

TO: DISTRIBUTION
FROM: C NEUMEYER
SUBJECT: COIL PROTECTION ALGORITHMS IN PSRTC

References:

- [1] “Update Of NSTX Influence Matricies And EM Loads”, 13_041120_CLN_01, C. Neumeyer, 11/20/4
- [2] “Revision to EM Loads on TF Flags”, 13_041027_CLN_01, C. Neumeyer, 10/27/4
- [3] “TF Operations Review, Simplified Modeling & Protection”, C. Neumeyer, 2/10/5
- [4] “Loads On Flag Box/Hub Friction Interface”, 13_041208_CLN_01, C. Neumeyer, 12/8/4

The purpose of this memo is to document new coil protection algorithms which have been implemented in the Power Supply Real Time Control (PSRTC) software in the “pulsecurrent” subroutine of “rtc.f”. These include....

- 1) Calculation of axial loads on coils and comparison against limits
- 2) Calculation of peak pressure on outer layer TF joint and comparison against limits
- 3) Calculation of force on friction interface between outer layer TF flag boxes and hub

Axial Loads

Influence coefficients given in [1] are used to calculate the force on PF coil x due to its current and the forces in the other y coils as follows...

$$F_x = \sum_y C_{xy} I_x I_y$$

This calculation is performed once each time step in PSRTC for each of the PF coils, namely OH, PF1aU, PF1aL, PF1b, PF2U, PF2L, PF3U, PF3L, PF4, PF5. Limits are included in the PSRTC c.d file for each coil. If the sign of the limit is positive, then a positive force greater than the limit causes a trip, and if the sign of the limit is negative, then a negative force less than the limit causes a trip. The influence coefficients are hard coded into the “rtc_init.f” program. The data generated for the forces on each coil is available as an output which can be selected in the “o.d” file and viewed after each pulse via “readrtc”.

Peak Pressure on TF Joint

The first step in calculating the pressure is to calculate the prospective moments in-plane (IP) and out-of-plane (OOP). The in-plane moment is assumed proportional to the square of the TF current. Prior calculations [2] indicated a generated moment of 70653 in-lbf on the outer layer flags and links at 6kG (71.166kA). So the applied EM moment at any value of current is...

$$M_{EM_IP} = \left(\frac{I_{TF}}{71167} \right)^2 * 70653$$

The amount of moment which ends up at the joint depends on how much is reacted by the structure. Structural coefficients have been estimated by I. Zatz and will be updated based on analysis of field measurements. These are used to estimate the amount of the moment which is reacted by the joint...

$$M_{Joint_IP} = C_{Structure_IP} * M_{EM_IP}$$

Similar calculations are performed for the out-of-plane moment based on the influence matrix given in [1] for the out-of-plane moment, and on structural coefficients estimated by I. Zatz to be updated based on analysis of field measurements. These take the following form...

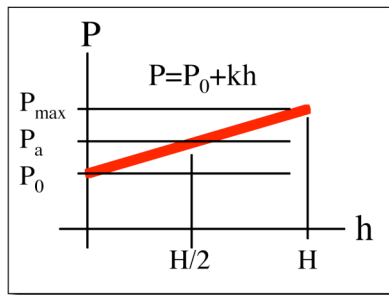
$$M_{Joint_OOP} = \sum_x C_{x_OOP} I_x I_{TF}$$

The coefficients C_{x_OOP} are the product of the aforementioned influence matrix coefficients and the structural coefficients, and are hard coded into "rtc_init.f"

The data generated for the in-plane and out-of-plane moments is available as an output which can be selected in the "o.d" file and viewed after each pulse via "readrtc"..

Once the moments are known then peak pressure at the joint can be calculated based on the linear pressure distribution model [3].

Linear Pressure Model w/o Liftoff



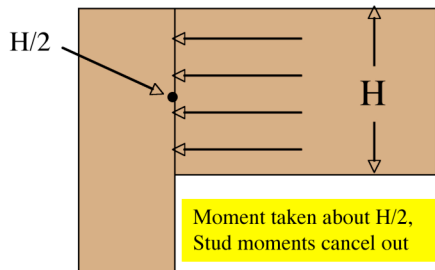
$$F = \int P dA = w \int_0^H P dh = \frac{A}{H} \int_0^H (P_0 + kh) dh$$

$$k = \frac{2(F - AP_0)}{AH} \quad A = HW$$

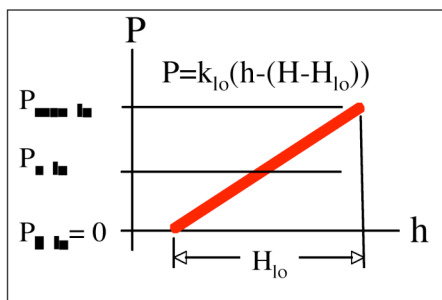
$$M = 2 \int_0^{H/2} (P_a - P)(h - H/2) dA$$

$$P_0 = \frac{6M}{AH} - \frac{F}{A} \quad P_{\max} = \frac{6M}{AH} + \frac{F}{A}$$

$$M_{\text{liftoff}} = \frac{FH}{6}$$



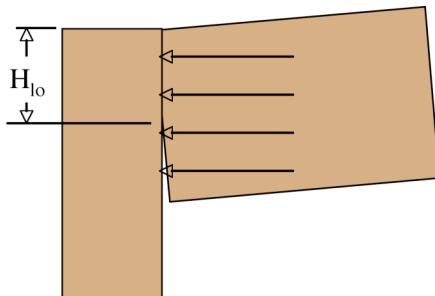
Linear Pressure Model w/Liftoff



$$H_{lo} = \frac{H}{2} - \frac{3M}{F} \quad P_{0_lo} = 0$$

$$A_{lo} = H_{lo}W \quad k_{lo} = \frac{2F}{A_{lo}H_{lo}}$$

$$P_{\max_lo} = \frac{2F}{3W} \left[\frac{H}{2} - \frac{M}{F} \right]$$



In PSRTC the in-plane and out-of-plane pressures are calculated separately using the following equations, where H=5", W=0.781", F=20000lbf...

$$K_{1_IP} = \frac{F}{HW} = K_{1_OOP} = 5.122E3$$

$$K_{2_IP} = \frac{6}{H^2W} = 0.3073, K_{2_OOP} = \frac{6}{HW^2} = 1.967$$

$$K_{3_IP} = 2 * F = K_{3_OOP} = 4.0E4$$

$$K_{4_IP} = \frac{3HW}{2} = K_{4_OOP} = 5.850$$

$$K_{5_IP} = \frac{-3W}{F} = -1.172E-4, K_{5_OOP} = \frac{-3H}{F} = -7.5E-4$$

The gross average pressure is...

$$P_{avg} = \frac{F}{HW} = 5122$$

The peak normalized pressure in-plane is...

$$\bar{P}_{max_IP} = \frac{K_{1_IP} + K_{2_IP} * M_{IP}}{P_{avg}} \longrightarrow M_{IP} \leq M_{IP_LO}$$

$$\bar{P}_{max_IP} = \frac{K_{3_IP}}{P_{avg} (K_{4_IP} + K_{5_IP} * M_{IP})} \longrightarrow M_{IP} > M_{IP_LO}$$

And for out-of-plane...

$$\bar{P}_{max_OOP} = \frac{K_{1_OOP} + K_{2_OOP} * M_{OOP}}{P_{avg}} \longrightarrow M_{OOP} \leq M_{OOP_LO}$$

$$\bar{P}_{max_OOP} = \frac{K_{3_OOP}}{P_{avg} (K_{4_OOP} + K_{5_OOP} * M_{OOP})} \longrightarrow M_{OOP} > M_{OOP_LO}$$

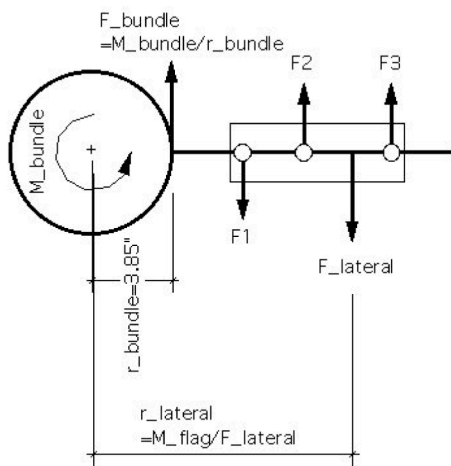
The in-plane and out-of-plane are then combined by multiplying the in-plane and out-of-plane normalized pressures...

$$P_{\max} = \bar{P}_{\max_IP} * \bar{P}_{\max_OOP}$$

The maximum pressure is compared each time step to an allowable value which is entered in the "c.d" file.

Force On Friction Interface Between Flag Box and Hub

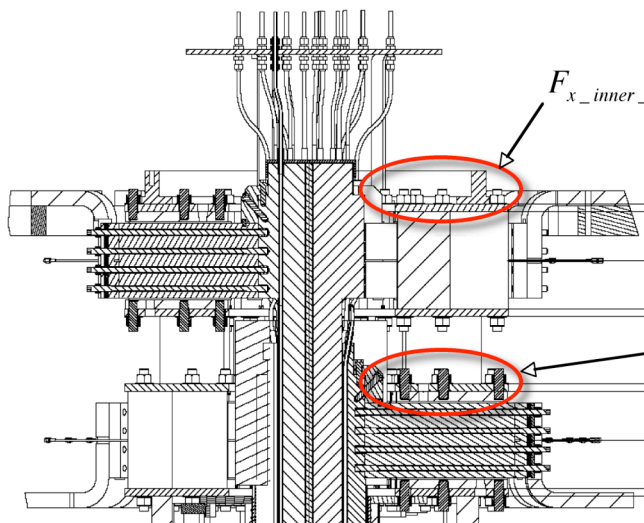
A simplified model of the interface is described in [4]. Governing equations are as follows...



$$F_3 = \frac{\left[\frac{(F_b * r_b + F_l * r_l)(r_3 - r_1)}{(r_1(r_3 - r_1) + r_2(r_3 - r_2))} - \frac{(F_b + F_l)(r_3 - r_1)}{(2r_3 - r_1 - r_2)} \right]}{\left[\frac{(r_3 - 2 * r_1 + r_2)}{(2r_3 - r_1 - r_2)} - \frac{(r_3 * (r_3 - r_1) + r_2 * (r_2 - r_1))}{(r_1(r_3 - r_1) + r_2(r_3 - r_2))} \right]}$$

$$F_1 = \frac{-[F_3(r_3 - 2r_1 + r_2) + (F_b + F_l)(r_3 - r_1)]}{(2r_3 - r_1 - r_2)}$$

$$F_2 = F_1 - \frac{(F_1 - F_3)(r_2 - r_1)}{(r_3 - r_1)}$$



$$F_{x_inner_oop} = \frac{F_{x_inner}}{2} + \frac{\sum F_{x_inner}}{3} + \frac{\sum F_{x_outer}}{3}$$

$$F_{x_outer_oop} = \frac{F_{x_outer}}{2} + \frac{\sum F_{x_outer}}{3}$$

Prior analysis showed that the innermost stud location (F1) on the outer layer flag box interface with the middle hub disk is the one most highly stressed. For this case the PSRTC calculations for the out-of-plane shear load are as follows...

$$K_1 = R_{bundle} = 3.848$$

$$K_6 = R_3 \square R_5 = 6.375$$

$$K_3 = \frac{(R_1(R_3 - R_1) + R_2(R_3 - R_2))(R_3 - 2R_1 + R_2)/(2R_3 - R_1 - R_2) - (R_3(R_3 - R_1) + R_2(R_2 - R_1))}{(R_1(R_3 - R_1) + R_2(R_3 - R_1))} = -38.781$$

$$K_4 = \frac{(2R_3 - R_1 - R_2)(R_3 - 2R_1 + R_2)/(2R_3 - R_1 - R_2) - (R_3(R_3 - R_1) + R_2(R_2 - R_1))}{(R_1(R_3 - R_1) + R_2(R_3 - R_1))} = \square 5.180$$

$$K_5 = -(R_3 - 2R_1 + R_2) = -9.000$$

$$K_6 = 2R_3 - R_1 - R_2 = 10.125$$

$$K_7 = \frac{R_2 - R_1}{R_3 - R_1} = 0.412$$

$$F_3 = \frac{)F_{bundle} * K_4 + M_{lateral} ** K_2 -)F_{bundle} + F_{lateral} ** K_2}{K_3 \quad K_4}$$

$$F_1 = \frac{(F_3 * K_5 - (F_{bundle} + F_{lateral}) * K_2)}{K_6}$$

$$F_2 = (F_1 - (F_1 - F_3)) * K_7$$

$$F_{1_OOP} = \frac{F_1}{2} + \frac{(F_1 + F_2 + F_3)}{3}$$

...where F_{bundle} , $F_{lateral}$, and $M_{lateral}$ are forces and moments calculated via the influence matrices given in [1].

The in-plane shear load is based on the shear load calculated per square ampere of TF current at 6kG...

$$K_8 = 3.. . 0E - 7$$

$$F_{1_IP} = K_8 * I_{TF}^2$$

Finally the net load is the vector sum of the in-plane and out-of-plane loads...

$$F_{1_NET} = \sqrt{F_{1_IP}^2 + F_{1_OOP}^2}$$

The calculated force is compared to a limit value set in the “c.d” file. The data generated for the force is available as an output which can be selected in the “o.d” file and viewed after each pulse via “readrtc”.

cc:

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