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LAWRENCE LIVERMORE LABORATORY

University of California/Livermore, California

SCALING OF FERF C-CLAMP STRUCTURE WITH
COIL RADIUS AND MAGNETIC FIELD STRENGTH

Charles J. Schwer and Gustav A. Carlson

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SCALING OF FERF C-CLAMP STRUCTURE WITH COIL RADIUS AND MAGNETIC FIELD STRENGTH

ABSTRACT

A C-clamp coil structure was proposed in a conceptual design study for FERF. The purpose of this paper is to generalize this structural design to permit scaling of the C-clamp structure with coil radius and magnetic field strength.

SCALING OF FERF C-CLAMP STRUCTURE WITH COIL RADIUS AND MAGNETIC FIELD STRENGTH

INTRODUCTION

The conceptual design study for FERF⁽¹⁾ resulted in a magnetic configuration as shown in Figure 1 with inner major and minor radii of 143.1 and 55.0 cm, respectively. The inner and outer major arcs in each winding have displaced centers and include an angle of 140 degrees.

A C-clamp coil structure was proposed as shown in Figure 2. No attempt was made to optimize design of this structure. The structure was designed to support only major forces, and calculations were intended only to demonstrate feasibility. Design was based on a major force of $2.76 \times 10^8 \text{ N}$ ($6.21 \times 10^7 \text{ lbf.}$) on one quarter turn for a magnetic field strength at the conductor of 12.3 tesla. Total mass for this design was given as $6.33 \times 10^5 \text{ kg}$ ($1.4 \times 10^6 \text{ lbm.}$).

The purpose of this paper is to generalize the above design to permit scaling of the C-clamp structure with coil radius and magnetic field strength. A simplified model of the FERF coil was developed to permit this.

SIMPLIFIED MODEL OF FERF COIL

The simplified model of the FERF coil has concentric circular arcs to outline the shape of the magnet configuration. The model shown in Figure 3 is an attempt to preserve the geometric parameters of the bare FERF coil (excluding the coil case). These parameters are the angle of open mirror, the

area of each coil face, the distance between the outer coil faces, and the inside and the outside major radii of the coil face. The first three parameters-- 60 degrees, 10.9 square meters, and 2 meters, respectively-- are in almost exact agreement. There is some discrepancy in the fourth parameter because the major arcs in each winding of FERF have displaced centers. A comparison between the geometry of FERF and the simplified model can be seen in Figure 4.

Dimensions in Figure 3 have been given in terms of a mean radius, R, defined as the average of the radii of the inside and outside arcs. (To determine R for FERF a mean coil width was measured from Figure 1, halved, and then added to the inside radius to give 2.38 meters).

DESCRIPTION OF C-CLAMP STRUCTURE FOR SIMPLIFIED MODEL

Consider a large number of C-clamps each with its own dimensions, as shown in Figure 5, to work together to nearly cover the coil face, as shown in Figure 3. Each clamp will be sized as required to meet design criteria as the length L changes from clamp to clamp. The inside dimension of the mouth of the clamp, M, will remain a constant for all clamps of the same structure. The distance M represents the distance between the two coil faces including the coil case thickness T. The mass of one single clamp is

$$\text{mass} = \rho \left[2 \left[.01 \text{ RL} \left(\frac{H + .1H}{2} \right) \right] + .01 \text{ RD}(2H + .84 \text{ R} + 2 \text{ T}) \right]$$

$$\text{mass} = \rho [.011 \text{ RLH} + .01 \text{ RD}(2H + .84\text{R} + 2 \text{ T})]$$

where ρ is the density of the material ($\rho = 8 \times 10^3 \frac{\text{kg}}{\text{m}^3}$ was used for calculations).

STRESS ANALYSIS AND DESIGN OF C-CLAMP STRUCTURE

Consider the total magnetic force this structure must support. For FERF the force on each coil face was given as $5.55 \times 10^8 \text{ N}$ ($2 \times 62.1 \times 10^6 \text{ lbf}$). This force is assumed to be proportional to both B^2 , the square of the magnetic field strength, and R^2 , a measure of the area of the coil face. Using SI units $F = 6.45 \times 10^5 B^2 R^2 \text{ N}$. This force will be distributed over an area of

$$\frac{1}{2} [(1.37 R + T)^2 - (.62 R - T)^2] \frac{148}{180} \pi$$

where T is the thickness of the coil casing. The cantilever part of each clamp must support a force per unit length, w . w is defined as

$$\frac{\text{total force on one coil face} \times \text{the thickness of the clamp}}{\text{the area on which this force is distributed}}$$

$$\text{so } w = \frac{F}{\frac{1}{2} [(1.37 R + T)^2 - (.62 R - T)^2] \frac{148}{180} \pi} (.01 R) .$$

The length of the cantilever part of each clamp is a function of Z as seen in Figure 3.

For $.38 R \leq Z \leq (.62 R - T)$ ($T = .13 \text{ meters}$ was used for calculations)

$$L = \sqrt{(1.37 R + T)^2 - Z^2} - \sqrt{(.62 R - T)^2 - Z^2}$$

For $(.62 R - T) \leq Z \leq (1.19 R + T \cos 30^\circ)$

$$L = \sqrt{(1.37 R + T)^2 - Z^2}$$

To determine the height H of the tapered cantilever the shear stress along face 'A' in Figure 5 is assumed to be small compared to the bending

stress (less than 10%). The section modulus for a rectangular section is $S = \frac{(.01 R) H^2}{6}$. Since S is also equal to $\frac{M}{\sigma_{\text{design}}}$ where $M = \frac{wL^2}{2}$ and σ_{design} is the design stress, therefore,

$$H = \sqrt{\frac{300 wL^2}{R \sigma_{\text{design}}}} \quad (\sigma_{\text{design}} = 7 \times 10^8 \frac{\text{N}}{\text{m}^2} = 10^5 \text{ psi was used for calculations}).$$

The depth of the neck of the C-clamp, D , will depend upon the bending and axial stress across face 'B' in Figure 5. Employing the flexure formula the maximum bending stress σ_B is found to be

$$\sigma_B = \frac{wL(L+.5D)}{(.01 R) D^2}.$$

The axial stress is found to be $\frac{wL}{(.01 R) D}$. Since the design stress must be equal to the sum of these stresses, then

$$\sigma_{\text{design}} = \frac{6 wL[L+.5D]}{(.01 R) D^2} + \frac{wL}{(.01 R) D}. \quad \text{This equation is in simple}$$

quadratic form, $[(.01 R) \sigma_{\text{design}}] D^2 + [-4 wL] D + [-6 wL^2] = 0.$

$$\text{Therefore, } D = \frac{[4 wL] + \sqrt{[4wL]^2 - 4[(.01 R) \sigma_{\text{design}}][-6 wL^2]}}{2[(.01 R) \sigma_{\text{design}}]}.$$

All dimensions shown in Figure 5 which are necessary in calculations of volume and mass have been described in the above equations or defined in the description of the C-clamp structure.

DEFLECTION ANALYSIS OF C-CLAMP

Deflection analysis will be based on a simple cantilever beam that is tapered as shown in Figure 6.

From strength of materials, $M_x = E I_x \frac{d^2 y}{dx^2} = \frac{wx^2}{2}$ where $I_x = \frac{(.01 R) H^3}{12 L^3} x^3$.

Therefore, $\frac{d^2 y}{dx^2} = \frac{1}{E} \times \frac{12 L^3}{.01 R H^3 x^3} \times \frac{wx^2}{2} = \frac{600 wL^3}{R E H^3} \left(\frac{1}{x}\right)$.

So $\frac{dy}{dx} = \frac{600 wL^3}{R E H^3} [\ln x + c_1]$ and $y = \frac{600 wL^3}{R E H^3} [x \ln x - x + c_1 x + c_2]$.

Since $\frac{dy}{dx} = 0$ at $x = L$, $c_1 = -\ln L$; and since $y = 0$ at $x = L$, then $c_2 = L$.

Therefore, $y = \frac{600 wL^3}{R E H^3} \left[\ln\left(\frac{x}{L}\right)x + L - x\right]$. Notice that the maximum deflection

at $x = 0$ is $\frac{600 wL^4}{R E H^3}$ ($E = 2 \times 10^{11} \frac{N}{m^2}$ was used for calculations).

RESULTS AND DISCUSSION

Results of the analysis as described in this paper are shown in Figures 7 to 10. Figure 7 shows the total mass of the C-clamp structures (for both coils) as a function of the magnetic field strength at the conductor and the mean radius, R , defined as the average of radii of the inside and outside arcs of the coil face. The FERF coil parameters are indicated on Figure 7, as is the previously reported value for the mass of the FERF coil structure.⁽¹⁾ The calculated mass in this paper for the FERF coil structure is approximately 15% greater than that reported in Reference 1. Also shown on Figure 7 are the parameters of the hybrid reactor coil. The

present calculation for mass for the Hybrid coil structure agrees well with the value reported in Reference 2.

The maximum deflection of any C-clamp structure as a function of magnetic field strength at the conductor and radius, R , can be found in Figure 8. Note that the B field in Figure 8 is the field strength for which the structure is designed. A consequence of the design constraint of fixed maximum stress is that the low field designs have greater deflections. The FERF and Hybrid cases are identified on Figure 8.

A deflection map for the FERF coil structure is shown in Figure 9. There is a discontinuity in the gradient of deflection across the z axis because of the simple model used for the deflection analysis (See Figure 6). A more realistic model should result in somewhat smaller deflections near the z axis.

The relative size of the C-clamp structure depends on the field strength designed for. Figure 10 illustrates this dependence and gives the structural dimensions of the largest clamp in terms of the mean radius, R .

Figure 1. Cross Section of Magnet without coil casing.

Figure 2. Plan view of C-clamp structure.

Figure 3. Simplified model of FERF C-clamp structure.

Figure 4. Comparison between FERF geometry.

Figure 5. C-clamp geometry for stress analysis.

Figure 6. C-clamp geometry for deflection analysis.

STRUCTURAL MASS VS. B FIELD AT THE CONDUCTOR

Structural
Mass
kg

Total C-clamp Structural Mass, kg

Fig 8

-13-

90 CM

80

70

60

50

40

30

20

10

MAXIMUM DEFLECTION, CM

STRUCTURE DESIGNED FOR $R=4$ YEARS

$B=6$

$B=8$

$B=10$

$B=12$

$B=14$

$B=16$

$B=18$

$B=20$

* - HYBRID (THIS STUDY)

FERE (THIS STUDY)

4

8

12

16

20 METERS

R (m) MEAN RADIUS

DEFLECTIONS FOR FERF

FIG 9

RELATIVE SIZE OF C-CLAMP STRUCTURE FOR B FIELDS OF 6, 12, 18 TELSA.

Fig 10

$B = 6$ Telsa
FOR LARGEST
CLAMP
 $H = .278 R$
 $D = .434 R$

$B = 12$ Telsa
FOR LARGEST
CLAMP
 $H = .555 R$
 $D = .960 R$

$B = 18$ Telsa
FOR LARGEST
CLAMP
 $H = .835 R$
 $D = 1.60 R$

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