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The ORNL Advanced Toroidal Facility: Physics Insight Leads to Efficient Computer-Aided Construction

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OPERATED BY
MARTIN MARIETTA ENERGY SYSTEMS, INC.
FOR THE UNITED STATES
DEPARTMENT OF ENERGY

Printed in the United States of America. Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road, Springfield, Virginia 22161
NTIS price codes—Printed Copy: A02 Microfiche A01

ORNL/TM-10756
Dist. Category UC-404, 405, 406

Fusion Energy Division

THE ORNL ADVANCED TOROIDAL FACILITY: PHYSICS INSIGHT LEADS TO EFFICIENT COMPUTER-AIDED CONSTRUCTION

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Date Published—March 1988

Prepared for the
Office of Technology Applications

Prepared by the
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Oak Ridge, Tennessee 37831
operated by
MARTIN MARIETTA ENERGY SYSTEMS, INC.
for the
U.S. DEPARTMENT OF ENERGY
under contract DE-AC05-84OR21400

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ACKNOWLEDGMENTS

The error analysis and Fig. 1 were supplied by D. K. Lee and J. H. Harris. B. E. Nelson developed the floating datum concept.

ABSTRACT

A method for accurate measurement of complex parts that contain no reference points is described. The technique is applied to the production of accurate castings, to their machining, and to their installation. Accuracies of ~2 mil can be achieved over distances of 7 ft.

1. INTRODUCTION

On many occasions the insight of a physicist can lead to a major improvement in what would ordinarily be termed "an engineering task." A number of these insights proved to be crucial in the construction of the Advanced Toroidal Facility (ATF) torsatron at the Oak Ridge National Laboratory. This report describes the solution to a particular problem, a solution that led to the development of a measuring technique applicable to any situation in which large, complex parts (e.g., propellers, turbine blades) require high-precision measurement, casting, and milling.

A torsatron is a type of stellarator that is projected to provide an attractive environment for controlled thermonuclear fusion. Briefly, it is a toroidal vacuum chamber upon which are wrapped two helical coils. The two coils determine the poloidal number ℓ (for the ATF, $\ell = 2$); the number of periodic helical turns in the toroidal direction determines the toroidal mode number m (for the ATF, $m = 12$). The ATF torsatron has a major radius of 2.1 m and a minor coil radius of about 0.5 m. Each helical coil is composed of 14 turns of copper to carry the current density required to produce a 2 T magnetic field; therefore the cross section of the coil is about 0.31 m wide and 0.22 m deep. The average plasma radius is about 0.30 m.

Because the equilibrium, stability, and confinement properties for the plasma are dependent upon the vacuum magnetic field configuration, the design and construction of these coils are crucial to the achievement of the physics goals of the experiment. In a stellarator (as opposed to a tokamak), all the confining fields are produced by external coils, so it is both necessary and possible to control error fields resulting from construction errors. In practice, the problems of magnetic errors can be avoided in the following ways:

- Choose the rotational transform profile to avoid major resonances; in particular, low-shear configurations can be adjusted to exclude the strongest resonances entirely.
- Provide substantial shear at resonant surfaces.
- Develop engineering design and construction techniques that restrict the magnitudes of spatially resonant perturbation fields to acceptably low values.
- Align the various coil systems.
- Implement control-by-design of incidental perturbation fields due to current feeds, buswork, and ferromagnetic materials (such as shielding for diagnostics, bending magnets, etc.) where significant improvements can often be obtained by careful location of potential error field sources.
- Conduct experimental mapping of the flux surfaces to verify their quality with subsequent application of correction fields, if necessary, to compensate for error fields.

Systematic error fields, which are the same in every field period, constitute a slight change in the winding law and are usually benign. Random errors are usually not resonant and are also not a problem. The fringing fields of torsatrons and heliotrons can be large enough to cause magnetization of even relatively distant pieces of iron; this is an effect that must be calculated. Transient eddy currents can also create error fields.

For ATF, numerical studies were performed to determine the magnitude of allowable errors in the helical coils, errors in the surrounding circular vertical field coils, and the relative displacements among the various coil sets (Fig. 1).

Field errors that resonate with the helical field lines on low-order rational surfaces are especially dangerous; magnetic errors arising from these interactions are negligible if the current center is controlled to an accuracy of around 1 mm. Random errors can be much larger, but this situation is unlikely to occur in practice. In addition, the alignment of the coil sets must be accurate to about 1 mm. Therefore, the ATF helical coils were built so that they were accurate to within 1 mm.

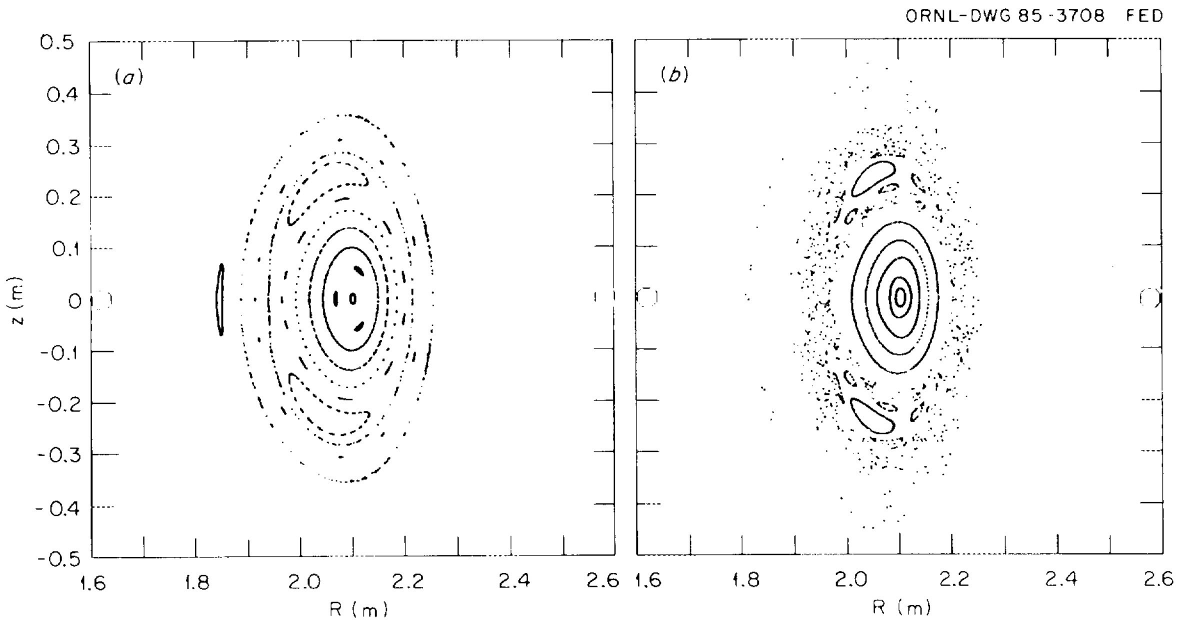

Fig. 1. The ideal ATF flux surfaces are nested ellipses. However, adding perturbations that resonate with a particular surface of $\Delta B/B$ = *(a)* 1 × 10^{-3} and *(b)* 2 × 10^{-3} causes severe disruption of the surfaces.

2. ATF COIL DESCRIPTION

A toroidal vacuum chamber is usually constructed in a robust manner with an accurate helical trough into which the coils are wound. The vacuum chamber serves as the structural support for the coils. The construction of the ATF was different in that each helical coil was segmented into 12 identical upper and lower pieces with joints on the midplane at the inside and outside of the torus. This design allowed the coil construction to be performed in parallel with the construction of the vacuum vessel and relaxed the accuracy requirements of the vessel itself. As a result, the ATF is built backwards from most torsatrons, and the helical coils must be structurally supported from the outside of the torus (Fig. 2). Each coil has a nonmagnetic stainless steel T-shaped structural support

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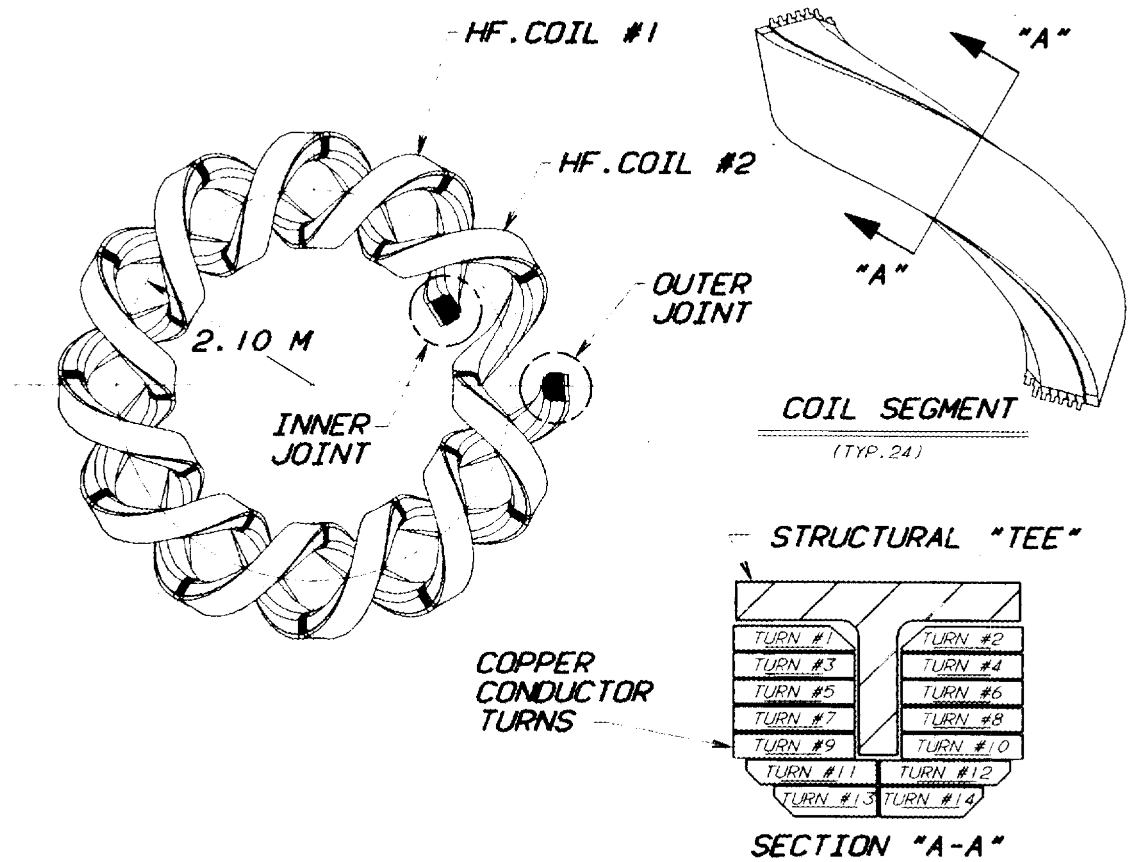

Fig. 2. Helical field coil segment concept.

member running the length of the segment. The 14 copper turns are accurately laid on either side of the stem of the T, and the entire segment is vacuum-impregnated with epoxy.

The coil joints are simple lap joints with insulating wedges inserted between the turns to take up any slack. The joints are held together with insulated bolts that run through insulating, match-drilled bushings. These joints have been successfully assembled, taken apart and reassembled.

The first major obstacle was encountered in manufacturing the structural Ts. An accuracy of 1/8 in. is required on the surfaces adjacent to the windings, and it was highly desirable that there be no surface machining. An attempt at bending and welding flat pieces failed because of considerable warpage during welding. A trial casting was made that was oversized 1 in. in all dimensions. Because this casting was inaccurate everywhere and because it contained no flat reference surfaces, deciding whether there was a "good" part within it was an interesting physics challenge. The following two sections describe the technique devised to meet this challenge and the further applications of this technique that improved the entire process of building the ATF and led to the development of methods for precise measurement and construction that are useful to industry.

3. MEASUREMENT AND ANALYSIS OF PARTS OF THE COIL: THEORY

The actual casting could be measured with a coordinate measuring machine (CMM), with the results being given in the CMM's coordinate system. However, because the CMM's software incorrectly used only one angle to describe rotation in three-dimensional space, its software had to be rewritten to carry out this seemingly simple process. Also, the ideal shape of the part is known in the ATF coordinate system. Using a computer and some elementary physics (the spring force law, $F = kx$), the CMM data were compared to the ATF data. About 12 mathematical "springs" were hung between the measured shape and the desired shape, and the coordinates of the measured part were rotated and translated until the energy values in the springs were minimized. This provided the best possible fit in a least-mean-square sense and determined whether the ideal shape resided within the actual casting.

The problem of positioning a complex object into a given region of space can be described in the following manner (Fig. 3).

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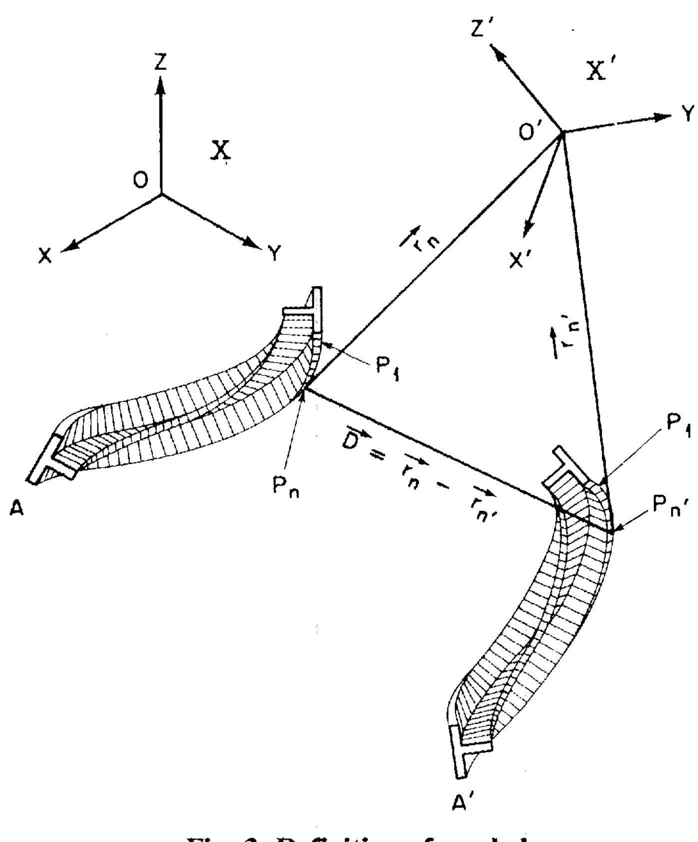

Fig. 3. Definition of symbols.

Suppose that one has an object A described in coordinate system X by a set P of measured coordinates ($P_1(x, y, z)$, P_2, P_3, ..., P_n). The object is to be positioned in some optimal way into the volume given by A'. It is described in coordinate system X' by a set of points P_1', ..., P_n'. The connection between the coordinate systems X and X' is initially unknown and is to be determined for an optimal fit. The functional equations describing the transformation of coordinates in X to X' are written as follows:

$$X' = BX + T\ ,$$

where X and X' are matrices whose elements are the values of the coordinates in their respective coordinate systems. T is the translation matrix connecting the two origins O and O'. B is a 3×3 orthogonal transformation matrix. The representation chosen for B is purely one of convenience. We chose the Eulerian angles ϕ, θ, ψ. The initial rotation about the Z-axis is ϕ; θ is the second rotation about the new X-axis, and ψ is the third rotation about the new Z-axis. This is the standard order given in many textbooks. The problem of determining a best position for A is one of finding the values of ϕ, θ, ψ, T_x, T_y, and T_z, which allow one to calculate the coordinates of the features of A in the X' system and have features close to their intended positions. The distance between P_n and P_n' is given by

$$\vec{D} = \vec{r}_n - \vec{r}_n{}'$$

$$D^2 = X^T X = X^T(BX + T) = f(\phi, \theta, \psi, T_x, T_y, T_z)\ ,$$

where X^T is the transpose of X. One can construct the term $W = (k_n/2)\ D^2$ where $k_n/2$ is an arbitrary constant. W is just the equivalent of the energy stored in a linear spring connecting points P_n and P_n'. Experience indicates that it is convenient to decompose the vector D into components whose directions can be chosen to suit a given problem. The W is then written as

$$W_n = .5 \sum_{i=1}^{3} k_n D_i D_i\ .$$

Thus the notion is to construct a system where we connect springs between a measured point and its ideal position in space. In this case the spring was broken into three equivalent springs, each with an independent spring constant and direction. Another degree of freedom can also be implemented. If one measures the points P_1 to P_n such that a spline can be used to interpolate between points, then point P can be allowed to slip along a smooth curve through the points P_1 to P_n. The functional

$$W = \sum_{N} W_N\ ,$$

which represents the total energy of the system, can be constructed and minimized in an unconstrained manner. The result is a rotation and translation that minimizes the energy in the spring system. The minimization process is a standard algorithm in nonlinear optimization (H. Goldstein, *Classical Mechanics,* Addison Wesley Publishing, Reading, Mass., 1950).

By using this technique, one is able to define in a statistical sense a position for an object in space. The error analysis of the position is a natural part of the solution. This example is an application of the idea of a least-squares fitting of a three-dimensional object into its design position.

4. MEASUREMENT AND ANALYSIS OF PARTS OF THE COIL: APPLICATION

Armed with the knowledge of the position of the coil, the ATF research team mounted about 10 small tooling balls on the outer surfaces of the T, located their centers with the CMM, and translated their locations to the ATF coordinate system. These balls then served as easily measured reference locations on the part. This concept is called a "floating datum."

It took several weeks of machining to create a finished, correctly shaped part from the oversized casting. It would have been an unacceptably slow and costly process to redesign the molds using the old techniques. The new measuring technique enabled the casting manufacturer to redesign the molds to produce castings that met the tolerance requirements in only two tries. The final parts cost about $5000 and required no surface machining. All 24 pieces were produced in 2 weeks.

The next problem to be faced was to create a set of fixtures that could be used to shape the turns of the helical field (HF) coil segments accurately. The accuracy along the length of the coil pieces had to be 1 mm, and the joint locations had to be held to 0.05 mm to allow proper assembly of the coil. It was decided to manufacture a fixture out of the oversized castings, which could be accurately machined (~5 mil) to match the outside of the tolerance window for the coil stack. On each end of the fixture, a finger joint jig held the joints to accuracies of 1 mil. Accurately sized shims were placed between the turns as they were stacked up, and each turn's contour was measured with the CMM and verified using the floating datum technique.

Machining such a complicated part, even on a numerically controlled 5-axis milling machine, requires several setups to reach all the surfaces. The usual technique for doing this is to first move the part into the "correct" position for each setup, and then do the machining. Because of the large size of these parts, their complicated shapes, and the high accuracy required, it was very time-consuming and nearly impossible to position the parts correctly on the machine bed. Once again, the floating datum technique proved invaluable. Each part was adjusted to about the correct position. (They barely fit on the machine.)

The locations of the tooling balls were then measured with the milling machine to specify the transformation between the ATF coordinate system and the milling machine coordinates. It took only about 20 min using a VAX computer to make a new machine tape, and no readjustment of the part location was needed. In contrast, attempts at manual setups took up to a day and did not yield accurate results. In addition, by careful choice of the machining geometry, the two ends of the coil were held to within 2 mils of true position.

The next use of the spring adjustment technique occurred when it was decided that a crush plane had to be inserted between the top of the T and the outer windings of the coil. To make room for this design change, it was necessary to machine these surfaces of the castings. By readjusting the cast Ts within the tolerance window (by changing the spring constants), the castings were repositioned so that only very light machining cuts were required from the tops of the Ts, and a lot of metal was taken off of the much smaller noses of the Ts. This formidable machining task was thus reduced to a manageable one that only took about 4 h of machine time.

The final use of these techniques occurred when the helical coil was assembled. To yield the best possible fit at the coil joints, the envelope of the entire coil segment was adjusted very slightly (keeping within the 1-mm tolerance) to eliminate any net offset of the joint holes from one segment to the next. The resulting displacement of the joint holes was less than 50 mils, so the joint bushings could be match-drilled with a sufficient wall thickness.

5. CONCLUSION

Using very simple physics, new techniques were developed for casting, measuring, and machining of large, complicated parts. Without such advances, it would have been impossible to complete the ATF in a timely and cost-effective manner. These techniques can be used in industry to save time and ensure accuracy in manufacturing similar parts.

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