laboratory, ANL-FPP-84-2 and ANL-FPP-84-3 (1984).

[2] Praeg, W. F., et al., "FELIX, An Experiment Facility to Study Electromagnetic Effects of First Wall, Blanket and Shield Systems," Proceedings of the 9th Symposium on Fusion Engineering, p. 1763, Chicago, IL (1981).

[3] Praeg, W. F., et al., "FELIX: Construction and Testing of a Facility to Study Electromagnetic Effects for First Wall, Blanket and Shield Systems," Proceedings of the 10th Symposium on Fusion Engineering, p. 186, Philadelphia, PA (1983).

[4] Bialek, J. and Weissenburger, D. W., "The Coupling of Mechanical Dynamics and Induced Currents in a Cantilevered Beam," Princeton Plasma Physics Laboratory, PPPL-2187 (1985).

[5] Hua, T. Q., et al., "Experimental Modelling of Eddy Currents and Deflection for Tokamak Limiters," Proceedings of the 7th Topical Meeting on the Technology of Fusion Energy, Reno, Nevada (1986).

[6] Hua, T. Q., Nygren, R. E., and Turner, L. R., "Studies of Coupling Between Displacement and Eddy Currents in the FELIX Plate Experiments," Fusion Technology, Vol. 10, 3 (1986).

[7] Willems, N. and Lucas, Jr., W. M., Matrix Analysis for Structural Engineers, p. 338, Prentice-Hall Inc., Englewood Cliffs, NJ (1968).

[8] Bialek, J., et al., "Modelling the Coupling of Magnetodynamics and Elastomechanics in Structural Analysis," Proceedings of the 10th Symposium on Fusion Engineering, p. 51, Philadelphia, PA (1983).

[9] Weissenburger, D. W., "SPARK Version One: Reference Manual," Princeton Plasma Physics Laboratory, PPPL-2040 (1983).