REVIEW OF MFTF YIN-YANG MAGNET DISPLACEMENT AND MAGNETIC FIELD MEASUREMENTS AND CALCULATIONS

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Abstract

During the recent testing of the MFTF yin-yang magnet, measurements of coil position, structural case strain, and magnetic field were made to verify calculated values. Measurements to detect magnet movement were taken throughout cooldown and during the operation of the magnet. The magnetic field at the mirror points was measured by Hall-effect probes. The magnet position, structural case strain, and magnetic field measurements indicated a reasonably close correlation with calculated values. Information obtained from the yin-yang test has been very useful in setting realistic mechanical alignment values for the new MFTF-B magnet system.

Introduction

Results from the MFTF yin-yang technology demonstration [1] have been very useful in determining the installation and alignment requirements for the larger MFTF-B facility [2] now under construction. Because the yin-yang magnets were installed and aligned under ambient temperature conditions, the magnetic centers of the coils underwent considerable movement during cooldown and power operation. Special equipment was installed to measure magnet movement during vacuum pumpdown, cooldown of the coil, and power operation. Numerous strain gages were mounted in high-stress areas on the outer magnet case. During coil operation, a number of Hall-effect probes were used to measure the magnetic field at the mirror points and near the conductor pack. Calculations of stress-strain, C-coil lobe deflections, thermal stress, and displacements were performed by General Dynamics/Convair, while the magnetic field calculations were performed by LLNL.

Magnet Position Measurements

A mechanical/electrical system was designed and built [3] to measure yin-yang movement during the technology demonstration. Each coil was measured at two points on the outer lobe surface near the z-axis and in the xy plane (Fig. 1). Movement of the points activated a dead-weighted wire and a linear position potentiometer mounted on a bracket near the vessel foundation support. Measurements were recorded at various stages of the startup and during operation of the magnets. These stages included: vacuum pumpout of vessel, cooldown of magnet, operation of the magnet at various power levels, and return to ambient conditions.

The displacement of points A and D on EM1 and EM2 coils are plotted in Fig. 1. To obtain the location of the yin-yang center it was assumed that a line between points A and D on coils EM1 and EM2 intersect the z-axis at the starting point (S). The following results were obtained from the plot of the point displacements:

- Points D (EM2) and A (EM1) moved 0.05 in. when the vessel was subjected to vacuum and returned to this position after the magnet tests. Apparently a small displacement occurred in the magnet/vessel strut support system for which the cause was not determined.

- The center of the yin-yang moved 0.62 in. diagonally up and south from the starting point during cooldown (see Fig. 1, S to C). This displacement is consistent with that determined by GDC with use of a simple beam finite-element analysis of the yin-yang coil. The simple NASTRAN beam model was used to evaluate the overall coil motions and determine overall coil case loads for unsymmetric temperature or magnetic loading conditions. In the case of the steady-state cooled-down condition, strut temperature distributions calculated with GDC's finite-difference thermal-analysis code (Thermal Analyzer) were used to calculate strut deflections for input into the NASTRAN finite element analysis. The small differences (15%) between the analysis data and value observed during technology demonstration are attributed to the failure of the LN_2 intercepts on the vertical hanger struts to adequately cool the intercept point on the strut, thereby causing higher average temperatures (less deflection) in the hanger struts. Before the start of the MFTF-B magnet installation, we plan to use similar beam-element computer models to determine magnet displacement for alignment purposes.

- Under full magnet power (5775 A), the center of the yin-yang moved from the cooldown position, 1.1 in. diagonally downward and to the north (see Fig. 1, C to F). The displacement of the yin-yang center from its original installation position was 0.50 in..

- The displacement (spreading) of the lobes under full power (see Fig. 1, C to F) was 2.45 in. for the EM1 coil and 2.38 in. for the EM2 coil. General Dynamics/Convair calculated a displacement of 2.27 in. in their finite element analysis of the magnet. The magnetic and other symmetric loading conditions for the MFTF magnet were analyzed by General dynamics with a quarter-symmetric, 5000-DOF NASTRAN model. The model represented one quarter of each magnet including the interconnecting structure. The coil jacket, case structure, and intercoil structure were represented by linear strain plate elements. These elements simulated the axial shear and bending stiffnesses of the plate structure. The conductors were represented by six continuous rod elements that represented the lumped axial stiffness of the pack. These elements were connected to the surrounding case and jacket structure by other rod elements that simulated the transverse stiffness of the conductor pack including the conductor, insulation,

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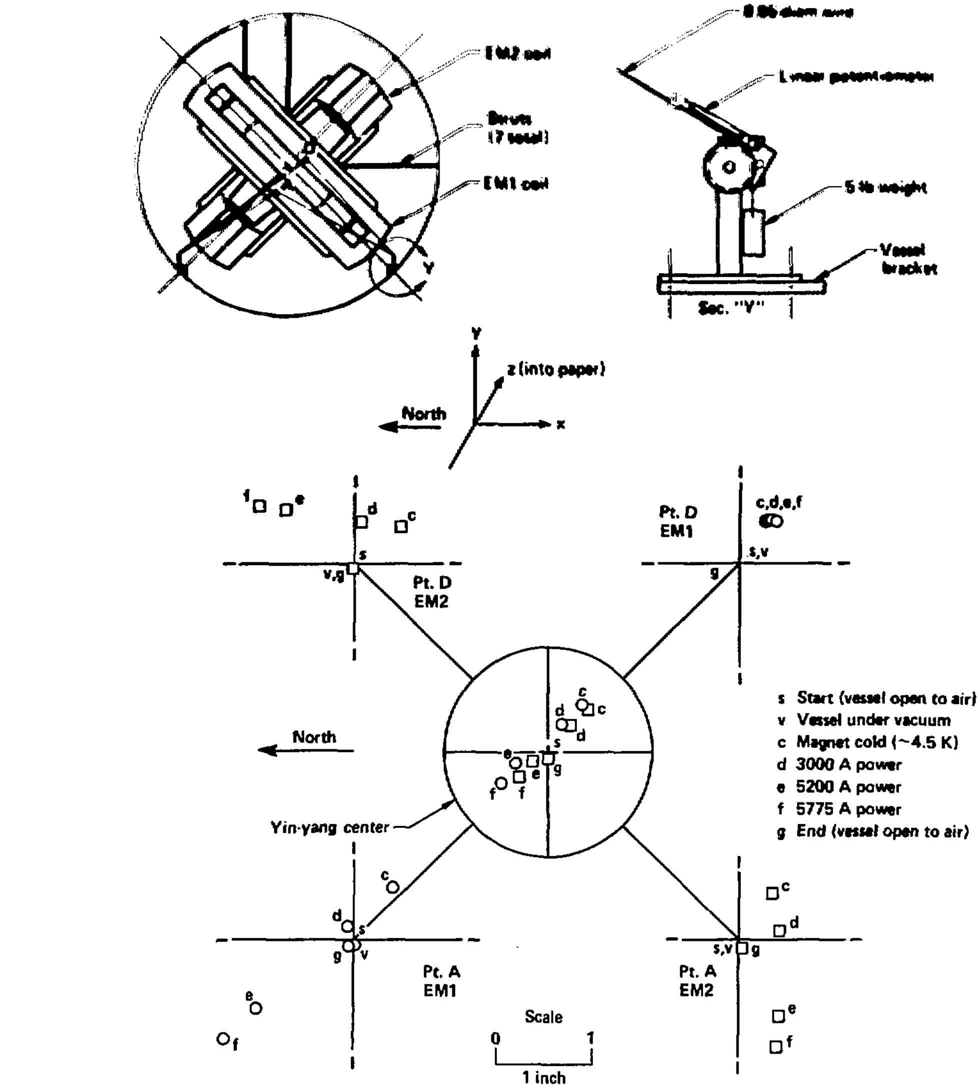


Fig. 1. Yin-yang displacement measurements. (MFTF-A tech demo)

and effective gaps. Stresses and deflections were calculated for normal operating and fault magnetic conditions and the steady-state 4.5 K operating temperature condition.

There was an 8% difference between the calculated and measured values for the EM1 coil.

<u>Yin-Yang Case Strain Measurements</u>

The structural case strain was measured [4] in the minor radius area where the highest stresses were expected to occur. Four rosettes were located on the surface of the curved 3-in.-thick plate near the junction of a T-section weld and four on the 5-in.-thick plate in the minor radius near the structural case closeout weld. Each of the two areas were monitored in four symmetrical positions. At the full current (5775 A), the measured values of maximum stress, minimum stress, and maximum shear stress in the 3-in.-thick plate were 75,500, -83,400 and 79,500 psi, respectively. The measured average values of these three peak stresses in the 5-in.-thick plate were respectively, 84,200, 0, and 42,400 psi.

General Dynamics NASTRAN finite element analysis predicted the stresses in the minor radius that were consistent with the data obtained from the strain gage readings. The peak principal stress predicted for the T-section weld at the intersection of the 3-inch inner base plate and the 5-inch intermediate crossover plate was 80,000 psi. The peak principal stress in the inner 5-inch crossover plate was calculated to be 81,500 psi. Both of these stresses are reasonably close to the measured value. The most significant difference between the analysis predictions and the measured values was in the underestimation of the transverse compressive stresses on the inner surface of the 3-inch inner case plate. This compressive stress is caused by the transverse bending in the case plate induced by the inward (towards center of curvature) deflection of the curved case plate under hoop tension. The NASTRAN analysis accurately predicted the hoop tension stress but did not predict compression stresses as large as those measured on the yin-yang. MFTF-B analyses are using refined solid element modeling techniques to refine the stresses in similar locations.

A line representing the maximum stress as being proportional to the square of the current was drawn through the predicted maximum stress points (Fig. 2). Then, at each incremental increase of the magnet current, the measured strain gage data was reduced and plotted. As shown on this graph, the measured values are linear and the peak values correspond to that predicted by the finite element calculations.

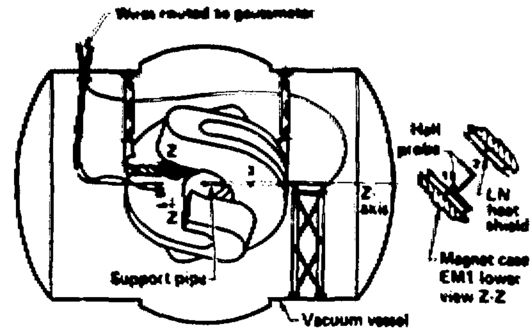


Fig. 3. Magnetic field measurements - Hall probe location. (MFTF-A tech demo)

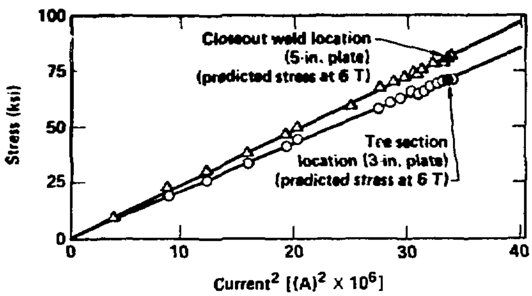


Fig. 2. Yin-yang magnet case showing maximum measured stress vs the square of the current at two locations inside the minor radius.

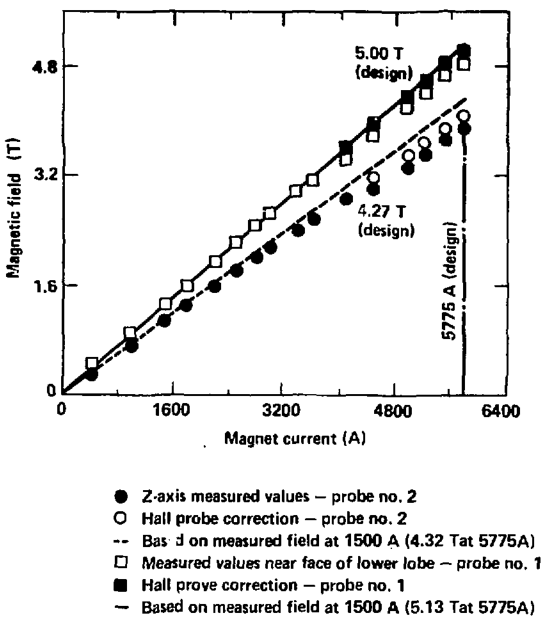


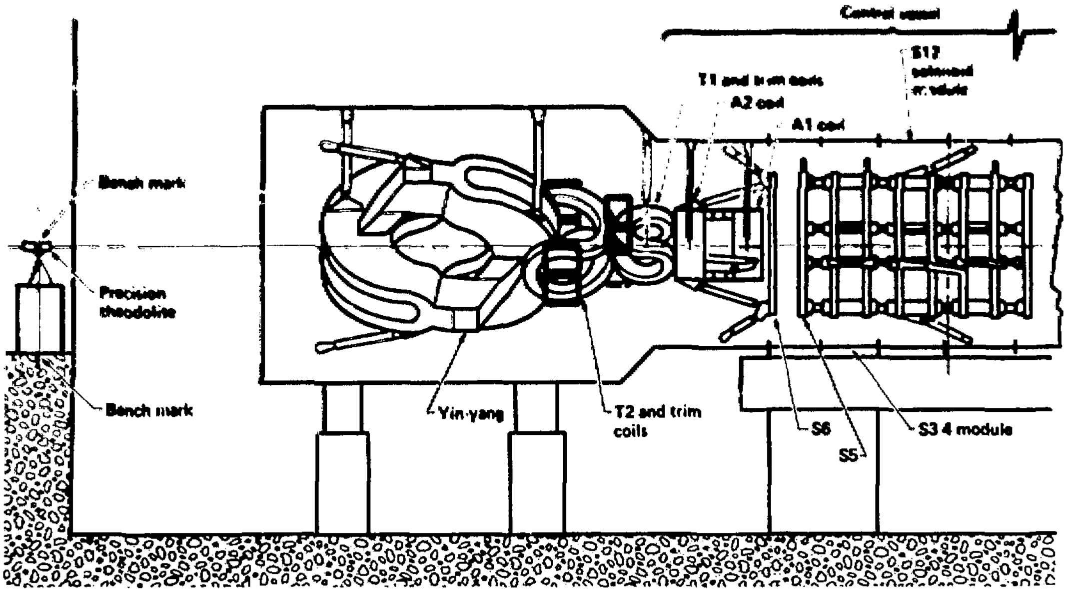
Fig. 4. Magnetic field at mirror point of EMI coil. (MFTF-A tech demo)

Magnetic Field Measurements

Three Hall-effect probes (Fig. 3) were used to measure the magnetic field at the yin-yang mirror points [3]. The axial-type probes were suitable for cryogenic use in magnetic fields of up to 7 T. The manufacturer of the Hall probe element supplied a correction table for values above 3 T because of nonlinearity in probe readings. The measured values at the mirror point of the FM1 coil are plotted in Fig. 4. Probe No. 1 was mounted on the lower lobe, 0.372 m from the z-axis at the mirror point. The corrected, measured value was 5.06 T which is very close to the 5.0 T calculated using the EFFI computer code. Probe No. 2 was mounted to the lower lobe (common support frame with probe No. 1) near the z-axis at the mirror point. It was mounted 1.25 in. off the z axis, so that the probe would be on axis at full magnet power. The corrected, measured value was 4.1 T which is less than the 4.27 T value calculated using the EFFI code. The EFFI value is larger because the code assumes that the conductor packs maintain a constant separation throughout the magnet power cycle. The solid line, which was located from the magnetic field measured at 1500 A before the lobes begin to move apart, indicates that the magnetic field would have been 4.3 T, if the lobe separation had remained constant. Probe No. 3 was supported by a cantilevered pipe and located on the z axis at the mirror point of EM2 coil. The corrected measured value for the EM2 mirror point at the center (z-axis) was 4.14 T.

MFTF-B Magnet Alignment and Installation

Trim coils have been added in the transition area (Fig. 5) to correct magnetic field lines distorted by misaligned coils. Maximum C-coil displacements and rotations of up to 0.6 in. and 0.5°, respectively, were determined to be possible even with a reasonable effort to align coils. These anticipated errors were based in part on the yin-yang test results and an evaluation of equipment and procedures used to align the MFTF-B coils. The causes and predicted magnitude of C-coil misalignment errors are listed in Table 1. Maximum solenoid displacement and rotation (misalignment) are anticipated to be ±0.3 in. and 0.1°, respectively.



Note: 1/2 of magnets shown

Fig. 5. MFTF-B magnet installation and alignment. (Only one-half of the magnets are shown)

Table 1. *Causes of magnet misalignment and estimated error magnitudes for C-coils.*

Causes of magnet misalignment	Error band Radial (±) (in.)	Error band Angular (±) (degrees)
Magnetic field mapping (warm)	0.10	0.08
Cooldown (magnet and struts)	0.10	0.01
Magnetic forces (magnet and struts)	0.10	0.21
Vessel deflections (load, temperature, creep, pin joint clearance, vacuum)	0.19	0.05
Reproducibility of alignment targets	0.03	0.05
Alignment of targets during installation	0.03	0.05
Total C-coils	0.55	0.45

Our procedure for alignment and final installation of the MFTF-B magnet will be:

1. Establish accurate mechanical centerline reference points on magnets cases as they are fabricated.

2. The C-coils will have their magnetic fields mapped (warm) and magnetic-field centerlines established in relation to the mechanical centerlines and to alignment targets. All other coils will be aligned to their mechanical centerlines.

3. The movement of coil during cooldown and under power operation will be calculated and related to alignment targets.

4. Install the magnets and displace the alignment targets to the values calculated in (3) above. Align the magnets using a precision theodolite.

Conclusions

The yin-yang magnet was successfully tested and measurements were made that increased our understanding of magnet performance and confirmed various structural and magnetic field calculations. Magnet motion measurements were especially useful because the motion of the magnet could be plotted, from startup through the magnet power cycle, and the cause of motion established.

Magnetic field measurements not only validated the calculations, but illustrated the effect of conductor pack motion within the pack and displacement of the lobes at high current levels.

Because the performance of the MFTF-B magnets is highly dependent on how accurate the coils are aligned, a detailed study of misalignment errors was made to determine the causes and their magnitude. The results of the yin-yang tests were very useful in this study.

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