MAGNETOELASTIC STABILITY AND VIBRATIONS
OF SUPERCONDUCTING MAGNETS

Progress Report
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Introduction

The present program on the magnetoelastic stability of superconduction magnets at Cornell University is supported jointly by the National Science Foundation and the Energy, Research and Development Administration. NSF funding started in 1969 in a grant to the principal investigator while he was at Princeton University. ERDA support began in 1974-75. The NSF grant is concerned with basic engineering research on problems in magneto-solid mechanics and has provided laboratory equipment for the experimental problems. The ERDA grant is directed solely to the application to the controlled thermonuclear reactor program, and the development of analytical and computer models to assist magnet designers to avoid lateral deflection problems.

Accomplishments under the 1974-75 grant

The main accomplishments under this grant were;

- a) development of a computer code to predict lateral instabilities of superconducting toroidal field magnets (TF).
- b) experimental observation of a lateral magnetoelastic instability (buckling).

Additional results included the development of a computer program to predict transient vibrations of a coupled set of magnets under earthquake type excitation. These programs were used to analyze the lateral stability of toroidal magnets in a number of reference designs for Tokamak reactors. A number of these designs were found to have insufficient lateral support on the TF magnets. Using our program we have been able to determine the proper amount of lateral support for the structural stability of several TF magnet designs.

Accomplishments and Progress on the present grant 1975-76.

Experimental

- a) We have developed a unique laboratory for simulating buckling and vibration problems in small superconducting models of Tokamak reactor coils.
- b) We have constructed 3 coil and 5 coil partial torus coil sets of both circular and "D" shaped superconducting magnets. The coils are constructed so as to simulate the elastic flexibility of large scale coils. (see Figure 1)
- c) We have successfully observed the decrease of lateral stiffness of superconducting coils with currents up to 10^4 Amp-turns/coil and subsequent lateral buckling of the coils under several lateral support conditions. (Fig. 2,3,4)
- d) In plane buckling of model TF coils has been examined experimentally and was found not to be a problem. (Fig. 2)
- e) The influence of current on the damping of lateral vibrations of superconducting coils has been investigated. (Fig. 5,6)
- f) We have observed thermoelastic buckling of epoxy potted superconducting coils producing significant out of plane deformations due to differences in thermal expansion coefficients.

In progress:

- i) a 16 coil flexible superconducting model torus is being built to test out computer codes for lateral stability and poloidal field excited vibrations in TF magnets, (Fig. 9).
- ii) the dynamic interaction of pulsed poloidal fields and toroidal coils will be studied in a 5 coil partial torus. (Fig. 7)
- iii) Vibrations induced in toroidal field coils by a fault condition in one coil will be studied.

Summary of Experimental Results

I. Magnetoelastic Buckling

As reported in earlier reports a set of toroidal superconducting coils can exhibit a lateral structural instability in which the elastic stiffness is countered by a negative magnetic stiffness due to mutual forces between the current carrying coils. At a critical value of the coil current the combined elastic and magnetic lateral stiffness goes to zero. Experimentally this is manifest by a decreasing natural vibration frequency with increasing current.

As reported in recent papers by Moon and Swanson and Moon (J. Applied Physics, March 1975) magnetoelastic buckling has been observed in experiments on 3 circular coils, 20 cm diameter in a partial torus. In these tests two side coils were held rigid while the center coil is flexible. In additional tests on a three coil set the center coil had both inplane and lateral or out of plane flexibility. As the results show in Figure 2, an increase in current raised the inplane stiffness, while the lateral stiffness decreased to zero at a critical value of the current. Therefore we conclude that an inplane buckling instability in toroidal coil sets appears not to be a problem.

In a new series of tests a five coil superconducting partial torus of a 24 coil set was constructed. The shape of the coils were close to a "D" type magnet wound with 40 turns of NbTi wire potted in epoxy, (Figure 1). With the three center coils flexible, current in all five coils produced an increasing deflection which become very large at a critical value of current (Figure 3). The corresponding natural frequency or lateral stiffness decreased with increase in current as in the

3 coil model (Figure 4). The coils were clamped along the inner or straight part of the "D" and were either free or pinned at the outter radius of the torus.

Comparison of the critical buckling currents with those predicted by Moon and Swanson (J. Applied Physics March 1976) is within 5-8%. This gives further confidence in the conclusions reached in the application of this theory to proposed fusion reactor design in which it was found that a number of advanced magnet designs had insufficient lateral supports.

II. Damping in Superconducting Coils

Since measurement of the natural frequency of the magnet coils is an important technique in the buckling tests, it was natural to investigate the effect of the superconducting currents on the damping of free vibrations. In one series of tests a single 40 turn 20 cm diameter superconducting coil of Nb-Ti wire was vibrated in the lateral direction. Significant increase in damping occurred with increase in coil current as shown in Figure 5.

Two cases were run to determine the contribution to the damping of nearby normal conductors. In one case the two copper exciter coils (approx. 100 gm each) were shorted during the free vibration of the superconducting coil, while in the other these coils were left open. As can be seen in Figure 6, the shorted copper coils, about 2 cm from the test coils, nearly double the damping effect. The other damping contribution is believed to be partly attributed to the stainless dewar and aluminum shielding in the vacuum walls. Calculations are being made to estimate how much the damping is intrinsic to the superconductor material itself.

III. Transient Vibration of a Toroidal Coil by a Pulsed Poloidal Coil

In proposed toroidal fusion reactors there are coils running around the torus which create a vertical or poloidal magnetic fields used to generate the plasma current and stabilize the plasma. The current in the poloidal coils will be pulsed which will produce a torque on the toroidal coils.

Using a single "D" shaped toroidal field coil, and a pulsed coil in a plane perpendicular to the toroidal coil transient vibrations of the flexible "D" coil were measured. The current in the "poloidal" coil ranged from 200-600 A in each of the 8 turns of the coil, with a duration time of from 10-100 msec. The natural period of the flexible coil was approximate 40 msec.

As shown in Figure 7 the maximum deflection increased with pulse duration and is proportional to the product of the currents $I_P I_T$. When the pulse length is longer than the half period of the coil, then the deflection or strain approaches twice the static strain which would occur under steady currents. This curve is known as a shock spectrum.

Further tests of shock spectrum for pulsed poloidal coils near the five coil partial torus are now under way.

Analytical - 1975-76 Program

Our major accomplishment has been to develop an analysis for the magnetoelastic stability of poloidal (equilibrium, and ohmic heating) coils under high superconducting currents. This analysis has led to prediction of a "corkscrew" or helical type instability in these coils when placed in a toroidal magnetic field. We have developed a stability criterion which depends on the toroidal field, poloidal current, elastic stiffness, cross-sectional properties, major radius and lateral support conditions. This instability is more likely when the coils are superconducting (i.e. having minimum lateral support to prevent heat leaks) and when placed inside the toroidal field coils. (see Appendix)

We are currently checking published reference designs of poloidal field coils for such a helical instability. Preliminary calculations of one design shows that the poloidal field coils will buckle in a helical shape without increased lateral support.

Another result of our analytical work has been to calculate the effect of twisting of superconducting filaments in filamentary superconductors. We have found that such twisting produces a magnetic moment on the superconductor when placed in a magnetic field and an increased force when placed in field gradients. It has not been determined at this time if such moment and correction forces due to twisting can be significant compared with the Lorentz force calculated on the basis of an untwisted current elements.

Also in progress is the development of a computer code to calculate the vibrations in the toroidal field magnets due to the pulsed poloidal field coils.

Completed under partial support from both NSF and ERDA is a review of the field of magnetosolid mechanics which includes stress analysis in superconducting magnets, stability of magnetoelastic systems, and eddy current induced stresses in solids. This review will appear in the review journal Mechanics Today published by the American Academy of Mechanics.

Communication of Research Results

Research results on lateral stability have been reported in visits to:

Argonne National Laboratory - F. Moon - 2 visits
spring/summer 1975

Oak Ridge National Laboratory - Magnet Program Review - F. Moon
Sept. 75

6th Symposium on Engineering Problem of Fusion Research - C. Swanson
Nov. 1975

Final Report on 1974-75 program including computer code for lateral stability and vibration sent to major magnet research centers.

Princeton Plasma Physics Labs - F. Moon, March 1975

ERDA (Washington, D.C.) To Review Research Progress - F. Moon
April 1975

Princeton Plasma Physics Lab. - F. Moon
March 1975

ERDA (Washington, D.C.) To Review Research Progress - F. Moon
April 1975

Transmittal of computer codes on magnetoelastic buckling of toroidal coil sets to Dr. W. Stoddard and Dr. Gray of Oak Ridge National Lab. - April 1975

Two articles to appear in March or April issue (1976) of Journal of Applied Physics on Magnetoelastic Buckling of Superconducting magnets.

Research Reports and Publications

under the ERDA-NSF grants

1. Vibration and Stability of a set of Superconducting Toroidal Magnets, F.C. Moon and C. Swanson, Princeton Report - Report No. AMS 1237, June 1975, also Jol. Appl. Phys. Vol. 47, No. 3, pp. 914-919, March 1976.
2. Magneto-Elastic Stability of Toroidal Magnet Designs for Proposed Fusion Reactors, C. Swanson and F.C. Moon, Cornell Report - ERDA(AEC No. AT(11-1)-2493, August 1975, to appear Proc. 6th Symp. on Engineering Problems of Fusion Research, San Diego, Calif. (Nov. 1975).
3. Elastic Stability and Vibration of Toroidal Magnets for Fusion Reactors, F.C. Moon and C. Swanson, Final Report to ERDA, Report No. 1248, September 1975.
4. Buckling of a superconducting coil nested in a three-coil toroidal segment, F.C. Moon, Jol of Appl. Phy., Vol. 47, No. 3, pp. 920-921, March 1976.

Reports in Preparation

1. Buckling and Vibration of a Superconducting Coil in a three-coil Partial Torus, F.C. Moon, C. Swanson.
2. Experiments on Buckling and Vibration of Superconducting Coils in a Five Coil Partial Torus, C. Swanson, F.C. Moon, S. King.
3. Stability of a Circular Superconducting Coil in a Circumferential Magnetic Field, F.C. Moon.

STABILITY OF SUPERCONDUCTING MAGNET SYSTEMS

PERIOD →	71-73	73-74	74-75	75-76	76-77
SPONSERS →	NSF	NSF	NSF- AEC	NSF- ERDA	NSF- ERDA
RESEARCH EFFORT →	1 1/4 Man Yr. Grad. Stu. + Prin. Invest.	1 1/4 G.S.+ P.I.	1 1/2 Post-Doc + P.I.	2 1/4 Post-Doc Techn.+P.I.	2 3/4 + Programmer
Problems in Magneto-Solid Mechanics Theory-Experiments					
Theory - Stability of T.F.* Coils					
Computer Code - of T.F. Coils					
Computer Code - Vibration T.F. Coils					
Experimental Observation of Buckling					
Exp. Verification of Buckling Code					
- / 3 coils / 5 coils / 16 coils					
Exp. Poloidal - T.F. Coil Interaction					
Exp. Damping of Magnet Vibrations					
Theory - Buckling of Poloidal Coils					
Exp. - Buckling of Poloidal Coils					
Dynamic Interaction - Poloidal Coils					
E.P.R.** Buckling Study					

* T.F. - Toroidal Field Magnets.

** E.P.R. - Experimental Power Reactor Program - 1985

Figure 1. Partial Torus with 5 coils each of 40 Turn Niobium Titanium Superconducting Wire used to Simulate Magneto-elastic Buckling.

RESONANT FREQUENCY VS CURRENT

Figure 3. Magneto Elastic Buckling in a 5 Coil Parital Torus.

5 A
TURN

5A closed.

75 A
TURN

75A closed.

150A
TURN

150A closed

Figure 5. Effect of current on the damping of lateral vibrations of a 20 cm diameter, single 40 turn coil NbTi potted in epoxy.

DAMPING vs. CURRENT

Figure 6. Damping of lateral vibrations versus current in a superconducting coil (NbTi) and the effect of a nearby normal copper coil.

Figure 7. Maximum bending deflection due to a pulsed poloidal coil near a toroidal coil with steady current, normalized by the product of currents $I_p I_T$.

Figure 8. Helical Buckling Shape of a Poloidal Coil in a Toroidal Magnetic Field B_T .

1"

Figure 9. Sketch of flexible 16 coil superconducting model torus for magnetoelastic buckling studies.

Appendix

Magnetoelastic Stability of Superconducting Rings in a Circumferential Magnetic Field

by F. C. Moon

Introduction

The potential success of the Tokamak concept of controlled thermonuclear fusion has spawned a number of designs for toroidal magnetic machines of enormous magnitude. Normal conductors, which are used in contemporary plasma devices, would generate intolerable heat losses in these machines and are to be replaced by superconducting magnets. Such materials, operating in liquid helium, must be thermally isolated from the warm environment. The combination of enormous size and minimum supports creates relatively flexible structures. Further the magnetic field requirements result in total currents of the order of megamperes, creating forces which will produce stresses in the coils approaching their yield limits. This combination of elastic flexibility and large magnetic forces raises the possibility of magneto-elastic instabilities in these magnets. Similar instabilities in the plasma have of course been the subject of intense research, but such phenomena in the magnets themselves have not received as much attention.

This paper is part of a continuing effort to investigate the possibility of magnetoelastic instabilities in Tokamak designs. Having demonstrated the potential for such failures in the toroidal field magnets we consider here the magnets which create the poloidal magnetic fields (Figure 1). Such magnets act as a primary of an air core transformer, generating the plasma current (ohmic heating coils), and providing a radial magnetic force on the plasma (equilibrium coils). The currents in

these coils are time varying in the order of megamperes. In some designs superconducting coils are planned of total circumferential length so up to 50 meters.

The forces on the coils arise from their self fields and from interaction with other coils. The former create radial magnetic forces and circumferential stresses. Ostensibly the toroidal magnetic field should produce zero force on these coils, However small perturbations out of the circular configuration of these coils can produce helical instabilities around the circumference of the poloidal magnets. In addition it is possible for the self forces to produce a "kink" type instability. Though the dynamic nature of the magnetic forces in these coils should ultimately be studied, a quasisteady analysis will be given in this paper since the time constants of the currents are in the order of seconds.

Equations of Motion

The poloidal field magnets will be treated as current carrying elastic rings which can deflect both in and out of its plane and exhibit bending and torsional flexibility but are otherwise inextensible along the circumference of the ring. If the ring were uniformly stretched along the circumference we could define a center of tension in the r - z plane (Figure 2) using the first moment of the circumferential stresses across the composite cross section of the ring. The circumferential element along the center of tension is assumed to be inextensible while elements off the axis can increase or decrease their lengths due to bending. The radial position of the center of tension is denoted by $\tilde{r}_T$ while the position of the center of current will be $\tilde{r}_C$. According to the theory of elastic rings there is a rigid body rotation of each ring element δ , about the center of tension in addition to the radial and axial deflections u_r, u_z . If ϵ denotes the radial separation of the centers of current and tension one can write the following relations

$$\begin{aligned}\tilde{r}_T &= (R_0 + u_r)\tilde{e}_r + u_z\tilde{e}_z \\ \tilde{r}_C &= \tilde{r}_T - \epsilon\tilde{e}_r + \epsilon\beta\tilde{e}_z\end{aligned}\tag{1}$$

According to the theory of elastic rings general force and moment vectors act on any cross section of the ring. If one chooses the components of these vectors with respect to axes which rotate with the deformed ring element (Figure 2) one can obtain the following equations of motion.

$$\left. \begin{aligned} \frac{dN_r}{dS} + N_z \tau_1 - T \kappa_1' + f_r &= m \frac{\partial^2 u_r}{\partial t^2} \\ \frac{dN_z}{dS} - T \kappa_1 - N_r \tau_1 + f_z &= m \frac{\partial^2 u_z}{\partial t^2} \\ \frac{dT}{dS} + N_r \kappa_1' + N_z \kappa_1 &= m \frac{\partial^2 u_s}{\partial t^2} \end{aligned} \right\} \quad (2)$$

$$\left. \begin{aligned} \frac{dG_r}{dS} + G_z \tau_1 - H \kappa_1' + N_z + K_r &= 0 \\ \frac{dG_z}{dS} - H \kappa_1 - G_r \tau_1 - N_r + K_z &= 0 \\ \frac{dH}{dS} + G_r \kappa_1' + G_z \kappa_1 + K_s &= 0 \end{aligned} \right\} \quad (3)$$

The curvatures κ_1 , κ_1' , τ_1 are related to the deformation by the following equations.

$$\begin{aligned} \kappa_1 &= \frac{\beta}{R_0} - \frac{\partial}{\partial S} \left(\frac{\partial u_z}{\partial S} \right) \\ \kappa_1' &= \frac{1}{R_0} - \frac{\partial}{\partial S} \left(\frac{\partial u_r}{\partial S} - \frac{u_s}{R_0} \right) \\ \tau_1 &= \frac{\partial \beta}{\partial S} + \frac{1}{R_0} \frac{\partial u_z}{\partial S} \end{aligned} \quad (4)$$

If the center of tension is treated as inextensible, then the following constraint must be imposed

$$\frac{\partial u_z}{\partial S} + \frac{u_r}{R_0} = 0. \quad (5)$$

In the linear momentum equations f_r , f_z represent the magnetic forces averaged over the cross-section. In the angular momentum equations (3,a,b,c) we have neglected the rotary inertias, and K_r , K_z , K_s represent the effective body torques produced by the magnetic forces about the center of tension. The shear forces N_z , N_r , tension T , bending moments G_z , G_r and torque H are shown in Figure 2.

Magnetic Forces

The magnetic forces have two sources; one from the magnetic field of the ring itself and the other from the interaction with the toroidal magnetic field. When the circular magnet is undeformed the self force is radially outward if the current is directed along the center of current* while the interaction with the toroidal field is nil. However when the ring is deformed, perturbation forces arise which are proportional to the deformation. These perturbation forces determine the stability of the ring and can be represented in the form

$$f_r = \frac{\mu_0 I^2}{R_0} [\psi_0 + \psi_1(u_r)] - I_0 B_0 \frac{\partial u_z}{\partial s} \quad (6)$$

$$f_z = \frac{\mu_0 I^2}{R_0} \psi_2(u_z) + I_0 B_0 \frac{\partial u_r}{\partial s}$$

The second terms in (6) couple the inplane and out of plane motions and are derived from the Lorentz expression for magnetic force

$$\vec{f}_z = \vec{I} \times \vec{B}_0 = [I_0 \vec{e}_s + \vec{\Omega} \times I_0 \vec{e}_s] \times B_0 \vec{e}_s \quad (7)$$

where the rotation vector of the center of current is given by

$$\vec{\Omega} = \frac{\partial u_z}{\partial s} \vec{e}_r - \frac{\partial u_r}{\partial s} \vec{e}_z \quad (8)$$

When the center of current and tension do not coincide these forces

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* In superconductors the filaments are twisted in a helical shape which produces an effective magnetization. This effect is neglected. Also such materials exhibit a degree of diamagnetism whose effects are also neglected.

produce a couple per unit length about the center of tension

$$K_s = \epsilon \left[\frac{\mu_o I_o^2}{R_o} \psi_o^{B+f_z} \right] \quad (9)$$

where only terms linear in the perturbed quantities are kept.

Toroidal field buckling

Pin Supports

Instabilities of elastic structures depend on the kind and number of constraints or supports the external environment places to restrict its motion. In the case of superconducting or cryogenically cooled coils the number of supports to and from the cold coils to the warm environment must be minimized.

To establish the existence of an instability we seek values of $I_o B_o$ which permit a nonzero deformation field of arbitrary amplitude and which satisfies the equations of motion and support constraints.

A buckling solution is a static deformation field which satisfies the equations (2), (3) with the dynamic terms dropped. For convenience a prime will denote a derivation with respect to the arc length s .

$$\begin{aligned} \left[\frac{Cu_z}{R_o^2} - Au_z'' \right]'' + \frac{(A+C)}{R_o} \vartheta'' - I_o B_o u_r' &= 0 \\ B \left[\frac{u_r}{R_o^2} + u_r'' \right]'' - \frac{T}{R_o} - I_o B_o u_z' &= 0 \end{aligned} \quad (10)$$

$$\frac{(A+C)}{R_o} u_z'' + C\vartheta'' - \frac{A}{R_o^2} \beta = 0$$

$$T'' + \frac{T}{R_o^2} + \frac{I_o B_o}{R_o} u_z' = 0$$

where the centers of current and tension are assumed to be coincident.

One can observe that a constant deformation is a solution. Also if the number of pin supports is "M" we will seek solutions of the form

$$\begin{bmatrix} u_r \\ u_z \end{bmatrix} = \begin{bmatrix} a_1 \\ a_2 \end{bmatrix} e^{\frac{iMS}{R_0}} \quad (11)$$

A form of solution which will satisfy both the equilibrium equations (10) and the pin constraints at $S_n = \frac{2\pi R_0}{M} n$, $n = 0, 1, \dots, M-1$

$$u_r = U_0 (1 - \cos \frac{MS}{R_0}) \quad (12)$$

$$u_z = \alpha U_0 \sin \frac{MS}{R_0}$$

This deformation is in the form of circular helix (see Figure 3)

The values of $I_0 B_0$ for which this solution is possible are

$$I_0 B_0 = \frac{B^{1/2}}{R_0^3} (M^2 - 1) \left[\frac{(C + M^2 A)(A + M^2 C) - M^2 (A + C)^2}{(A + M^2 C)} \right]^{1/2} \quad (13)$$

and the ratio of inplane to out-plane amplitudes is

$$\alpha = - \frac{B^{1/2} (M^2 - 1)}{M} \left[\frac{(C + M^2 A)(A + M^2 C) - (A + C)^2 M^2}{(A + M^2 C)} \right]^{-1/2} \quad (14)$$

To get an idea of the magnitude of $I_0 B_0$ required for buckling consider a circular crosssection of uniform material in that case

$$A = B = C/2 = E \pi r_0^4 / 4$$

For this case (13) becomes

$$I_0 B_0 = \frac{\pi}{4} E R_0 \left(\frac{r_0}{R_0} \right)^4 (M^2 - 1) \left[\frac{(2 + M^2)(1 + 2M^2) - 9M^2}{1 + 2M^2} \right]^{1/2} \quad (15)$$

For $M = 4$ or nodes at the intersection of the arc with two mutually perpendicular diameters

$$I_o B_o = E R_o \left(\frac{r_o}{R_o}\right)^4 \frac{\pi^4 5}{4} (50/33)^{1/2} \quad (16)$$

If L denotes the arc length between supports, then the straight filament limit is obtained by letting $M \rightarrow \infty$. In this limit the critical product of current and field becomes

$$I_o B_o = (AB)^{1/2} \left(\frac{2\pi}{L}\right)^3 \quad (17)$$

which would be obtained from the equations for a straight current filament in an axial magnetic field

$$A u_r'''' - I_o B_o u_z' = 0 \quad (18)$$

$$B u_z'''' + I_o B_o u_r' = 0$$

In this short wave length limit the torsional stiffness does not affect buckling.

Example

Application of this theory to a poloidal field coil in the design of a tokamak reactor UWMAK-III by the University of Wisconsin fusion group can readily be made using the following parameters; (see Fig. 4)

D-6 "Diverter Coil"

$R = 19.0$ meters

$I_P = 6.8 \cdot 10^6$ A

$B_T = 2.5$ Wb/m²

$r = 0.23$ m, $E = 2 \cdot 10^{11}$ N/m²

based on $J = 4100$ A/cm² in the composite superconductor

For these parameters

$$\frac{I_P B_T R^3}{E \pi r^4} = 35.7$$

This implies that the coil will need at least 6-8 supports to avoid helical buckling in the toroidal magnetic field.

Figure A-1

Figure A-2

Figure A-3 Helical Buckling Shape of a Poloidal Coil in a
Toroidal Magnetic Field B_T .

CROSS SECTION VIEW OF UWMAK-II

Figure A-4