NASA Technical Memorandum 86378

Effect of Superconducting Solenoid Model Cores on Spanwise Iron Magnet Roll Control

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SUMMARY

A preliminary study has been made of the effect of the superconducting solenoid fuselage model core concept on the spanwise iron magnet roll torque generation scheme for wind tunnel magnetic suspension and balance systems (MSBSs). Computed data for one representative configuration indicate that reductions in available roll torque occur over a range of applied magnetic field levels. These results indicate that a 30-percent increase in roll electromagnet capacity over that previously determined will be required for a representative 8-foot wind tunnel MSBS design.

INTRODUCTION

Magnetic suspension and balance systems (MSBSs) have been under development for many years. The goal in developing these systems is to provide improved wind tunnel test capability (ref. 1). Potential advantages of an MSBS include the complete elimination of model support interference, which is thought to be particularly important in the transonic regime, and the provision of enhanced dynamic test capability. However, certain technical problems remain to be fully resolved before construction of a large-scale facility can be attempted. Among these problems are the generation of sufficient magnetic roll torques and the high apparent cost of a large MSBS facility (ref. 2).

During large-scale testing of winged aircraft models, strong aerodynamic rolling moments are likely to be generated, particularly at high angles of attack or sideslip. If an MSBS is used to support and restrain the test model, these loads will normally be opposed magnetically. Thus a powerful method of magnetic roll torque generation will be essential for the operation of a large MSBS (LMSBS). Considerable research effort has been devoted to the provision of an adequately powerful magnetic roll torque generation scheme for LMSBSs. The spanwise iron magnet (SIM) scheme appears to be the most powerful of numerous methods studied to date. Computer predictions indicate that the SIM technique is capable of satisfying requirements relating to an 8-foot, Mach 0.9 atmospheric wind tunnel with representative aircraft models (ref. 3).

Magnetic cores are always installed in the fuselage of an MSBS model for the production of forces and torques other than roll. The SIM scheme utilizes additional cores mounted in the wings of the model for the production of roll torque. Previously, all cores consisted of ferromagnetic materials, which were typically magnetically soft (i.e., had low coercivity). These will hereafter be referred to as soft iron materials. A new design concept for the fuselage core is currently under investigation and promises a substantial reduction in projected LMSBS costs. This design completely replaces the soft iron fuselage core with a superconducting solenoid core (ref. 4) of significantly higher magnetic moment. This concept will impact SIM performance, perhaps adversely, because it will introduce strong additional magnetic fields in the region of the wing cores and force geometrical adjustments to those cores.

A search for new techniques of roll torque generation which exploit the presence of the superconducting solenoid fuselage core has commenced (ref. 5) but is still at an early stage.

This study represents a preliminary assessment of the effect of the existing superconducting solenoid fuselage core concept on the performance of the SIM roll torque scheme.

SYMBOLS AND ABBREVIATIONS

B	magnetic flux density (tesla)
E_m	magnetizing field electromagnet
E_r	through-wing field electromagnet
H	magnetic field strength (A/m)
I_D	current density (quoted in A/cm^2 here)
L	magnetic roll torque about x-axis, N-m
M	magnetization (tesla)
N,S	north/south magnetic poles
x,y,z	axis system with origin at geometrical center of tunnel test section; x into wind, z downwards
x',y'	transformed axis system used for wing core magnetization distribution plots (figs. 8 to 10)
μ	relative permeability of material
μ_o	permeability of free space ($4\pi \times 10^{-7}$ H/m)
LMSBS	large magnetic suspension and balance system
MSBS	magnetic suspension and balance system
SIM	spanwise iron magnet

SPANWISE IRON MAGNET ROLL TORQUE GENERATION

In the SIM scheme, the wings of the suspended model are constructed wholly or partly of soft iron core material. These cores are magnetized, primarily in the spanwise direction and symmetrically about the fuselage centerline, by suitable externally applied magnetic fields. Roll torque is generated by interaction between the spanwise magnetization components and the applied through-wing fields (ref. 3). This torque is due partly to an $\mathbf{M} \times \mathrm{H}$ (compass needle) effect and partly to the development of vertical force components along the wing span. Figure 1 illustrates typical electromagnet and wing core configurations.

The SIM magnetic configuration is inherently three-dimensional and can be nonlinear (for example, when magnetic core saturation is encountered). The general problem is therefore analytically intractable, and performance predictions require the use of a complex finite-element computer program. Extensive calculations encompassing a wide variety of core and external electromagnet geometries were made in 1981 using the program GFUN (ref. 6). Program predictions were corroborated at low applied field levels for simplified configurations (ref. 3). All computations implicitly assumed the presence of a conventional magnetically soft fuselage core, although because of restrictions on allowable geometrical complexity, most calculations were made with the fuselage core absent except insofar as the wing core was considered to be continuous through the fuselage region. It was felt that this approach was reasonable, since the addition of a soft iron fuselage core was shown to tend to augment the roll torque by small percentages for particular cases. This effect was presumed to be due to the provision of an easy flux path at the wing root (ref. 3).

SUPERCONDUCTING SOLENOID MODEL CORES

This type of core consists of a high-field superconducting solenoid mounted in a cylindrical liquid helium dewar, as illustrated in figure 2. Such a core arrangement is magnetically equivalent to a very powerful axially magnetized permanent magnet core. The solenoid is operated in persistent mode; that is, with its winding short-circuited and all external leads removed after charging (filling with liquid helium and initiating current flow). A small-scale prototype superconducting solenoid core has been successfully demonstrated (ref. 4). This type of core design promises significantly higher values of LMSBS fuselage core magnetic moment than those achievable with ferromagnetic cores. Values could be higher by as much as a factor of 2 at sizes appropriate for the 8-foot test section case (ref. 7). The required sizes (hence cost) of the external electromagnets (not including those required for roll torque production) can be reduced by a similar proportion. This possibility made the exploitation of this core concept desirable.

To maximize performance (magnetic moment and run time) with superconducting solenoid models, it is necessary to utilize all available volume for insulation, superconducting windings, or liquid helium space (refs. 4 and 7).

It is immediately apparent, as illustrated in figure 2, that some of the volume previously assumed to be available for wing cores is now occupied by the superconducting solenoid core. Further, the solenoid creates an intense external field in the region of the remaining wing cores. The induced magnetizations and perhaps the roll torque generated will be affected by this field.

At low applied field levels, the wing cores will be operating in a high-permeability region of their magnetization characteristic. Under these conditions the induced magnetizations will be dominated by the external air path. Thus the induced magnetization components from the fuselage field will simply be additive, in the vectorial sense, to those from other applied fields.

If the model exhibits suitable fore-and-aft symmetry, as is the case with centrally mounted unswept wings, the magnetization components due to the fuselage fields will not produce torque by themselves, and therefore will not affect the net roll torque generated, as shown in figure 3. However, previous calculations clearly indicated that the wing cores would normally have to be operated far into saturation in order to achieve the required roll torque capability (ref. 3). Under these conditions, the additional magnetic fields due to the fuselage solenoid will not result in extra magnetization components adding vectorially, as before. Rather, the strength of the induced magnetization vectors will remain more or less fixed (at the saturation value; perhaps greater than 2 tesla) and the fuselage field will result in rotation of the (saturated) wing core magnetization vectors away from their nominally spanwise directions. In the fore-and-aft symmetric case, this rotation will tend to reduce the spanwise components of magnetization and hence reduce the roll torque generated for any given applied fields. (See fig. 3.) Cases in which there is no fore-and-aft symmetry are more complex. The relative polarity of the fuselage becomes important, and either reductions or increases in roll torque are conceivable when the fuselage field is applied, with or without core saturation.

Assessment of the magnitudes of these effects is clearly of interest, since they might, at worst, preclude simultaneous use of a superconducting solenoid fuselage core and the SIM roll torque scheme.

F-16 WING CORE STUDIES

It was decided to exploit the existing SIM data base by recalculating a representative configuration, with the necessary geometrical adjustments, using the same computer program GFUN. A representative aircraft geometry previously chosen for LMSBS design studies, including roll torque generation, is the F-16 fighter (refs. 3 and 7). This geometry presents a challenging case for the SIM roll torque scheme since the wing volume available for magnetic core is very limited. Nevertheless, computations described in reference 3 showed that roll torque capability was adequate for anticipated LMSBS requirements.

Figure 4(a) shows the wing core geometry and finite-element distribution used in the original computations. The modifications required to this geometry consisted of insertion of the fuselage break and revision of the element distribution, as shown in figure 4(b). The width of the break corresponds to fuselage core dimensions specified in previous LMSBS design studies (refs. 7 and 8). The magnetic properties of the wing core material were represented by the BH curve shown in figure 4(c) and were determined from core material recommendations given in reference 8. Figure 5 shows the external geometry and configuration of the electromagnets. These remained unchanged from those used in the original computations.

Because design studies of superconducting solenoid model cores are still in their early stages, the choice of a particular solenoid specification for these computations is somewhat arbitrary. For simplicity, the model design emerging from the most recent LMSBS design study was chosen (ref. 7), as illustrated in figure 6. Since a swept wing core is not symmetric in the y-z plane, the polarity of the fuselage solenoid is significant. The polarity chosen (illustrated in fig. 7) rotates the magnetization vectors in the region of the wing tips to a more nearly spanwise orientation. Therefore, this choice was expected to affect torque less than would the opposite polarity. However, subsequent data analysis indicated very powerful adverse effects in the region of the wing roots. No data for opposite fuselage polarity (relative to the wing cores) are available.

WING CORE MAGNETIZATION DISTRIBUTIONS

The computation of induced magnetization distributions with GFUN, particularly where iron cores are partly or wholly saturated, is time consuming and subject to significant error, and therefore was not attempted. However, some GFUN results are available for linear calculations ($\mu = 1000$) and are presented in figures 8 and 9 to illustrate some general points. These data, in fact, represent the results of the first stage in GFUN's iterative solution procedure. Figure 10 gives the coordinate transformation used in the magnetization plots of figures 8 and 9. A simplified pictorial interpretation of the information in figures 8 and 9 is presented in figure 11.

When the superconducting solenoid is absent, induced magnetization is seen to be predominantly spanwise with the highest values near the wing tips (figs. 8(a) and 9(a)). When the superconducting solenoid is included the picture changes dramatically. Large axial and adverse spanwise components appear near the wing root, and their effect is to deplete the spanwise components around the wing tip (figs. 8(b) and 9(b)). Since the peak magnitudes of the fuselage-induced magnetization are considerably above the saturation value (2.3 tesla), the final magnetization distributions, with the effects of saturation incorporated, would not closely follow the distributions of figures 8 and 9. Instead, the peak induced magnetizations would be attenuated, and the effect on areas of lower magnetization would not be clear.

Contour plots of the computed field distributions in the region of the wing cores due to the external electromagnets and the superconducting solenoid are shown in figures 12 and 13, respectively.

ROLL TORQUE CAPABILITY

GFUN roll torque computations include the full effect of core saturation (BH curve as in fig. 4(c)). Roll torque at any given applied field level appears to be only slightly diminished by the reduction in core volume, as shown in figure 14. This slight reduction corresponds to previous results concerning a rectangular "slab" core (ref. 3) and is due to the fact that the core material close to the wing root has a short moment arm about the usual roll axis and tends to be rather weakly magnetized by the quadrupole roll fields (fig. 1). The effect of the presence of the superconducting solenoid is very significant, as shown in figure 14. The percentage of roll torque lost is particularly high at low applied field levels. Around the region of interest (140 N-m, which corresponds to existing design study specifications (refs. 7 and 8)), at least 30 percent higher applied fields are required to meet the roll torque requirement.

Reversal of the fuselage polarity might reverse the apparent adverse effects on the magnetization distribution around the wing root, and hence deplete roll torque by a lesser amount or even augment it, but the relevant data are not available.

CONCLUDING REMARKS

For the case studied here, the spanwise iron magnet (SIM) roll torque scheme appears to be significantly affected by the presence of the superconducting solenoid fuselage core. With the core and external electromagnet configurations chosen, roll torque is seriously depleted at low applied field levels, but is somewhat less affected at higher fields. If these results prove typical, the increase in roll field capability necessary to satisfy the full specified roll torque requirement for existing large magnetic suspension and balance system (LMSBS) design studies (more than 30 percent here) is a serious concern. However, in the context of the current relatively early stage of LMSBS technical development, such a factor might be considered acceptable. Whether variations in relative core polarity or the choice of alternative geometries would alleviate the adverse effects of the external field of the superconducting solenoid remains to be determined.

The results presented in this report are too limited and specific to permit general conclusions to be drawn concerning the use of the SIM roll torque scheme with a superconducting solenoid fuselage core. It is clear, however, that the fuselage core interacts strongly with the wing cores. The feasibility of LMSBSs presently appears to depend heavily on the successful exploitation of the superconducting solenoid concept. Therefore further studies of its interaction with the SIM roll torque scheme would be appropriate, as would continued efforts to develop alternative schemes of roll torque production.

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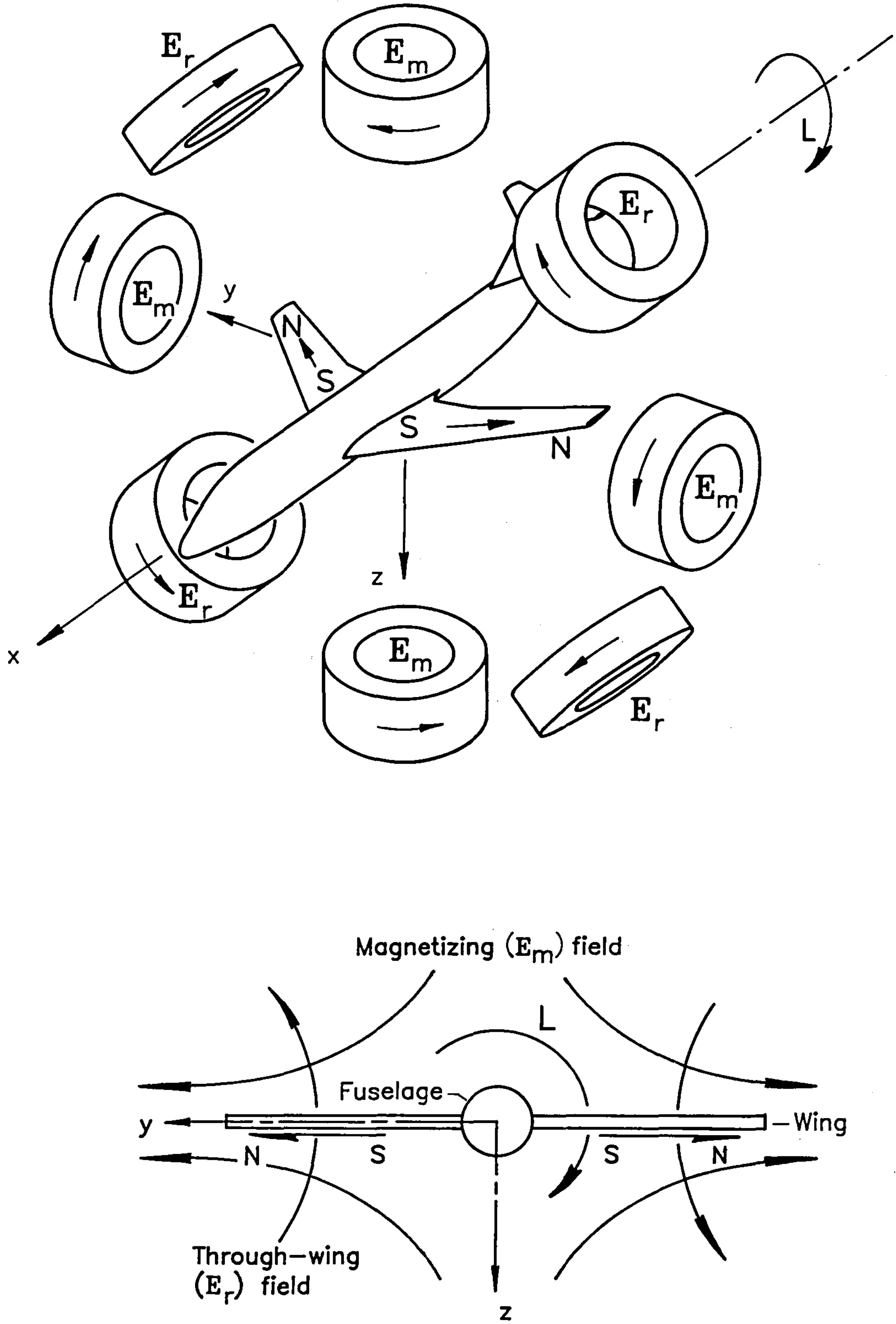
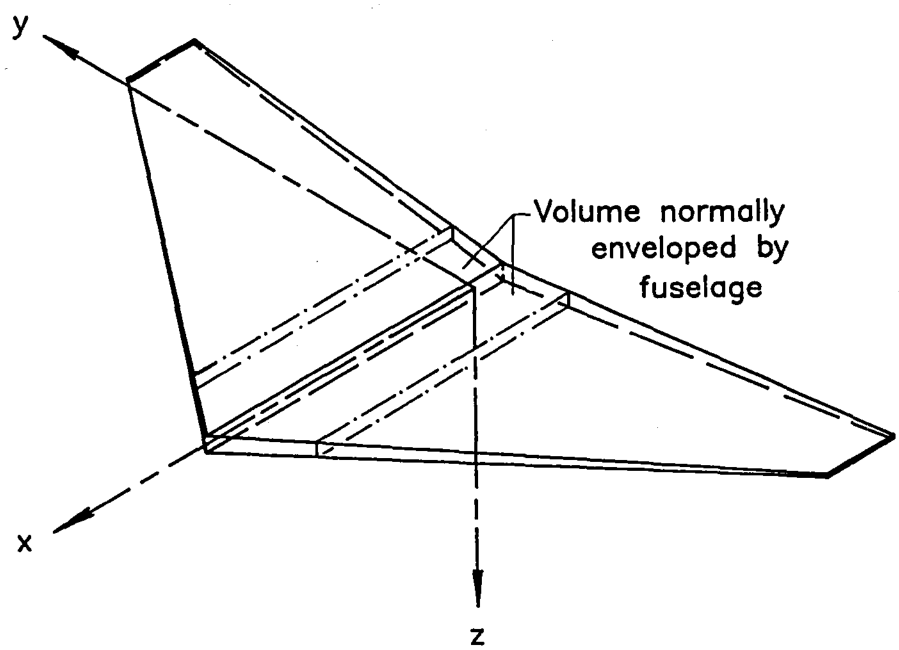
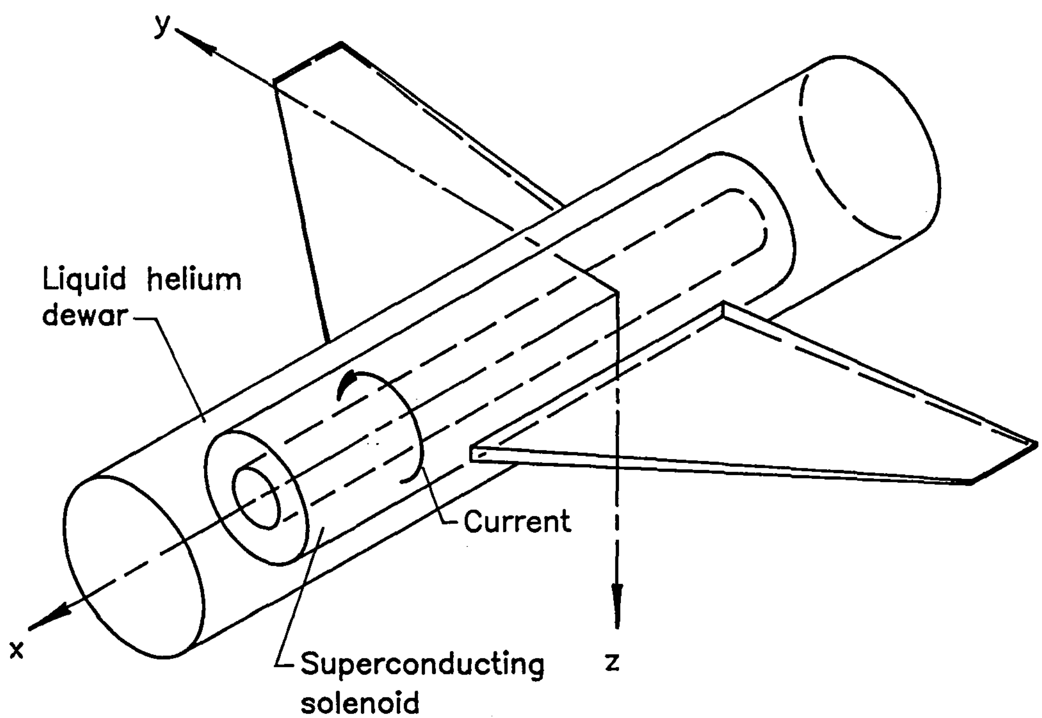


Figure 1.- Typical electromagnet and wing core configurations. Electromagnets E_m magnetize wing cores. Electromagnets E_r produce torque.

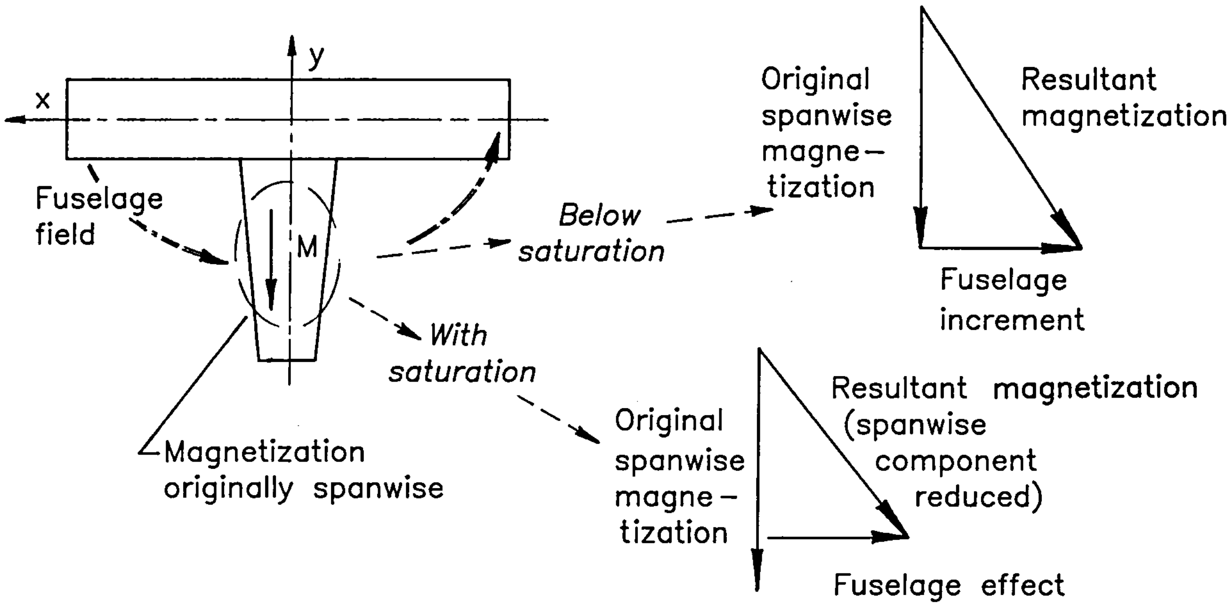


(a) SIM core with no fuselage.

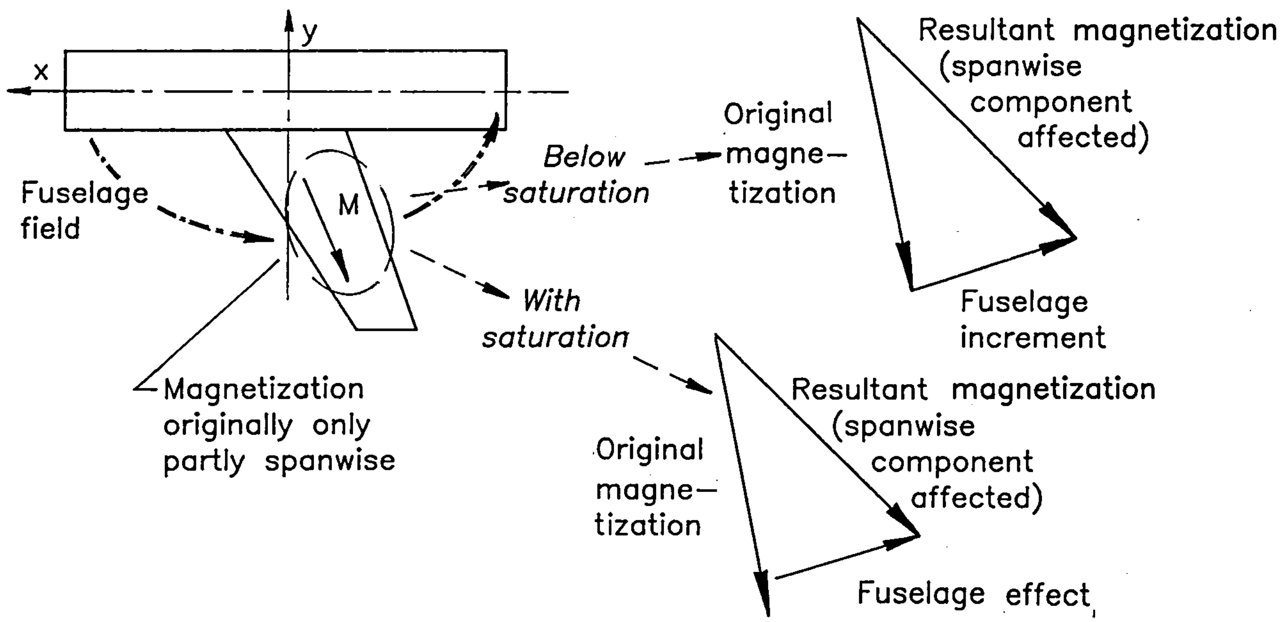


(b) SIM cores with superconducting solenoid fuselage core.

Figure 2.- SIM and superconducting solenoid fuselage cores.

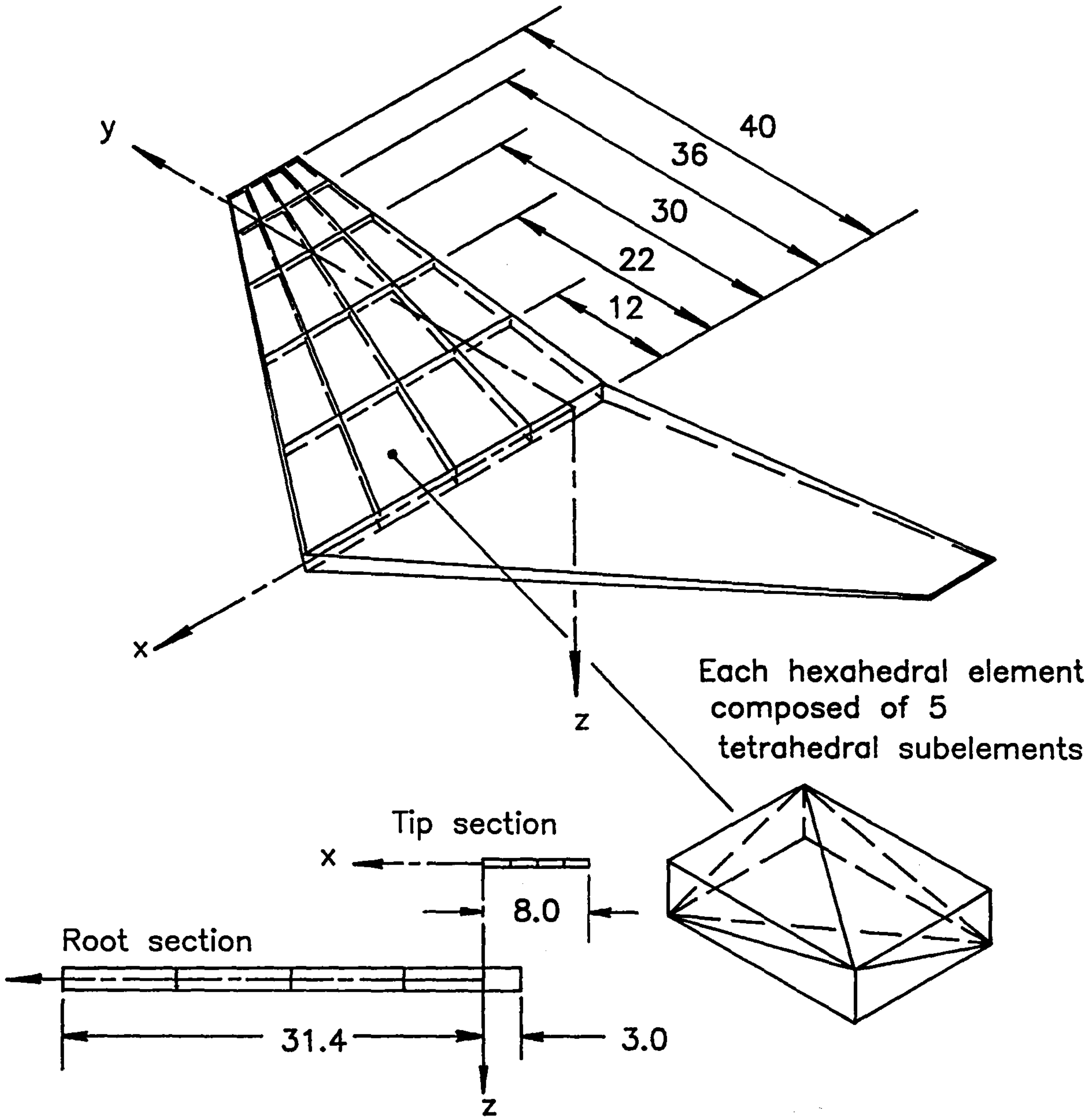


(a) Configuration symmetrical in y-z plane (unswept wing).



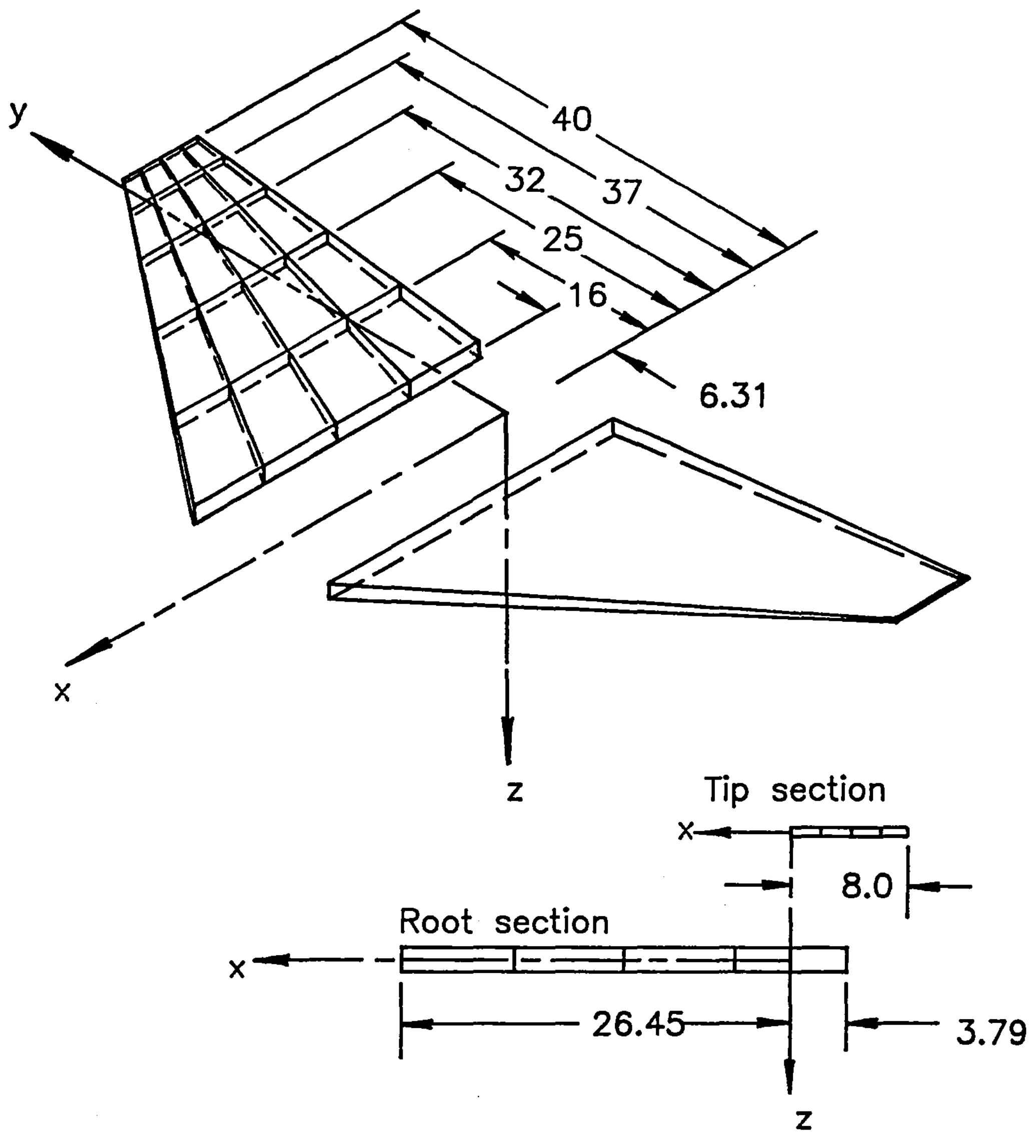
(b) Configuration unsymmetrical in y-z plane (swept wing).

Figure 3.- Effect of fuselage core field on roll torque generation.



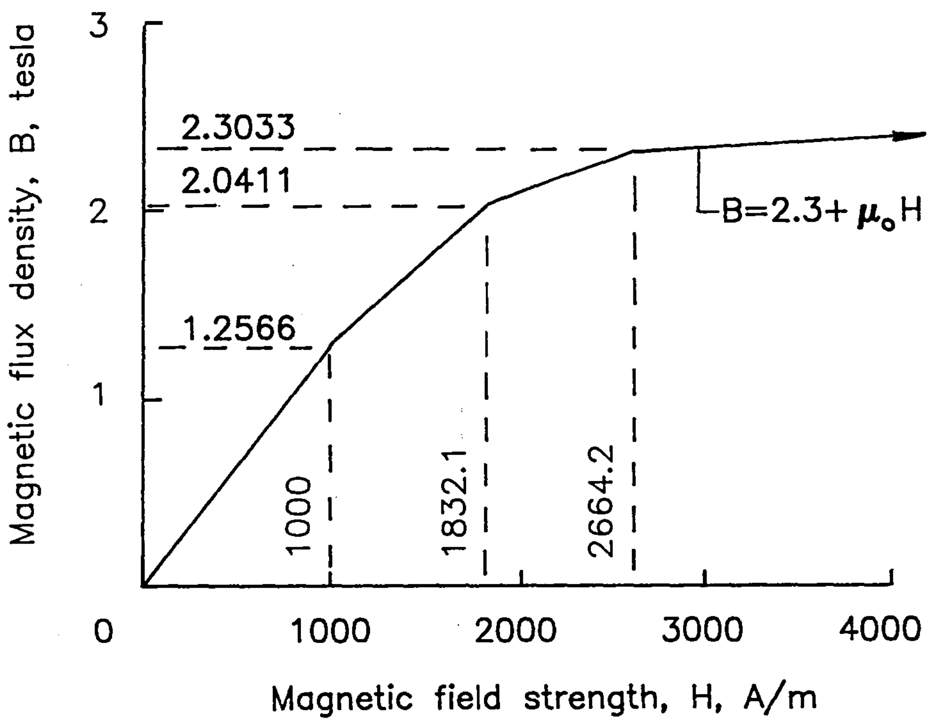
(a) Original baseline geometry. BH curve as in figure 4(c). Dimensions in centimeters.

Figure 4.- F-16 wing core geometry.



(b) Modified geometry. BH curve as in figure 4(c). Dimensions in centimeters.

Figure 4.- Continued.



(c) BH curve for original and modified cores. BH curve, initial permeability (μ = 1000), and saturation magnetization (2.3 tesla) representative of vanadium Permendur class (ref. 8).

Figure 4.- Concluded.

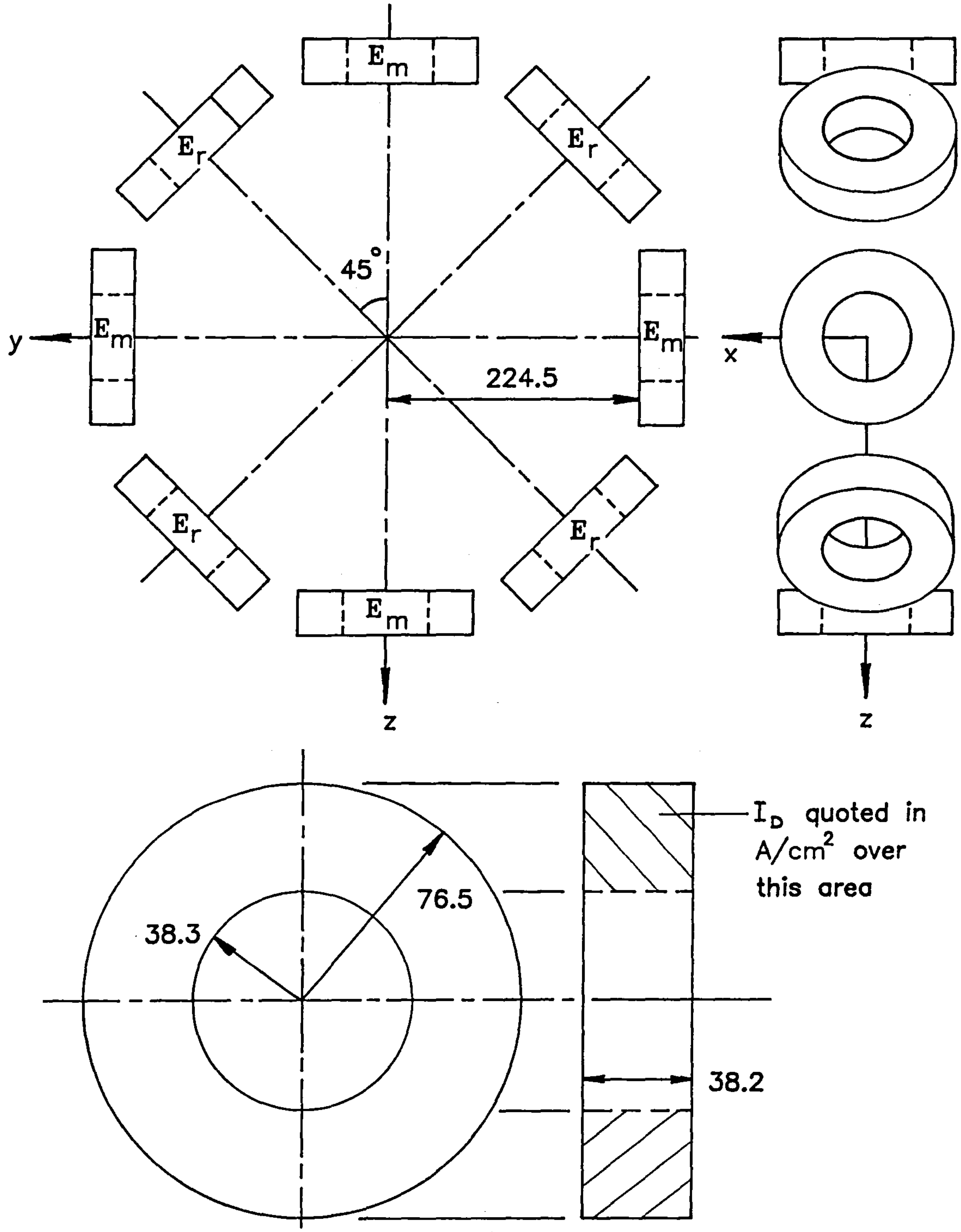


Figure 5.- External configuration of electromagnet. (All electromagnets identical.) Dimensions in centimeters.

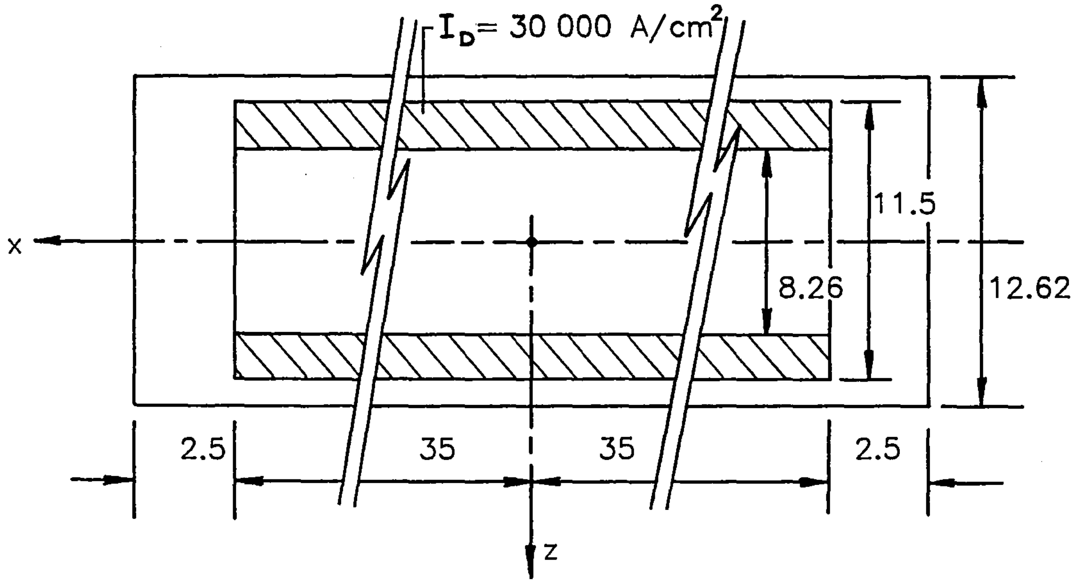


Figure 6.- Superconducting solenoid fuselage core geometry. Field at origin = 6.1 tesla. Equivalent magnetization = 3.5 tesla (based on total volume). Dimensions in centimeters.

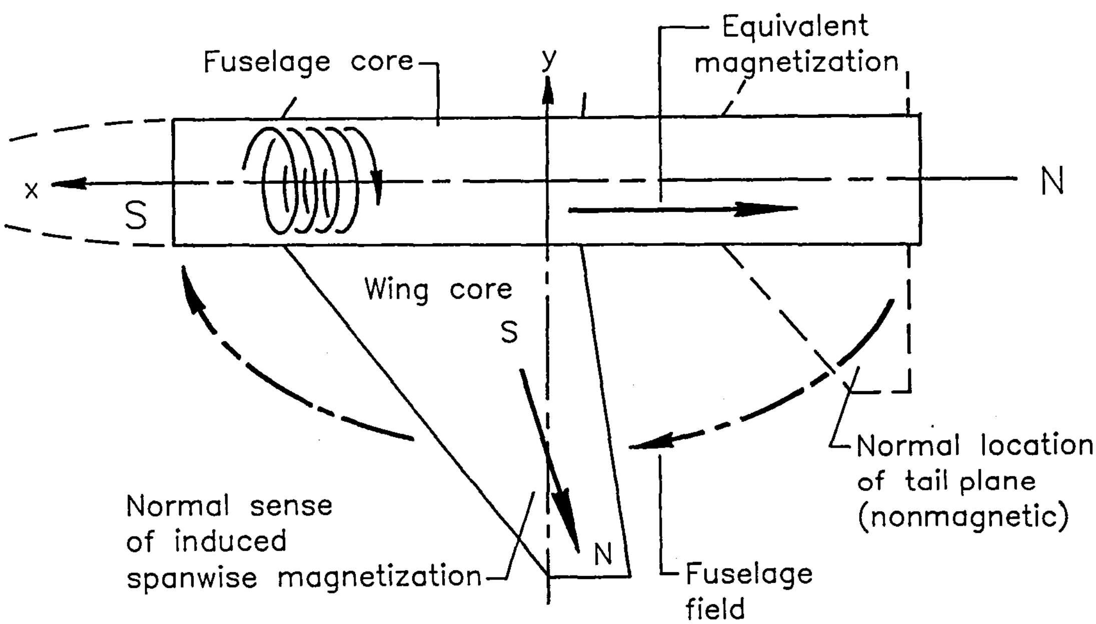
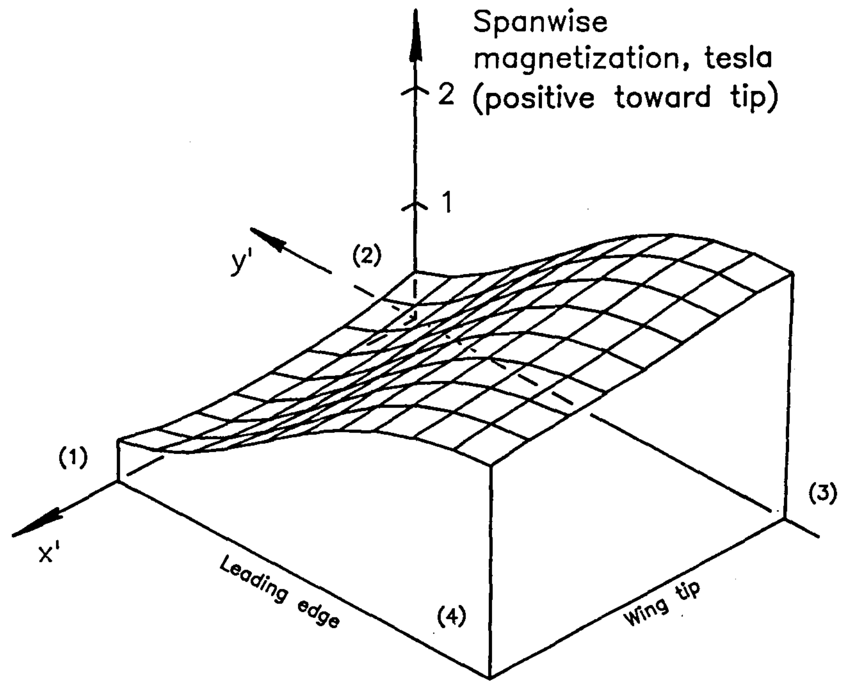
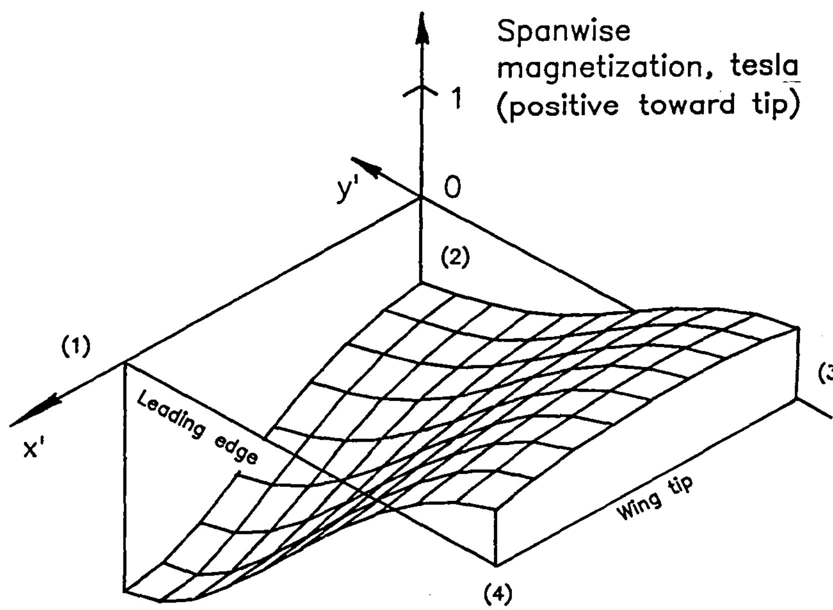


Figure 7.- Fuselage and wing core polarities.

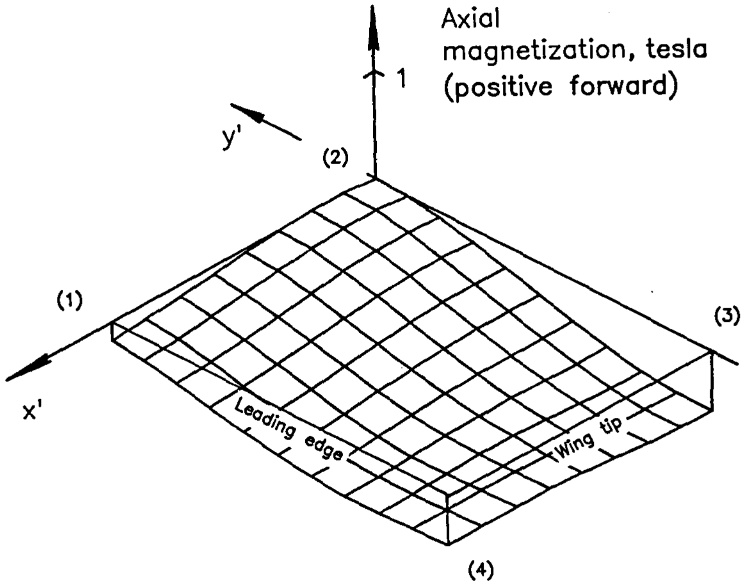


(a) Modified F-16 core alone (μ = 1000).

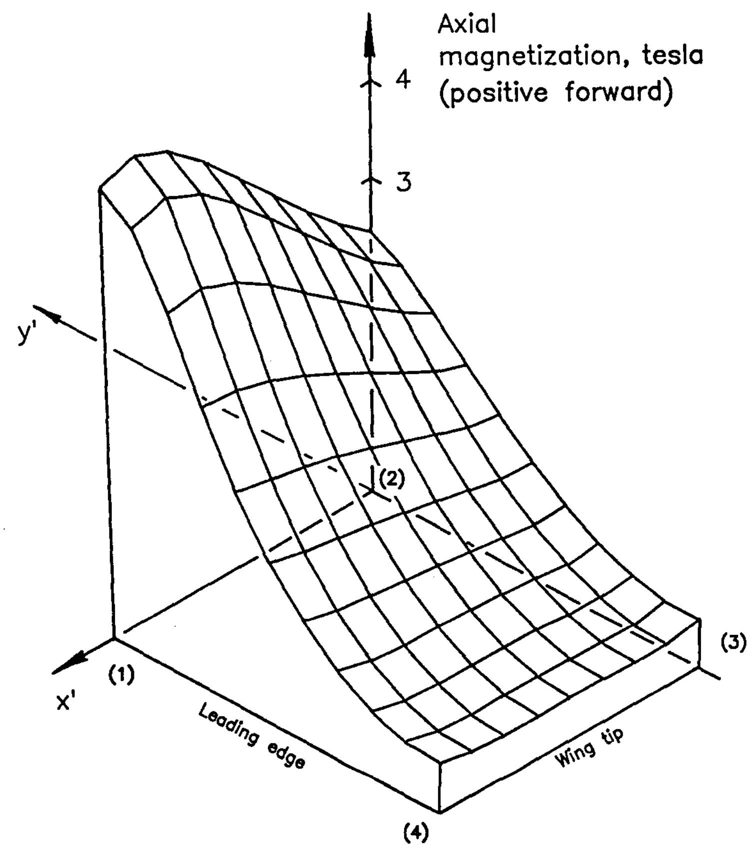


(b) Modified F-16 core with superconducting solenoid (μ = 1000).

Figure 8.- Spanwise magnetization distributions for F-16 core.

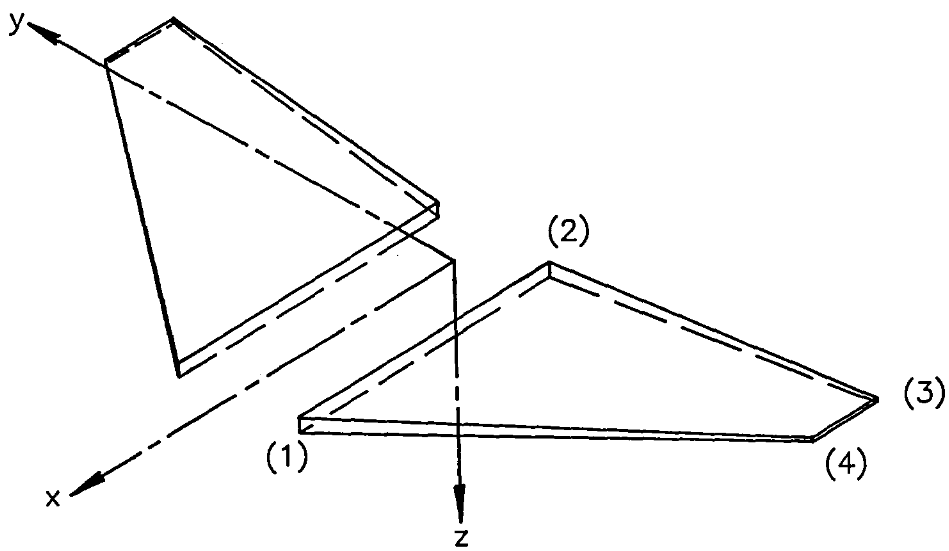


(a) Modified F-16 core alone (μ = 1000).

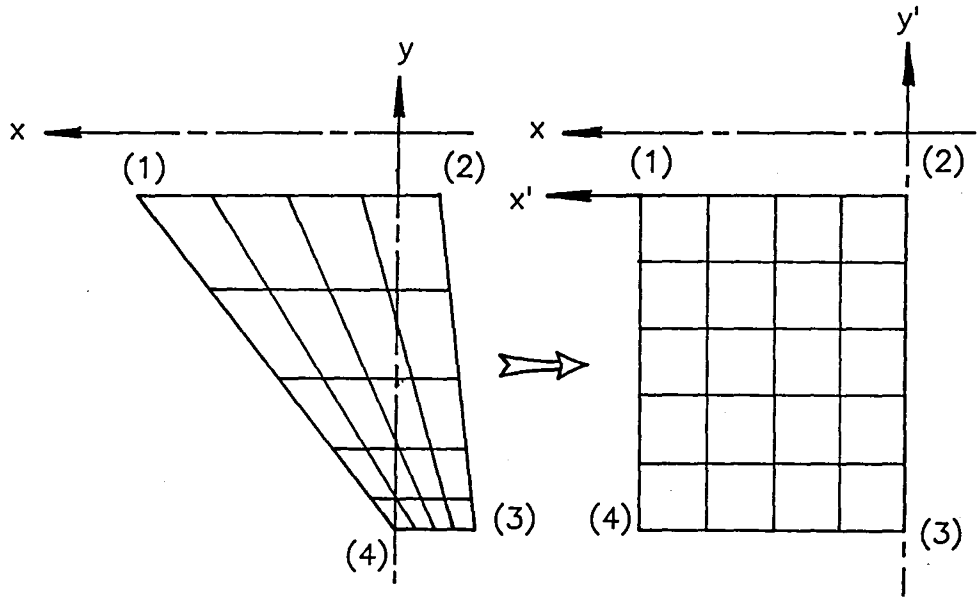


(b) Modified F-16 core with superconducting solenoid (μ = 1000).

Figure 9.- Axial magnetization distributions for F-16 core.

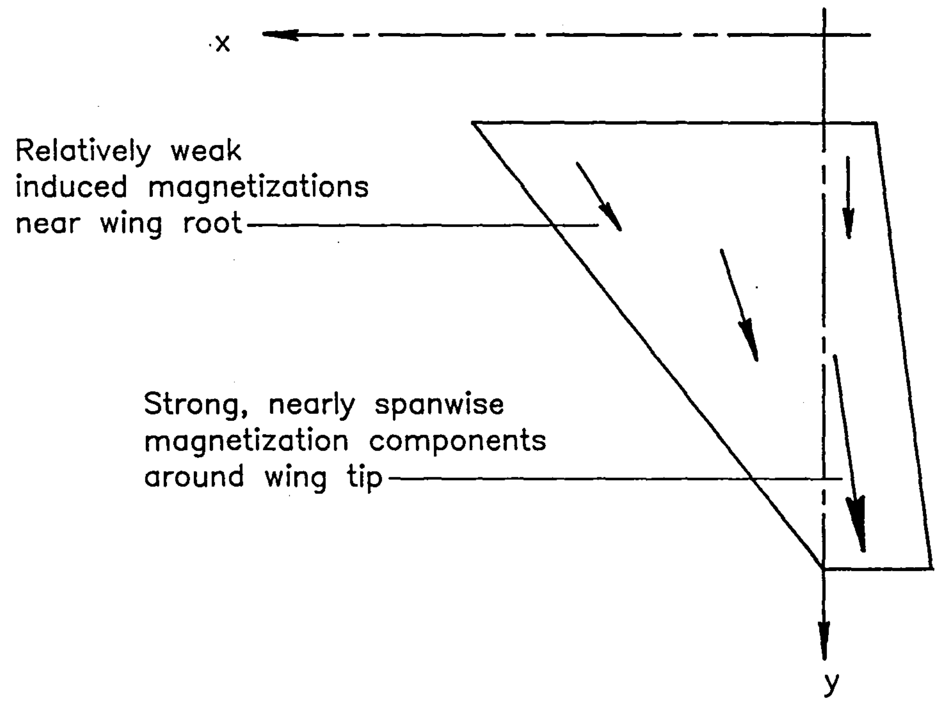


(a) Physical geometry.

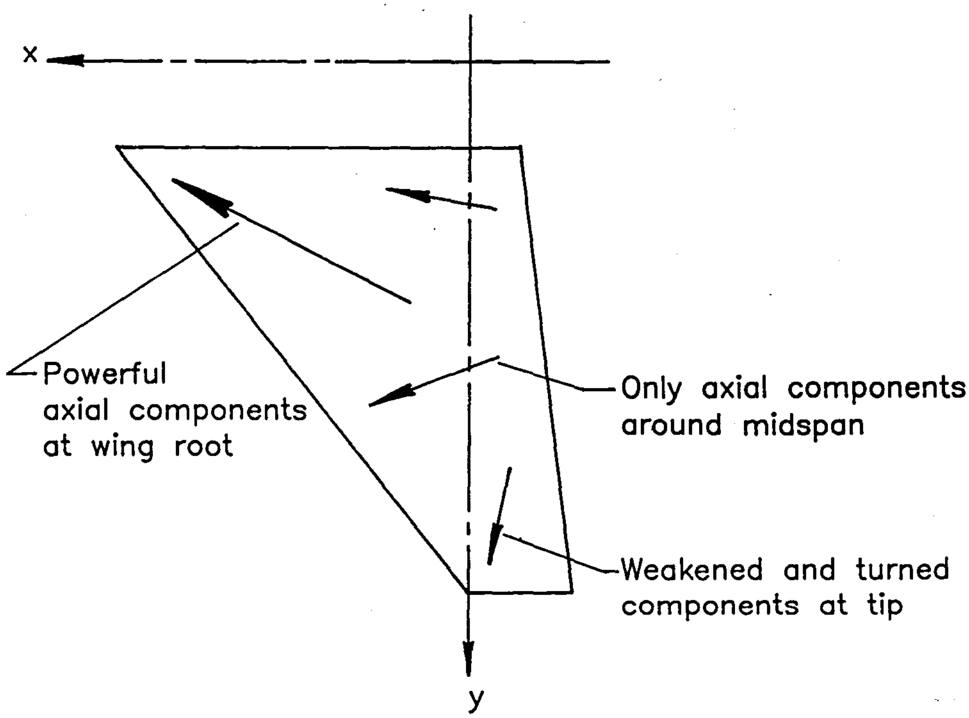


(b) Element transformation. Hexahedral elements transformed as shown. Magnetization computed at element centroids, interpolated at grid points.

Figure 10.- Coordinate system used for magnetization plots.

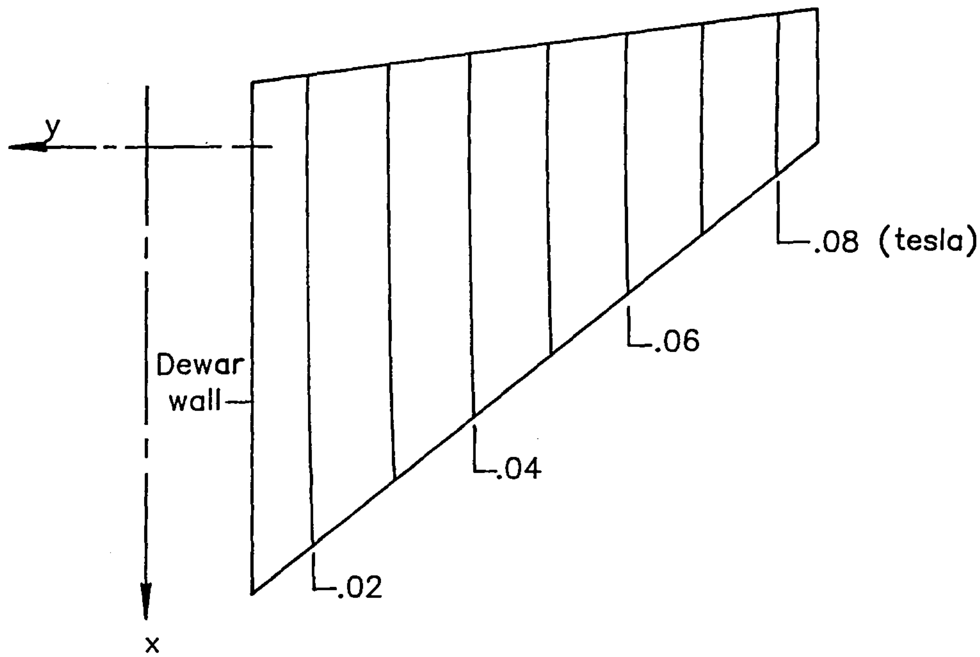


(a) Wing core alone.

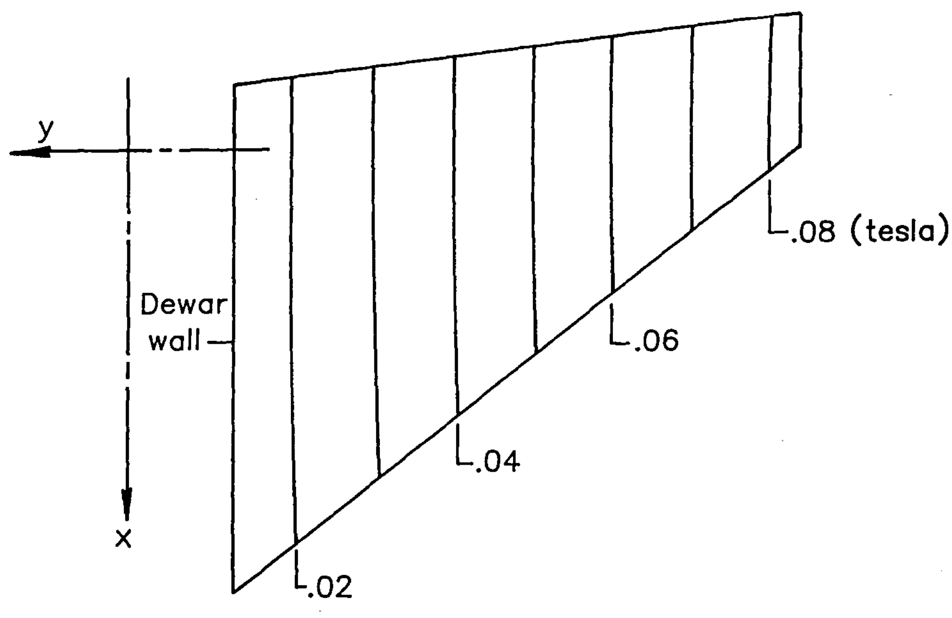


(b) Wing core with superconducting solenoid.

Figure 11.- Simplified wing magnetization distributions.

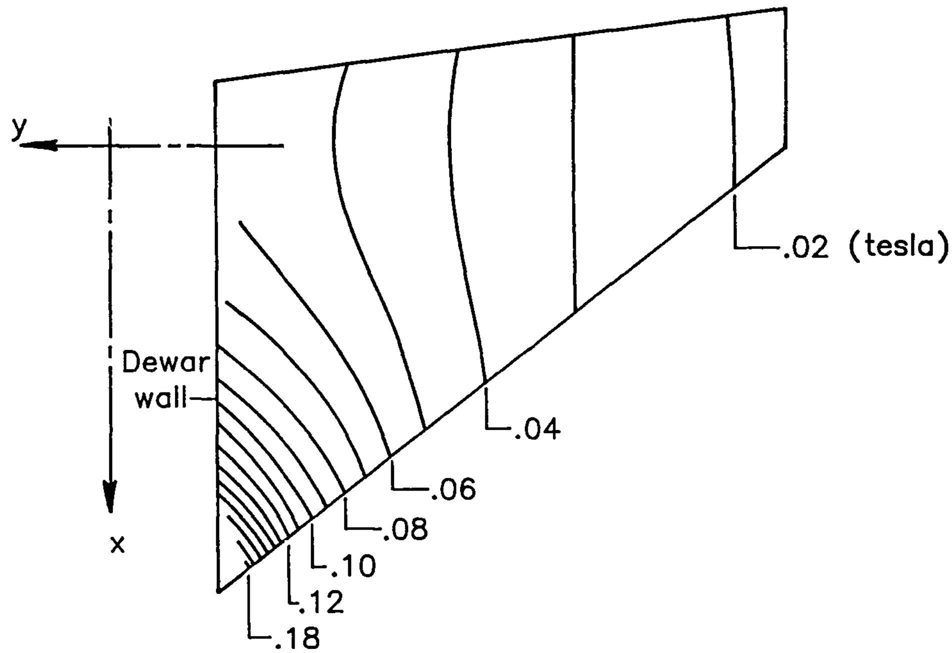


(a) Spanwise (y) component of magnetizing (E_m) field (positive toward tip). Other components negligible.

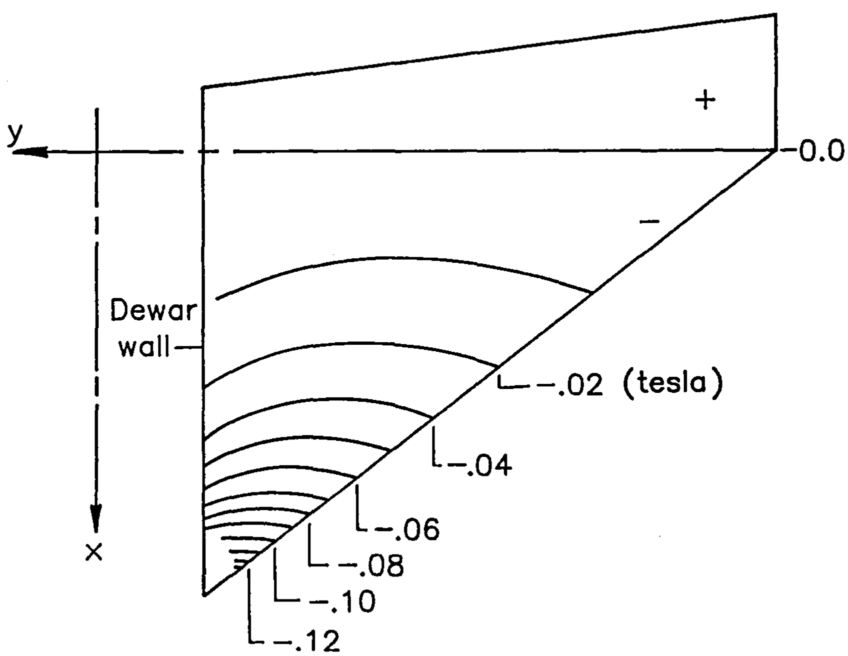


(b) Through-wing (z) component of through-wing (E_r) field. Other components negligible.

Figure 12.- Contour plots of magnetic field distributions in region of wing cores due to external electromagnets. Electromagnets as in figure 5. $I_D = 3000$ A/cm^2 (approximate design point for 8-ft wind tunnel). Fields are free-air values, SIM cores are absent.



(a) Axial (x) component of fuselage field (positive forward). Through-wing components negligible.



(b) Spanwise (y) component of fuselage field (positive toward tip).

Figure 13.- Contour plots of magnetic field distribution in region of wing cores due to superconducting solenoid. Superconducting solenoid fuselage core geometry as in figure 6. I_D = 30 000 A/cm^2. Fields are free-air values, SIM cores are absent.

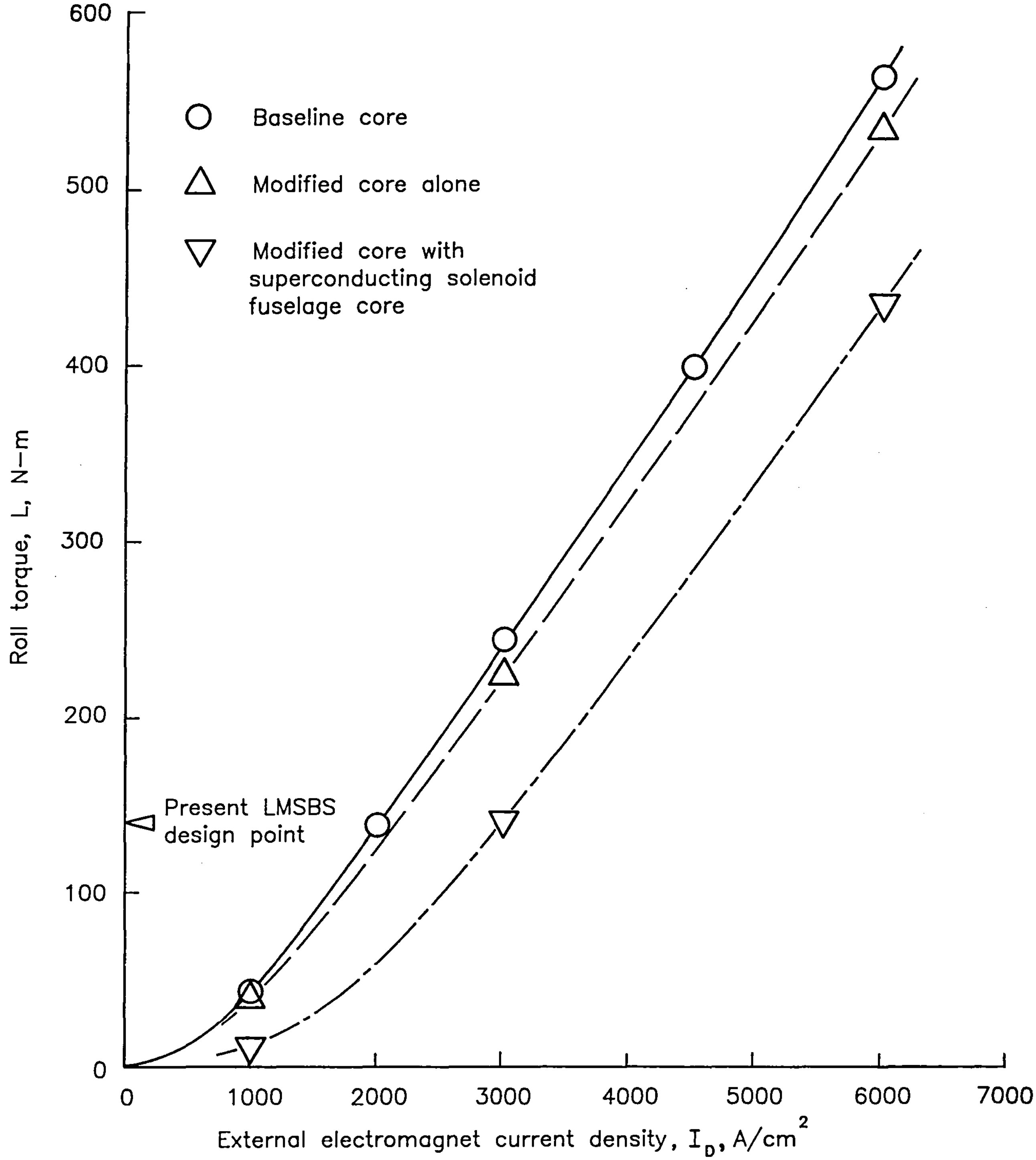


Figure 14.- F-16 core roll torque capability. BH curve as in figure 4(c).

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15. Supplementary Notes

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16. Abstract

Compared with conventional ferromagnetic fuselage cores, superconducting solenoid cores appear to offer significant reductions in the projected cost of a large wind tunnel magnetic suspension and balance system. The provision of sufficient magnetic roll torque capability has been a long-standing problem with all magnetic suspension and balance systems; and the spanwise iron magnet scheme appears to be the most powerful system available. This scheme utilizes iron cores which are installed in the wings of the model. It was anticipated that the magnetization of these cores, and hence the roll torque generated, would be affected by the powerful external magnetic field of the superconducting solenoid. A preliminary study has been made of the effect of the superconducting solenoid fuselage model core concept on the spanwise iron magnet roll torque generation scheme. Computed data for one representative configuration indicate that reductions in available roll torque occur over a range of applied magnetic field levels. These results indicate that a 30-percent increase in roll electromagnet capacity over that previously determined will be required for a representative 8-foot wind tunnel magnetic suspension and balance system design.

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