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NEW DEVELOPMENTS IN PROGRAM STANSOL VERSION 3*

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STANSOL is a computer program that applies a solution for the mechanical displacement, stress, and strain in rotationally-transversely isotropic, homogeneous, axisymmetric solenoids. Careful application of the solution permits the complex mechanical behavior of multilayered, nonhomogeneous solenoids to be examined in which the loads may vary arbitrarily from layer to layer. Loads applied to the solenoid model by program STANSOL may consist of differential temperature, winding preload, internal and/or external surface pressure, and electromagnetic Lorentz body forces. STANSOL version 3, the latest update to the original version od the computer program, also permits structural analysis of solenoid magnets in which frictionless interlayer gaps may open or close. This paper presents the new theory coded into version 3 of the STANSOL program, as well as the new input data format and graphical output display of the resulting analysis.

Introduction

Program STANSOL[1,2] (Structural Analysis of Solenoids) was the first computer program that integrated the mechanical behavior of axisymmetric solenoid magnets due to winding prestress, internal and/or external surface pressure, thermal contraction and/or expansion, and electromechanical Lorentz body force. Based upon the theory derived in Ref. 3 for an axisymmetric, plane-stress solenoid magnet with rotationally-transversely isotropic material properties, program STANSOL has been used to perform stress analyses upon several successful superconducting and normal magnets designed and built at the Oak Ridge National Laboratory (ORNL). Two recent solenoid magnets that were partially designed with the information from a STANSOL analysis were CWTX[4] and EBT-P[5]. Copies of program STANSOL have been distributed free-of-charge to nearly every DOE laboratory, to seven private industrial corporations, and to eleven universities.

Presented here are the most significant additions that have been programmed into STANSOL to change it from version 2 to version 3. Four major changes have occurred between version 2 and 3. They are (1) all input data is accepted in free-format, (2) a summary of the extremum of the stress and strain is printed out, (3) a computer graphics capability has been added so that plots of the mechanical displacement, stress, and strain are drawn, and (4) the solution algorithm can develop frictionless gaps that may open or close during magnet cooldown (warmup) and energization[6]. The following sections individually discuss each of these four modifications.

Free-Format Input Data

Originally, program STANSOL was coded to accept input data on card images based upon input fields that were eight characters wide. (This scheme was a hold over from input to COSMIC/NASTRAN.) STANSOL version 3 now accepts input card images in free-format, an option available with most higher-level FORTRAN run-time operating systems. Briefly described in the Appendix are the ten types of input card images program STANSOL version 3 understands. Card images that contain more than one data variable per image must separate the variables by a comma and/or a space. With the exception of card type 4 there is no restriction placed upon where the variable data must be located upon a card image, as long as the data is present in the order the variables are listed for a specific card type in the Appendix. Standard FORTRAN variable declarations are used throughout; i.e., variable names that begin with the letter I through N, inclusive, are automatically defined as integers. All other variables are defined as real or double precision.

Output Extremum Summary

Originally, program STANSOL presented the results of a solenoid stress analysis as a voluminous numerical tabulation of the mechanical displacement, stress, and strain for each layer of the solenoid under consideration. With version 3 of program STANSOL, this output data is still available as it is printed out on a data channel for future examination; however, two more concise methods are available to inspect the results of an analysis. The best method is graphical examination - which is the subject of the next section of this paper. The quickest method is to examine the output extremum table that is typed out on the user's terminal.

The output extremum summary individually lists maximum and minimum stress and strain for each material type in the solenoid. Rapid evaluations of the overall stress analysis are possible from the quick examination of the extremum summary. Parametric studies benifit enormously from this output data.

Output Data Representation Using Computer Graphics

Instead of having to digest the printout of program STANSOL, a computer graphics capability has been developed to examine the results of an analysis. A subroutine was added to program STANSOL to plot the mechanical displacement, stress, and strain directly on the screen on a user's Tektronix terminal (of any compatable equipment) using standard Tektronix software. Figure 1 and 2 are representative example plots produced by version 3 of program STANSOL.

The general problem and case description are plotted as page titles for future output identification as well as the date and time of program execution. The units used to represent the data are drawn as annotation to the x- and y-axis labels. The title of the plot is indicative of the type of loads that have been applied to produce the variable's distribution. Distinguishing symbols are used to differentiate between material types. To simplify the plotting subroutine, a straight line is drawn between the dependent variable values at the inner and outer radial locations for a given layer material, instead of drawing a smooth curve. This technique is generally sufficient since the distance within one layer is usually such a small interval.

Another method of producing plots is available with the new version of program STANSOL. A special data file is created by the plotting subroutine that contains coordinates of the end points of the lines that represent the requested variable's distribution. This special data file is written in a format suitable

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Fig. 1. A plot generated by version 3 of program STANSOL showing the predicted radial distribution throughout the EBT-P development coil D1.

Fig. 2. A plot generated by version 3 of program STANSOL showing the predicted tangential distribution throughout the EBT-P development coil D1.

for the MAPPER[7] program. By using a LOCATE MAPPER command and a few other easy to learn instructions, plots like fig. 3 can be generated.

Frictionless Gap Solution Capability

By using the linear solution derived in Ref. 3 and incremental loading, a piecewise-continuous, nonlinear solution may be assembled for magnets in which frictionless gaps are permitted to open and close. By choosing load increments that correspond to incipient frictionless gap formation or termination, complex, geometrically nonlinear structural behavior can be mathematically modeled. Within each loading increment a linear solution is calculated for each continuous section of the solenoid. (In the limit there could be as many sections as there are layers, since, in principle, there could be a gap between each layer.)

Each gap formation modifies the solution boundary conditions by introducing another interface where the radial stress (and, therefore, the interface pressure) must be zero. Each gap termination removes the corresponding gap-introduced radial stress boundary condition. The solution increment for each section is added to the current solution, and the magnet is redivided (or recombined) into sections based upon the new gap definition. The next load increment is calculated, and the process is repeated until all the loads have been fully applied. Thus, because of this updating of the model's geometry, the solution becomes nonlinear even though within any solution increment, linear small displacement theory is used. This theory was programmed into version 3 of the STANSOL computer program using the mathematical steps presented in Ref. 6.

Fig. 3. A plot generated by MAPPER using data output from version 3 of program STANSOL showing the predicted radial and tangential stress distribution throughout the EBT-P development coil D1.

Conclusions

The latest updates to program STANSOL version 3 have been presented in this paper. Briefly summarized these updates (1) permit more flexibility in input data formatting, (2) enhance the output capabilities of the program by using computer graphics and extremum summaries, and (3) add an additional solution capability to calculate mechanical behavior of solenoids if frictionless gaps develop.

References

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Appendix

Free-Format Input Data Summary for Version 3 of Program STANSOL

Card Type 1

DESC Eighty columns of alphanumeric characters are read and stored as a general problem description. This data is used as a major heading for all subsequent output during this execution of program STANSOL. The first input card image is used for this purpose.

Card Type 2

DESCA Eighty columns of alphanumeric characters are read and stored as the case description. This data is used as a minor heading for all subsequent output during this execution of program STANSOL. The second input card image is used for this purpose.

Card Type 3

COMMENT Any comments which the user desires to include as distinguishing remarks for future interpretation of his input and/or output data. There is no limit to the number of comment cards.

Card Type 4

CT The type 4 input data card is a comment terminator. The dollar sign ($) character typed in column 1 serves as a delimitor for comments and thus terminates comment input data cards.

Card Type 5

r_{in} The vaiable r_{in} is the inner radius of the assembled magnet in inches.

w_1 The variable w_1 is the assembled length in the axial direction of the magnet in inches.

p_{in} The variable p_{in} represents a surface pressure to be applied to the inner surface of the assembled magnet. The units of p_{in} are psi.

p_{out} The variable p_{out} represents a surface pressure to be applied to the outer surface of the assembled magnet. The units of p_{out} are psi.

DMULT This variable is no longer supported.

MODE This variable is no longer supported.

IPLTCN The variable IPLTCN controls the generation of computer graphic output. If IPLTCN is equal to zero, then computer graphic output is not generated. If IPLTCN is not equal to zero, then it is used to indicate which variable distribution is to be drawn.

Card Type 6

Since program STANSOL is a general purpose program that permits multilayered, nonhomogeneous solenoids to be mathematically modeled, a convenient method was derived to allow the multilayered design of a solenoid to be input to the program with a minimum of effort. As most solenoids have a repetative design to their winding pack, the method chosen was based upon the concept of layer sets. A layer set is defined as a set of layers of materials that repeat themselves somewhere within the magnet. For example, consider a magnet with 50 radial turns of superconductor that is insulated turn-to-turn with a spiral wrap of insultation and further insulated layer-to-layer with a sheet of insulating material. Use material number 1 to represent the superconductor, number 2 to represent the turn-to-turn insulation, and number 3 to represent the sheet insulation, then the layer geometry may be described by the material number sequence 2,1,2,3 repeated 50 times. Program STANSOL simplifies the required amount of input data by reading a repeat count for the number of layer sets followed by the layer set material number definition. Obviously, if a nonrepetative material, such as a bobbin, is to be input, then a repeat count of 1 followed by a single matering number can be specified.

MNLSET The variable MNLSET is the number of material layer sets defined on this card. It is the repeat count for the following material number layer definition. Layer set one begins with the first layer and proceeds radially outward through the magnet.

$MN_1,\ldots,MN_8$ The variables MN_1 through MN_8 represent the material numbers for this layer set. Currently, there can be a maximum of 8 material numbers per layer set definition.

A blank card terminates card type 6 input data.

Card Type 7

Like the material layer sets defined and used on card type 6, the concept of a load layer set is used to simplify input data for the load definition. Usually, these data are an echo of the material layer set definition; however, there are special cases where the added flexibility of having a different load number from that of a material number for a given layer is required.

LNLSET The variable LNLSET is similar to MNLSET except it refers to the repeat count for the load layer sets defines on this card.

$LN_1,\ldots,LN_8$ The variables LN_1 through LN_8 represent the load numbers for this layer set. Currently, there can be a maximum of 8 load numbers per load layer set definition.

A blank card terminates card type 7 input data.

Card Type 8

Type 8 input data card images define the material properties for a particular material number. The material number is the pointer used on card type 6 to identify the magnet geometry by associating a layer material number with a group of material properties.

MN The variable MN is the material number to be associated with the following set for material properties. MN has a one-to-one correspondence with a material number input on card type 6.

TT The variable TT is the layer thickness in inches for material number MN.

WT The variable WT is the axial length of the magnet used to determine the winding preload for material number MN.

E_θ The variable E_θ is the Young's mudulus in the tangential (or hoop) direction for material number MN. The units of E_θ are psi.

$\nu_{\theta r}$ The variable $\nu_{\theta r}$ is the major Poisson's ratio $(-\epsilon_r/\epsilon_\theta)$ for material number MN.

a_θ The variable a_θ is the thermal coefficient of contraction (expansion) in the tangential direction for material number MN. The units of a_θ are in/in/K. The material is assumed to be isotropic if the remainder of the data card is blank.

E_r The variable E_r is the Young's mudulus in the radial direction for material number MN. The units of E_r are psi.

$\nu_{r\theta}$ The variable $\nu_{r\theta}$ is the minor Poisson's ratio $(-\epsilon_\theta/\epsilon_r)$ for material number MN. The reprocality relationship will be used to define this variable if it is not defined on this data card.

a_r The variable a_r is the thermal coefficient of contraction (expansion) in the radial direction for material number MN. The units of a_θ are in/in/K.

There must be one type 8 input data card for every layer material number defined on the type 6 input data cards. A blank card terminated type 8 input data.

Card Type 9

These input card images define the load types and magnitudes for a particular load number. The load number is the pointer used on card type 7 to identify the layers that are loaded.

LN The variable LN is the load number used on card type 7.

DENST The variable DENST is the current density in the units of A/cm² for load number LN.

PLDT The variable PLDT is the winding preload in units of lb_f/in of axial length for load number LN.

WPT The variable WPT is the axial length of the magnet used to determine the winding preload for load number LN. The units of WPT are inches.

TEMPT The variable TEMPT is the differential temperature to be applied to the layer for load number LN. The units of TEMPT are degrees C or K.

There must be one type 9 input data card for every layer load number defined on the type 7 input data cards. A blank card terminated type 9 input data.

Card Type 10

These input card images define the magnetic field distribution for the magnet. The magnetic field distribution is input as a table of points of radii versus magnetic field. The radii, magnetic field point pair must be input in order of sequentially increasing radii. The radii do not have to correspond to any physical location in the magnet as a table lookup is automatically performed for the user when the value of the magnetic field is needed at a particular radial coordinate. The units for the radii, magnetic field point data are inches and Tesla, respectively. A blank radii, magnetic field point pair terminates type 10 input data. There can be a maximum of 4 radii, magnetic field points per card type 10.

R_1, B_1 The variables R_1, B_1 represent the magnetic field B at the radial coordinate R.

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R_4, B_4 The variables R_4, B_4 represent the magnetic field B at the radial coordinate R.