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Application of Structural Mechanics Methods to the Design of Large Tandem Mirror Fusion Devices (MFTF-B)

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Abstract

The Mirror Fusion Test Facility (MFTF-B) at Lawrence Livermore National Laboratory requires state-of-the-art structural-mechanics methods to deal with access constraints for plasma heating and diagnostics, alignment requirements, and load complexity and variety. Large interactive structures required an integrated analytical approach to achieve a reasonable level of overall system optimization. The Tandem Magnet Generator (TMG) creates a magnet configuration for the EFFI calculation of electromagnetic-field forces that, coupled with other loads, form the input loading to magnet and vessel finite-element models. The analytical results provide the data base for detailed design of magnet, vessel, foundation, and interaction effects.

1. Introduction

The Mirror Fusion Test Facility (MFTF-B) is a large magnetic fusion energy experiment that will test advanced plasma-confinement concepts in tandem configuration. The experimental goal is to reach break-even performance on a near-reactor scale. The MFTF-B has evolved from a minimum "B" single cell device to a thermal-barrier tandem-mirror axicell configuration [1]. (See Fig. 1.)

This dramatic evolution posed the challenge of maximizing performance for existing equipment and facilities. Also, in an experimental fusion device, access constraints for plasma heating and diagnostics combined with the complexity and variety of loads require application of the best available, most efficient, structural-mechanics methods.

2. Description of MFTF-B [2]

MFTF-B is composed of highly interdependent structures. The main ones consist of the 2,700-kip magnet array suspended in a 3,400-kip vacuum vessel which is housed in a 70,000-kip vault. The magnet array is made up of 42 superconducting coils, cooled in 4.5-K liquid helium, that generate a magnetic field varying from 1 to 12 Tesla. All of the coils except the high field inserts use a niobium-titanium superconductor. The insert coils use a niobium-tin superconductor. The coil cases are manufactured from 304 LN stainless steel.

The vacuum vessel is a 58-m-long horizontal cylinder made of 304 stainless steel, with circumferential and longitudinal stiffeners. The central cell is 8 m in diameter and the end cells are 10.8 m in diameter. The vault is a 2-m-thick box-shaped structure with a central stiffening buttress. Its exterior dimensions are 73.5 m by 26 m and it is 24.8 m high.

3. Structural-System Analysis and Design Process

Structural design was dictated by the basic plasma parameters, magnetic fields, and physical access considerations. Material-selection considerations included environmental conditions, operating cycle, lifetime, fabricability, and maintenance requirements.

MFTF-B demands accurate relative alignment of many components. Stringent requirements are placed on positions of magnet coils to maintain proper field line configuration. The accurate prediction of deflections for vessel and magnet-system components under a variety of loads and thermal conditions is essential to achieve the required alignment under operating conditions of initially misaligned components. These alignments place an extra demand on analytical and design methods. The overall schematic of the integrated approach, depicting interdependence of various analytical elements and identifying the key structural models employed, is shown in Fig. 2.

From the conceptual configuration and basic plasma parameters, the Tandem Magnet Generator (TMG) [3] creates a magnet configuration for the EFFI [4] calculation of electromagnetic-field forces that, coupled with other loads, determine input loading for the magnet and vessel finite-element models. The vessel finite-element model is again used as an integral part of a larger model to capture soil-structure interaction effects. The analytical results provide the data base for the detailed design of magnet, vessel, and foundations.

3.1 Magnet System

EFFI was used to calculate self and mutual inductances and electromagnetic-field forces for the magnets. A load matrix was developed to describe coil self-loads, interactive loads between coil-pairs and groups of coils, fault modes, misalignments, quench, and a multitude of operating scenarios.

3.1.1 Magnet-Case Design Including Conductor Pack Analysis

NASTRAN [5] finite-element models were used extensively for structural analysis of magnet cases, conductor packs, and supports. Three-dimensional models having up to 7,000 degrees of freedom were constructed.

The coil-pack characterization introduces one of the largest uncertainties in the design of the magnets. STANSOL [6] code for solenoids and NASTRAN for C-shaped coils were used to predict conductor strain and to establish the sensitivity of winding gaps under a variety of loading conditions.

3.1.2 Fracture Analysis

A linear-elastic fracture-mechanics computer program called FLAGRO [7] predicted component life on the basis of a flaw-growth-damage integration package that interrelates material properties, cyclic loading, and flaw size and shape.

3.2 Vessel-System Analysis

The vessel is composed of stiffeners, cylinder shell, legs, and support frame. Simple two-dimensional analyses of major components yielded the vessel's initial sizing. A 3-D finite-element model of the magnet and vessel having 15,000 degrees of freedom was generated to simulate the structural interactions. To keep the model of this complicated system manageable, we made several simplifying assumptions while retaining an adequate representation of interactions. We have used a package of LLNL-developed programs that includes an improved version of SAP4 [8], with SUBSP [9] and MODPAR [10] added.

3.3 Seismic Analysis

Seismic loads are important system-design factors. Two distinctly different approaches are available for seismic hazard analysis: probabilistic and deterministic. The probabilistic approach [11] taken quantifies the uncertainty in the number, size, and location of possible future earthquakes and allows an analyst to present tradeoffs between more costly design or retrofits and the economic impacts of a failure. Because probabilistic analysis yields a measure of the seismic hazard expressed in terms of a return period, tradeoffs can easily be quantified. A risk-benefit analysis indicated that a return period of 100 years for MFTF-B was reasonable. Site-specific response spectra were developed after considering 33 different earthquake records.

3.4 Soil-Structure Interaction (SSI) Analysis

The vessel and vault walls are supported on separate but adjacent foundation mats. These are considered to be coupled through soil. A series of analyses studied the SSI and coupling between structures. To simulate the structures more realistically, the analysis considers the soil stiffness and damping. The SSI analyses are performed with a newly developed computer program CLASSI [12]. In-structure response spectra were generated for the attached design elements.

4. Results and Conclusions

Interactive structures subjected to complex loads and numerous constraints require a detailed, state-of-the-art, integrated, structural-mechanics analysis.

We found that detailed finite-element models were essential to achieve global optimization and cost-effective designs. The integrated analytical approach limited sub-optimization. At full performance, the test result of the yin-yang magnet, the largest of the magnet set, correlated well with the analytical model.

Analytical techniques currently used for characterizing the conductor-pack behavior, although adequate, need further improvement.

Seismic loads were an important factor in the total system design. A realistic assessment of these loads required maximum use of the best analytical techniques. Although extensive, the probabilistic seismic-hazards analysis resulted in a more tractable decision-making process.

The selected structural critical damping value was proven to be appropriate by vibration testing and model extraction.

Availability of a CRAY computer was essential to the successful completion of this effort.

A more detailed discussion of these results will appear in the conference proceedings.

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Soil-Structure Interaction	- Structural Mechanics Associates, J. J. Johnson.

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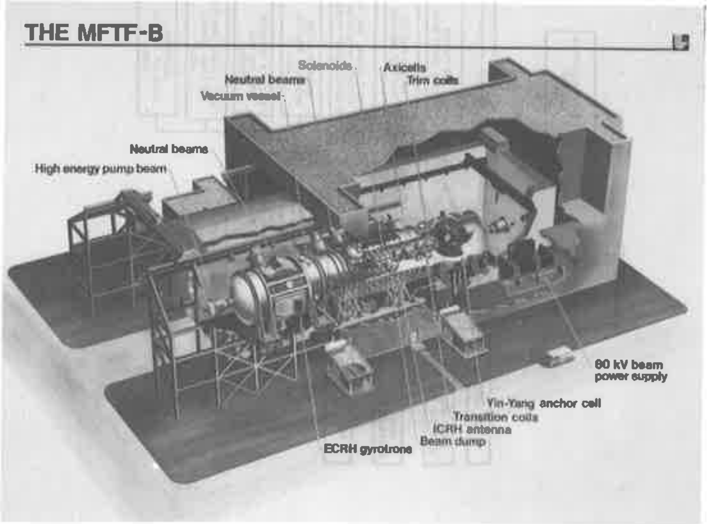

Fig. 1. The MFTF-B axicell.

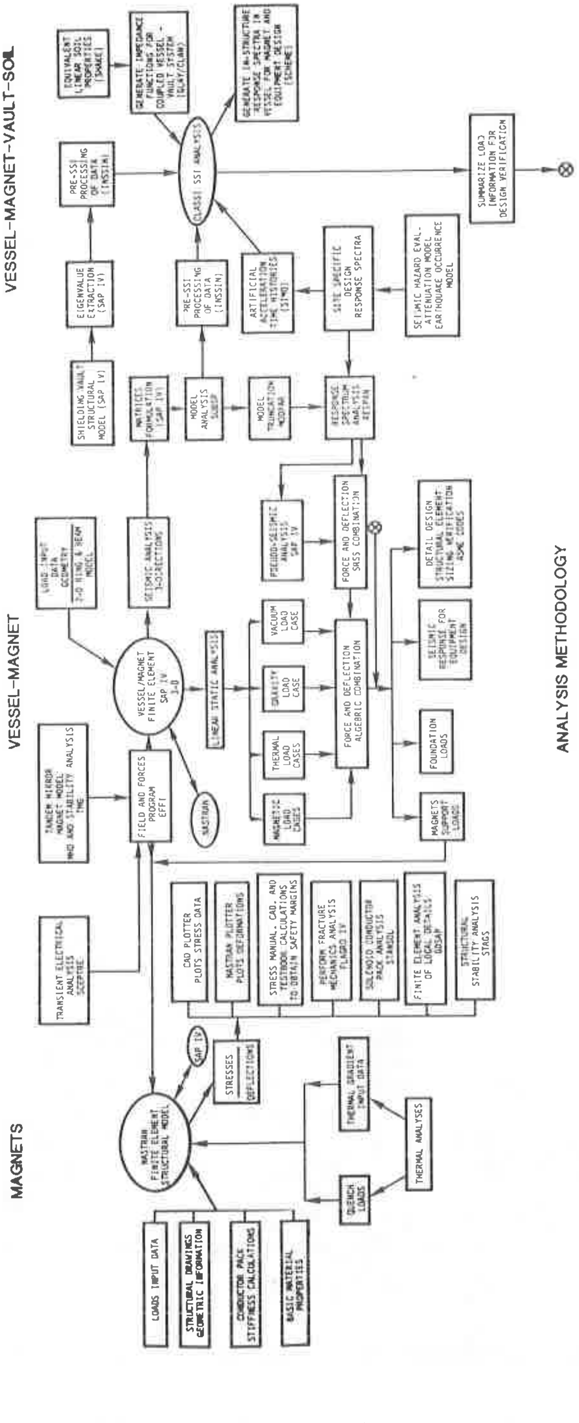

Fig. 2. Analytical link and interaction between various structural elements of MFTF-B.