Fermilab

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HARMONIC FLUCTUATIONS IN ENERGY DOUBLER DIPOLES FROM AZIMUTHAL WIRE DISPLACEMENTS INSIDE THE COILS

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1. INTRODUCTION

High field quality described by close tolerances on field harmonics is the most important property for magnets being used for accelerators and storage rings. For superconducting magnets the field quality is determined by accurate positioning of the wires inside the coils of the magnets. The production of such coils has to be carefully controlled to achieve high reproducibility. Room temperature measurements of complete coil sets are being used for judging the success of coil production and are intended also to act in a closed feedback loop to improve magnet quality. However, the use of this loop requires that effects changing the harmonics are completely understood. There have been some problems up to now with the understanding of the results coming out of the room temperature measurements. Investigations have been made to clarify what is happening inside the coils.

2. HARMONICS AND WIRE DISTRIBUTIONS

Some of the problems connected with the coil production can be seen from Fig. 1 where harmonics b_1 (quadrupole moment) and b_2 (sextupole moment) are plotted for coils of the same construction.

Especially, shims and key angles are the same for these magnets so that differences of up to 7 units for b_1 and 11 units for b_2 in 10^4 with respect to the dipole moment, should be due to changes of the coil interior. It is necessary to understand these fluctuations in harmonics and to find what is causing them.

2.1 Equipment for Investigations of the Coil Interior:

Changes in harmonics were already seen in much earlier magnets and some of the worst coils have been sliced into pieces in order to be able to look into the coil structure. A measuring facility has been developed by M.Kuchnir which allows us to measure the angular positions of the wires inside the coils. Measuring errors of about ±0.4 mrad or ±0.8 mil occur mostly due to difficulties in determining the boundaries of the conductors. Although some improvements of the measuring apparatus are under development (so far the radii of the conductors cannot be measured) the data available up to now give enough information to be used for conclusions.

2.2 Investigations of Magnet 231:

Magnet 231 showed a large negative sextupole moment during room temperature measurements (-13 units of 10^4). Actually the room temperature data are predictions for the behavior of the complete magnet at cryogenic temperatures and including the iron.

2.2.1 Harmonics from Measured Wire Positions: The measured wire positions of magnet 231 have been used as input for a program calculating the field harmonics. The effect of the iron yoke is included in this program assuming $\mu = \infty$. Results of this calculation are seen in Table 1. The sextupole moment is positive here at about 2 units. As the sextupole inside the magnet should be much more positive (about +14 units) in order to compensate for the negative sextupole at the ends, this result is in agreement with the results from the room temperature measurements of the whole coil.

2.2.2 Harmonics from Uniform Wire Positions: As the key angles of the coils are kept fixed and designed to achieve zero higher harmonics, the calculated harmonics reflect the inner structure of the coils. An ideal wire distribution would consist of equally spaced wires inside the quadrants. Therefore, new data sets of wire distributions have been produced keeping the positions of the first (near the median plane) and the last (near the key angle) conductor fixed and distributing the other conductors equally in the quadrants (Fig. 2). For the outer coils the second conductor near the median plane has been kept fixed because there are shims between the first and the second conductor in order to compensate for the thicker insulation of the return bus in the first quadrant. The calculated harmonics of this uniform wire distribution are shown in Table 2. The sextupole moment is much more positive (~+10 units of 10^4) and is much closer to what the magnet should have had. A comparison of all harmonics is given in Fig. 3.

2.2.3 Inner Properties of the Coils: In order to find the reasons for the harmonic behavior of the coils it is necessary to look closer into the internal structure of the coils. The difference in the wire positions between the measured and the uniform distribution is shown in Fig. 4 for the inner coil. The displacements are positive (up to 8 mil) at the average for all quadrants, meaning that the wire positions are shifted towards the key angles. This indeed produces negative sextupoles. The differences for the outer coil are much smaller (Fig. 5). Here the displacements are negative for the fourth quadrant.

A change in the wire distribution should be reflected in the insulation thickness which can be seen in Fig. 6 for the inner and Fig. 7 for the outer coil. There are large fluctuations at the inner coil of about ±4 mil.

A wire density equivalent to current density can also be derived from the data (Fig. 8 for the inner coil). There are clearly regions of lower density near the median plane (at angles 0. and 3.14 rad) and of higher density near the key angles, although the figure is disturbed a bit by large fluctuations. The effect can be seen easier in Fig. 9 where the fluctuations have been averaged out. A similar graph (Fig. 10) shows the density for the outer coil. The dip in the curve near the median plane is due to additional shims between the wires.

In an ideal coil the long axis of the wire cross section points towards the magnet axis. In a real coil there are deviations of the wire directions from the axial direction. This is shown in Fig. 11 for the inner coil of magnet 231. There is an interesting systematic behavior of the angle deviation. The sign of the error angle changes from quadrant to quadrant. For the outer coil (Fig. 12) the sign is opposite to that of the inner coil in most quadrants. This behavior is illustrated in Fig. 13. It can be explained as being produced by a force acting on a double coil package from above while the sides of the package are kept under frictional forces. It may be that these forces are producing different wire distributions depending on the amount of force and friction and on the elasticity of the coil. A similar wire distribution as described here is found in a second slice from magnet 231.

2.3 Investigations of Other Coils:

Two other slices of different magnets have been investigated with respect to wire displacements and harmonics.

2.3.1 Results from Magnet 209: Room temperature measurements of magnet 209 showed this magnet to be much better than magnet 231. There was only a slightly bad sextupole of -4.6 units of 10^4. A comparison between the harmonic calculations of measured and uniform data is shown in Fig. 14. There are only small differences between both cases. The average displacement in each quadrant for the inner coil is not far from zero as Fig. 15 indicates. The angular deviations are similar to those of magnet 231.

2.3.2 Results from Magnet 143: Magnet 143 shows considerable differences between harmonics calculated from the measured and from the uniform distribution (Fig. 16). The differences are about 4 units of 10^4 for the normal quadrupole as well as for the normal sextupole. The reason for this behavior is a large negative wire displacement in the fourth quadrant (Fig. 17). The angular deviation is similar to those in the above discussed magnets.

2.4 <u>Possible Sources for Different Wire Distributions</u>:

There are certainly a lot of possible sources for changes of the wire distribution. Principally the sources can be divided into two groups. The first group is concerned with the procedures of producing the coils; i.e., the methods of winding, pressing, curing and collaring. The mostly negative sextupole and the systematic behavior of the wire angles are pointing to this group of sources.

The second group is concerned with a change of material properties of the coil parts; i.e., properties of the B-stage, the Kapton, the epoxy and the wire itself. All parts are contributing to the elastic behavior of the coils which, if changing, may affect the wire distribution.

There is, finally, a high probability that both groups of sources act together to produce different wire distributions.

3. SUMMARY

Wire position measurements for several coils have shown to be useful to understand strange results from room temperature measurements made at the whole coil system. Big changes in azimuthal wire positions with respect to the ideal position have been observed, mostly increasing the current density towards the key angles thus producing a negative shift in the sextupole moment. This behavior, as well as systematic deviations of the wire angles, supports the assumption that the density fluctuations are produced by friction acting in the coil production procedure. Material properties may also be responsible.

TABLE 1

MAGNET NO. 231

HARMONICS CALCULATION INCLUDING IRON

HARM.NO	NORM.COMP.	SKEW COMP.
0	1.00000	-0.00021
1	0.00026	0.00016
2	0.00019	0.00052
3	0.00002	-0.00030
4	0.00030	0.00002
5	-0.00001	0.00001
6	0.00046	-0.00004
7	0.00001	0.00002
8	-0.00111	0.00002
9	-0.00001	-0.00000
10	0.00033	0.00000
11	-0.00000	0.00000
12	-0.00006	0.00000
13	0.00000	0.00000
14	0.00001	0.00000
15	0.00000	0.00000

E

TABLE 2

MAGNET NO. 231, UNIFORM DISTRIBUTION

HARMONICS CALCULATION INCLUDING IRON

HARM.NO	NORM.COMP.	SKEW COMP.
0	1.00000	0.00016
1	0.00011	0.00024
2	0.00096	0.00046
3	-0.00006	-0.00006
4	0.00039	-0.00001
5	-0.00001	0.00002
6	0.00644	-0.00003
7	-0.00000	-0.00001
8	-0.00110	0.00001
9	-0.00000	0.00000
10	0.00033	-0.00000
11	0.00000	0.00000
12	-0.00007	0.00000
13	-0.00000	-0.00000
14	0.00001	-0.00000
15	-0.00000	0.00000

E

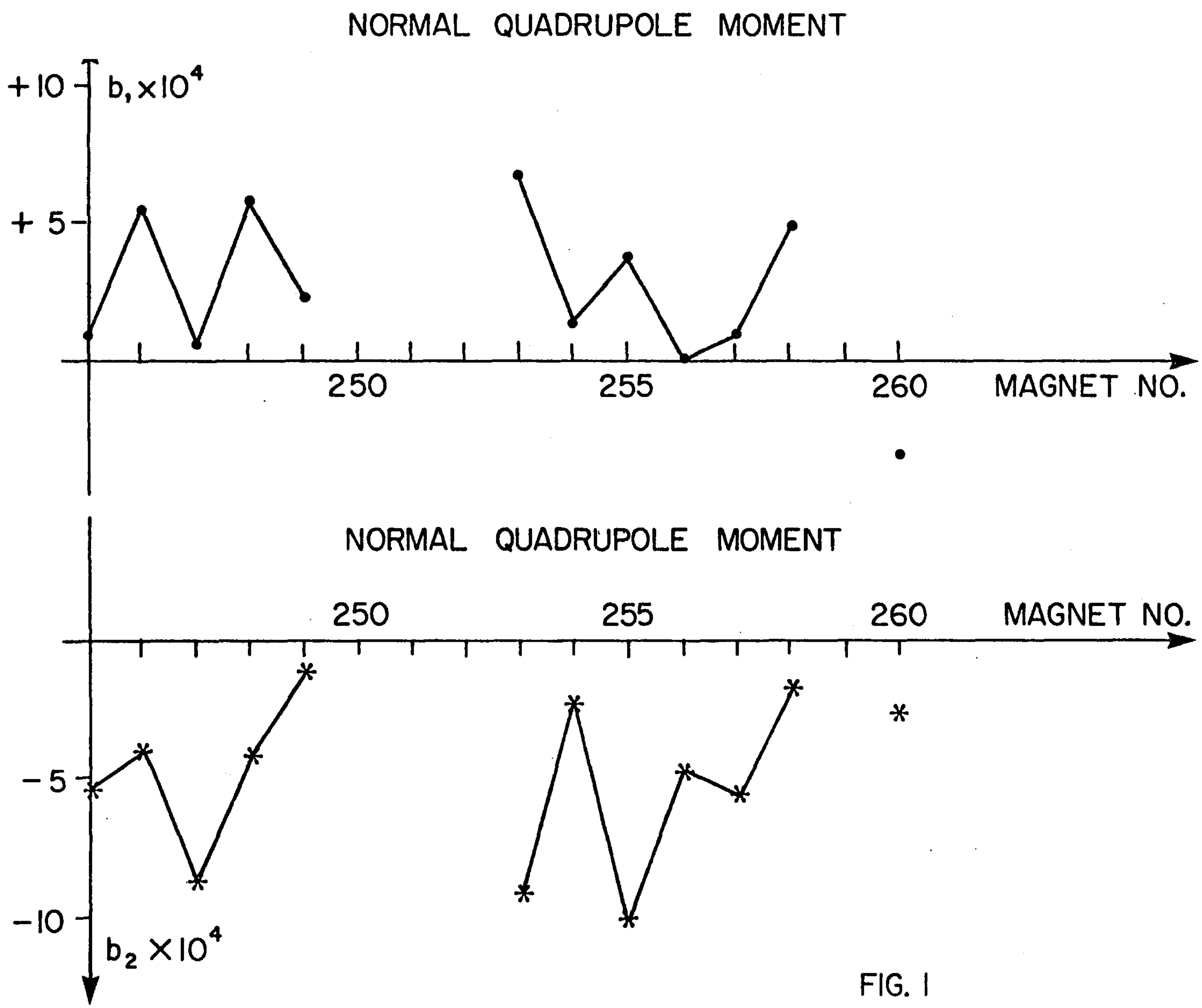


FIG. I
ROOM TEMPERATURE MEASUREMENTS
FOR MAGNETS OF SAME CONSTRUCTION

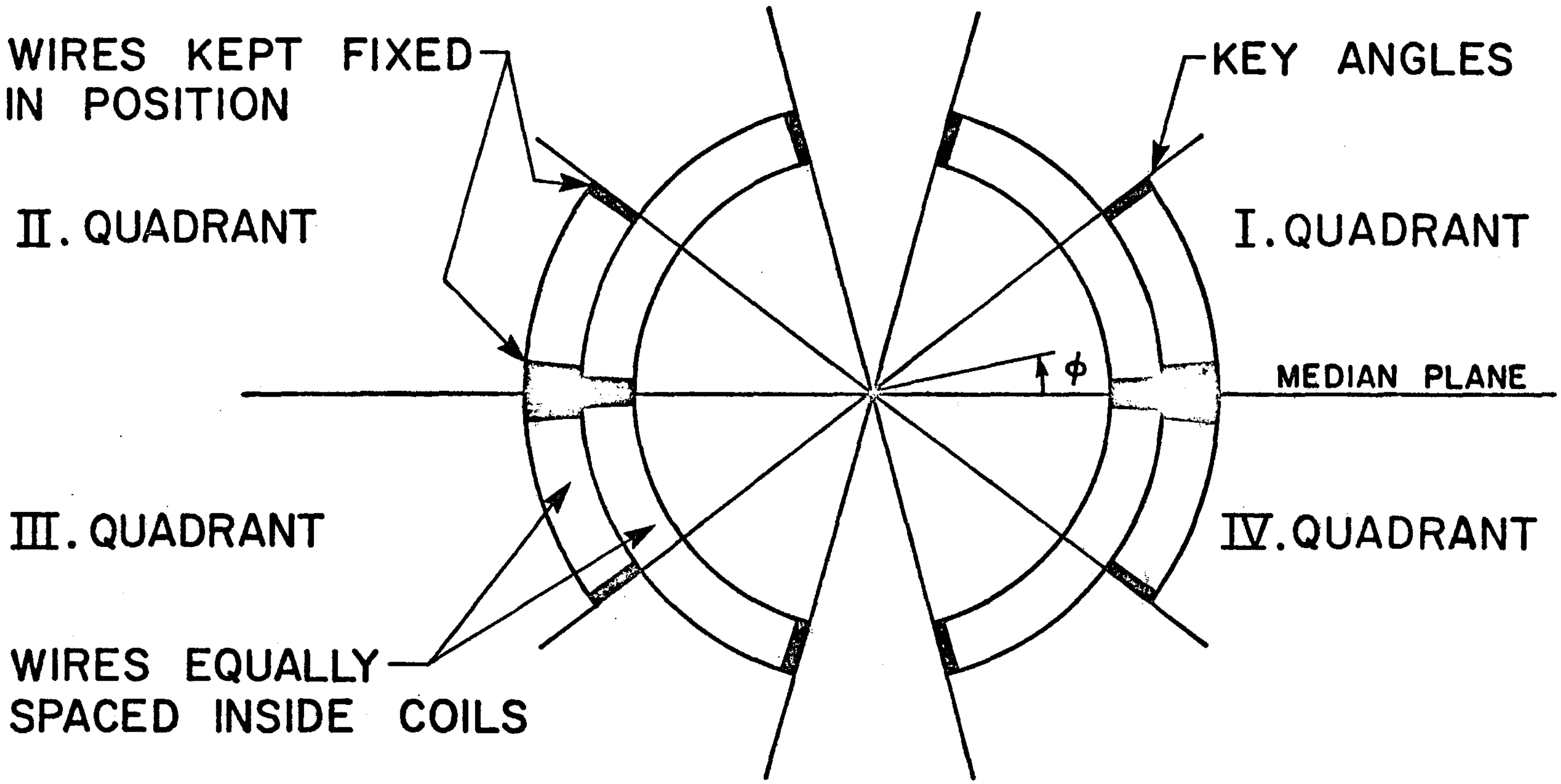


FIG. 2

COIL CROSS SECTION FOR UNIFORMED WIRE DISTRIBUTION

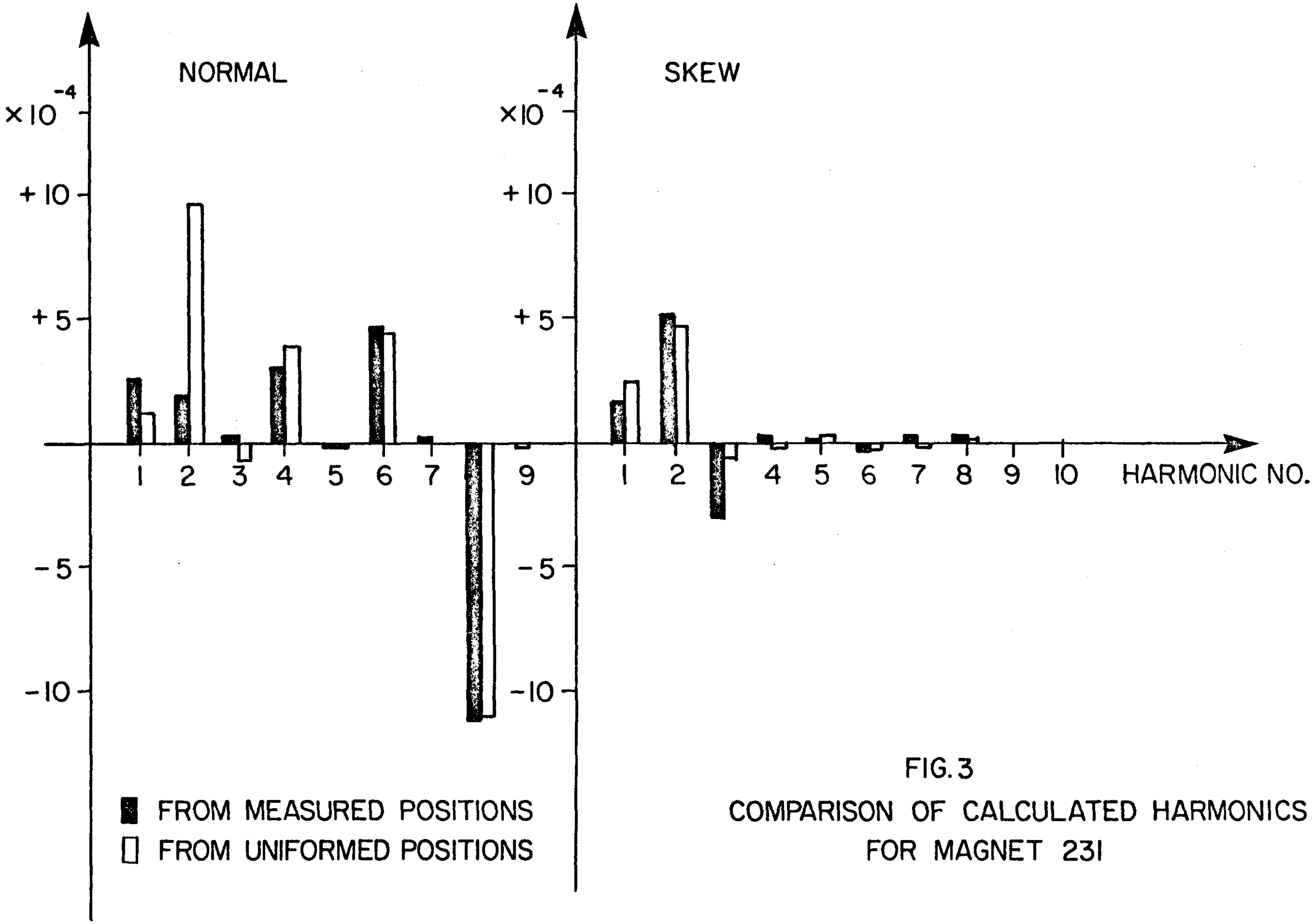


FIG. 3

COMPARISON OF CALCULATED HARMONICS FOR MAGNET 231

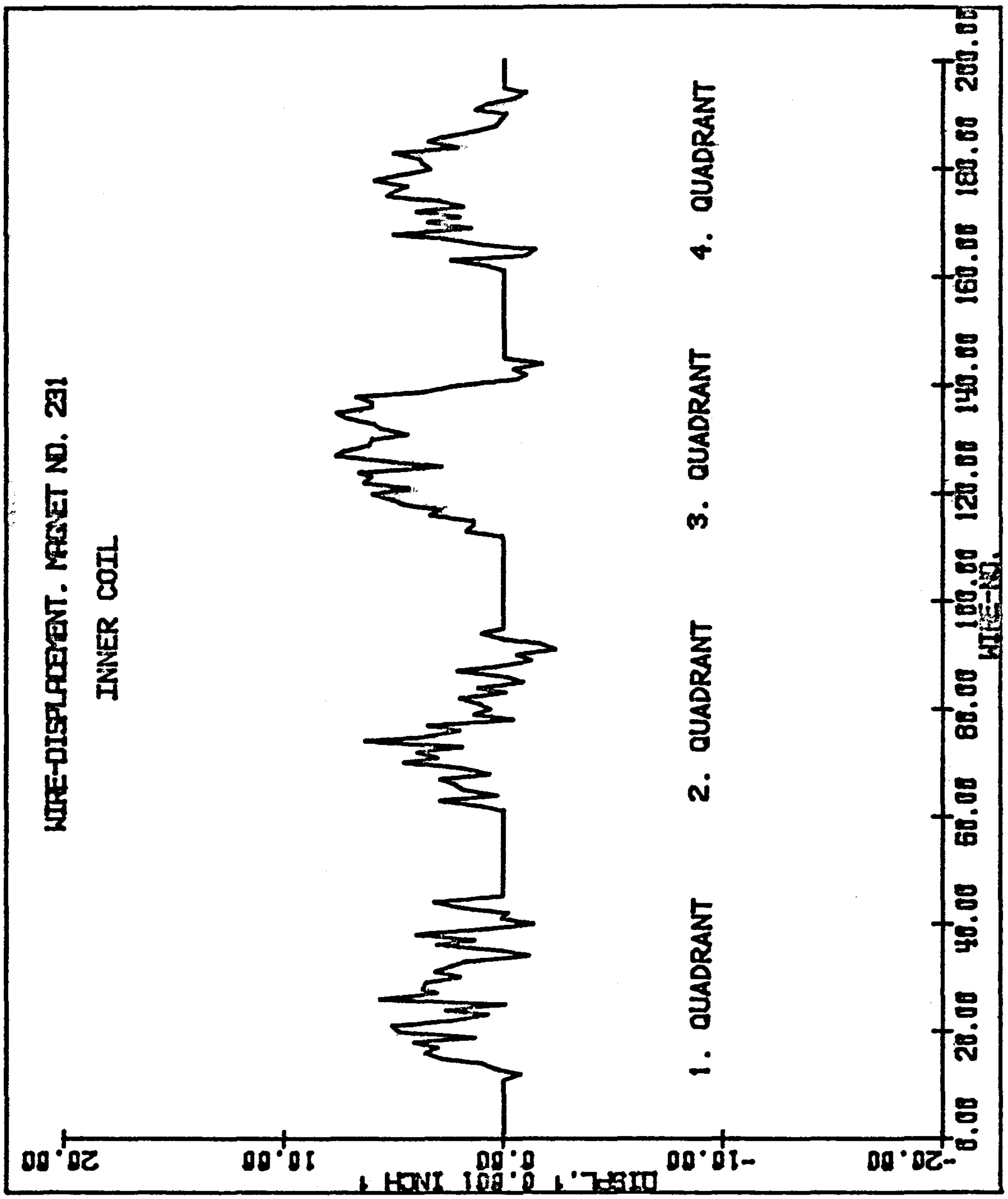

WIRE-DISPLACEMENT. MAGNET NO. 231
INNER COIL
1. QUADRANT
2. QUADRANT
3. QUADRANT
4. QUADRANT
0.00
20.00
40.00
60.00
80.00
100.00
120.00
140.00
160.00
180.00
200.00
WIRE-NO.
20.00
10.00
0.00
-10.00
-20.00
DISPL., 0.001 INCH

FIG. 4

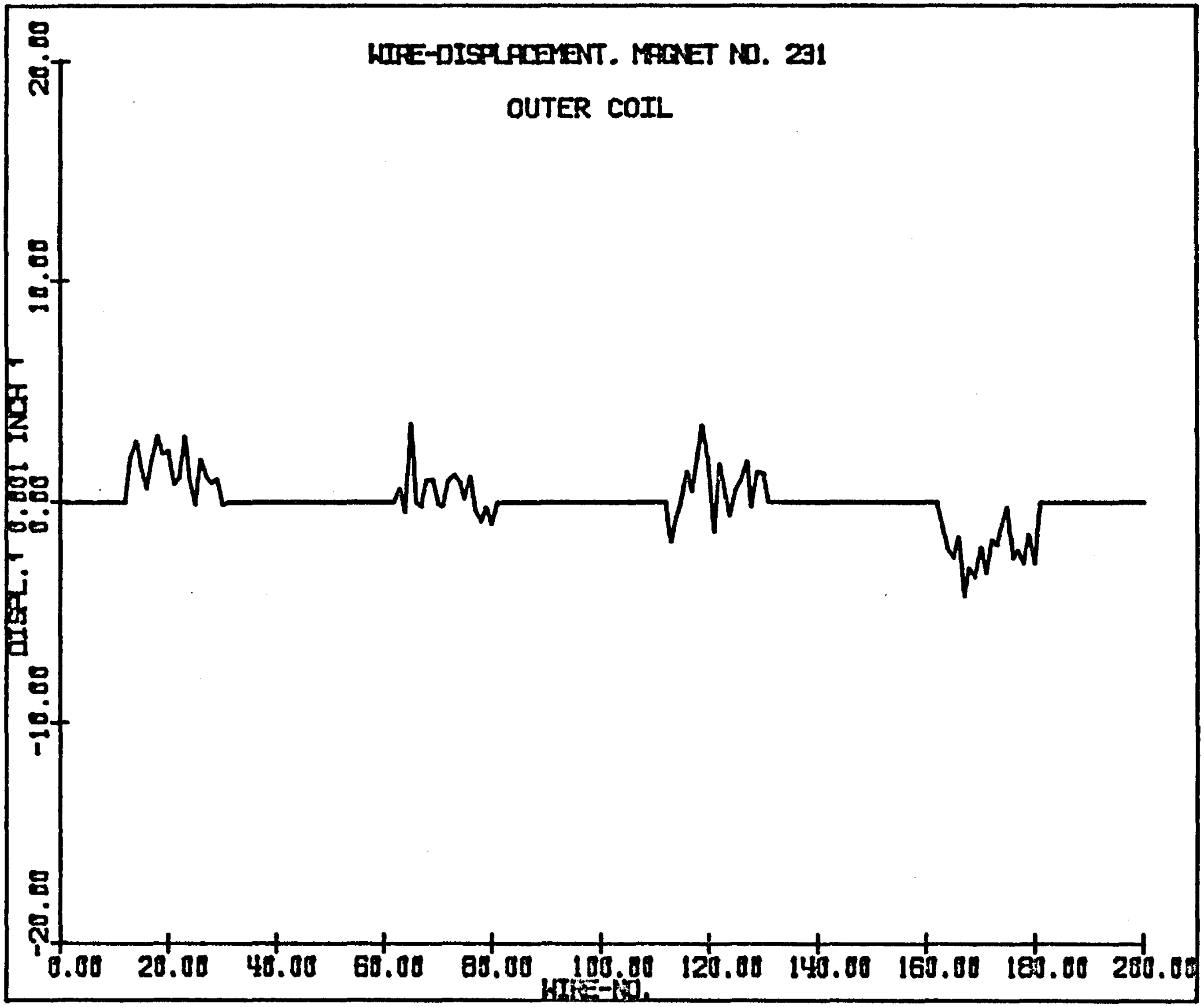
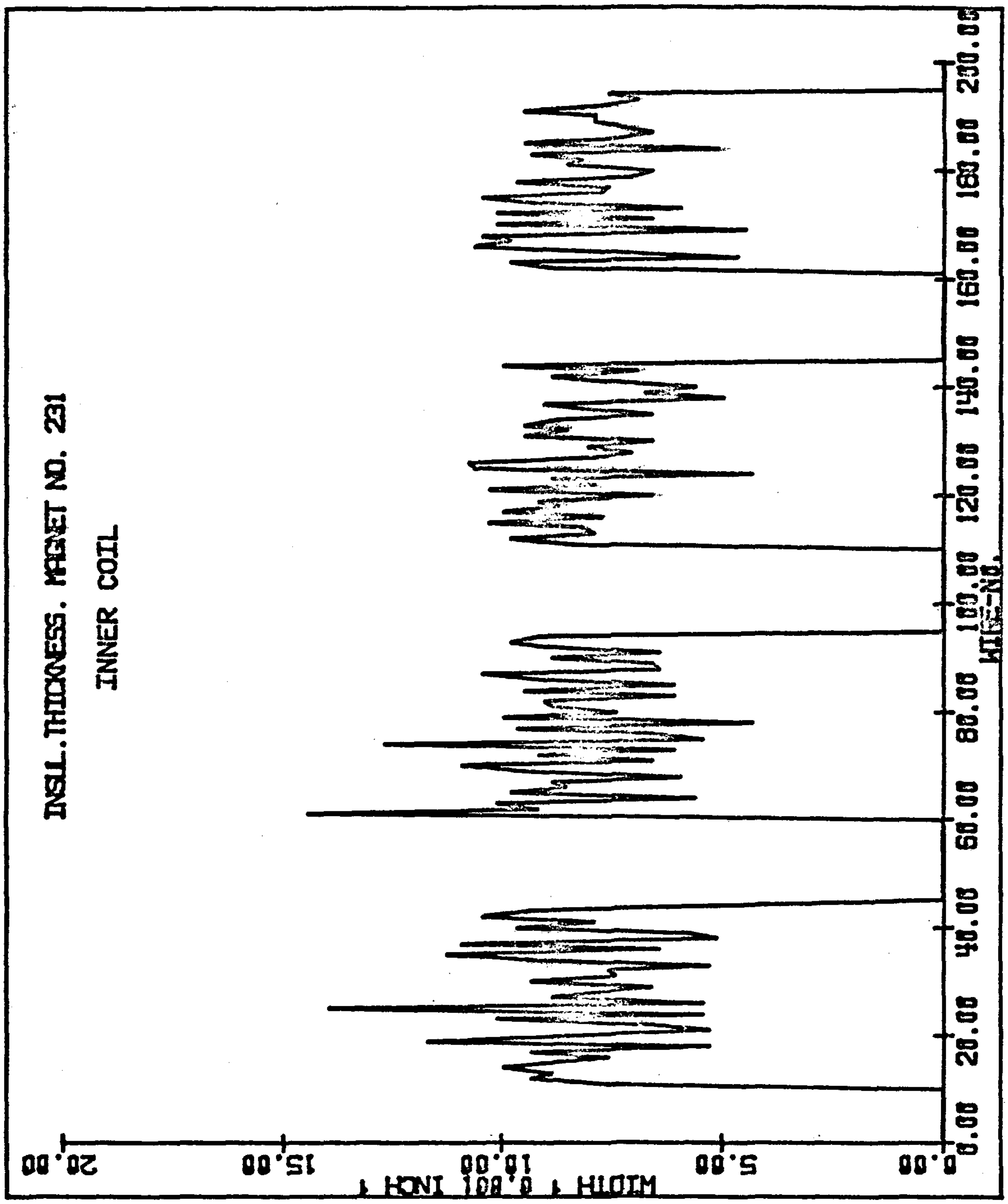

WIRE-DISPLACEMENT. MAGNET NO. 231
OUTER COIL
DISPL. (0.001 INCH)
20.00
10.00
0.00
-10.00
-20.00
0.00
20.00
40.00
60.00
80.00
100.00
120.00
140.00
160.00
180.00
200.00
WIRE-NO.

FIG. 5

FIG. 6


INSUL.THICKNESS. MAGNET NO. 231
INNER COIL
WIDTH (0.001 INCH)
WIRE-NO.
0.00
5.00
10.00
15.00
20.00
0.00
20.00
40.00
60.00
80.00
100.00
120.00
140.00
160.00
180.00
200.00

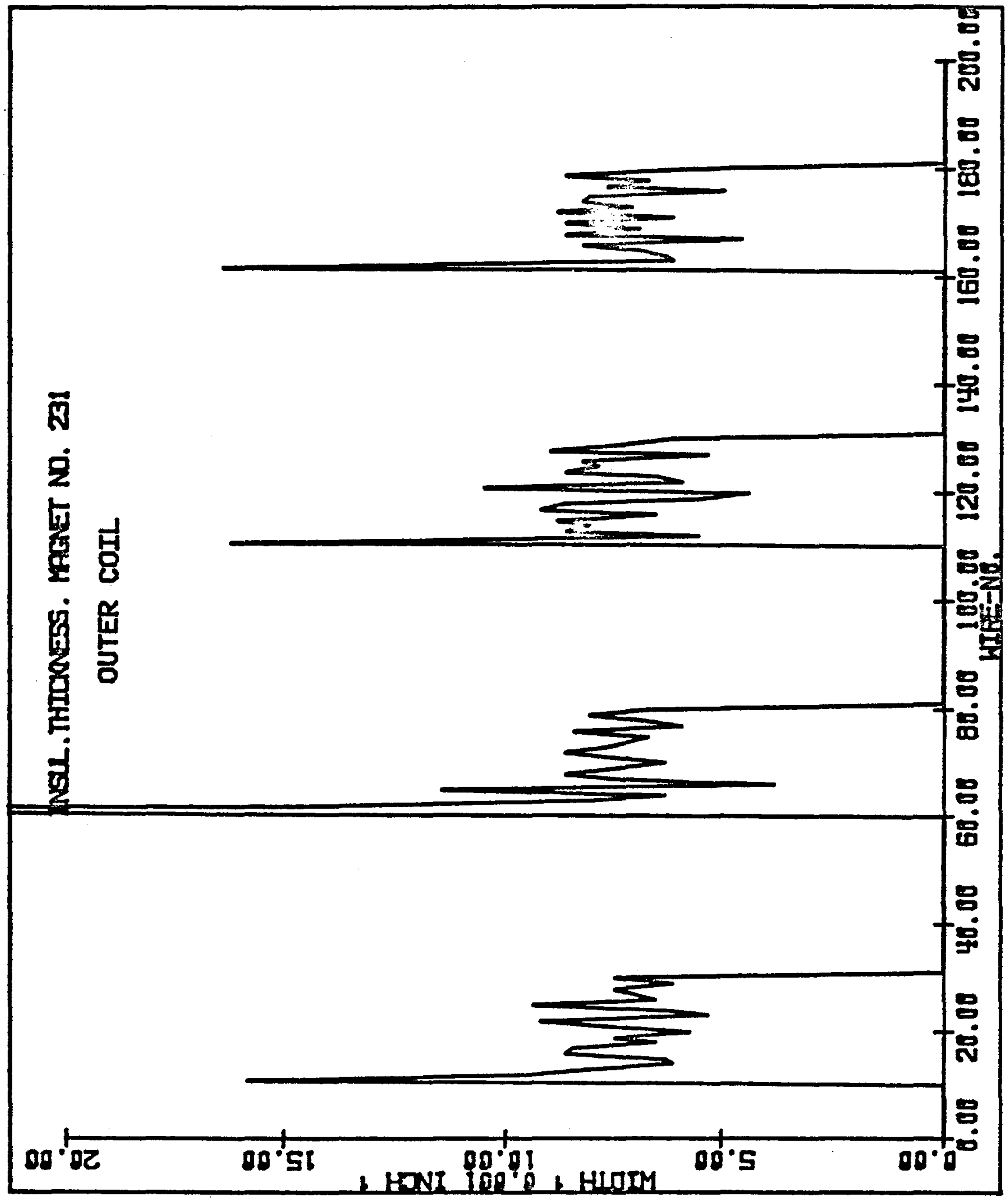
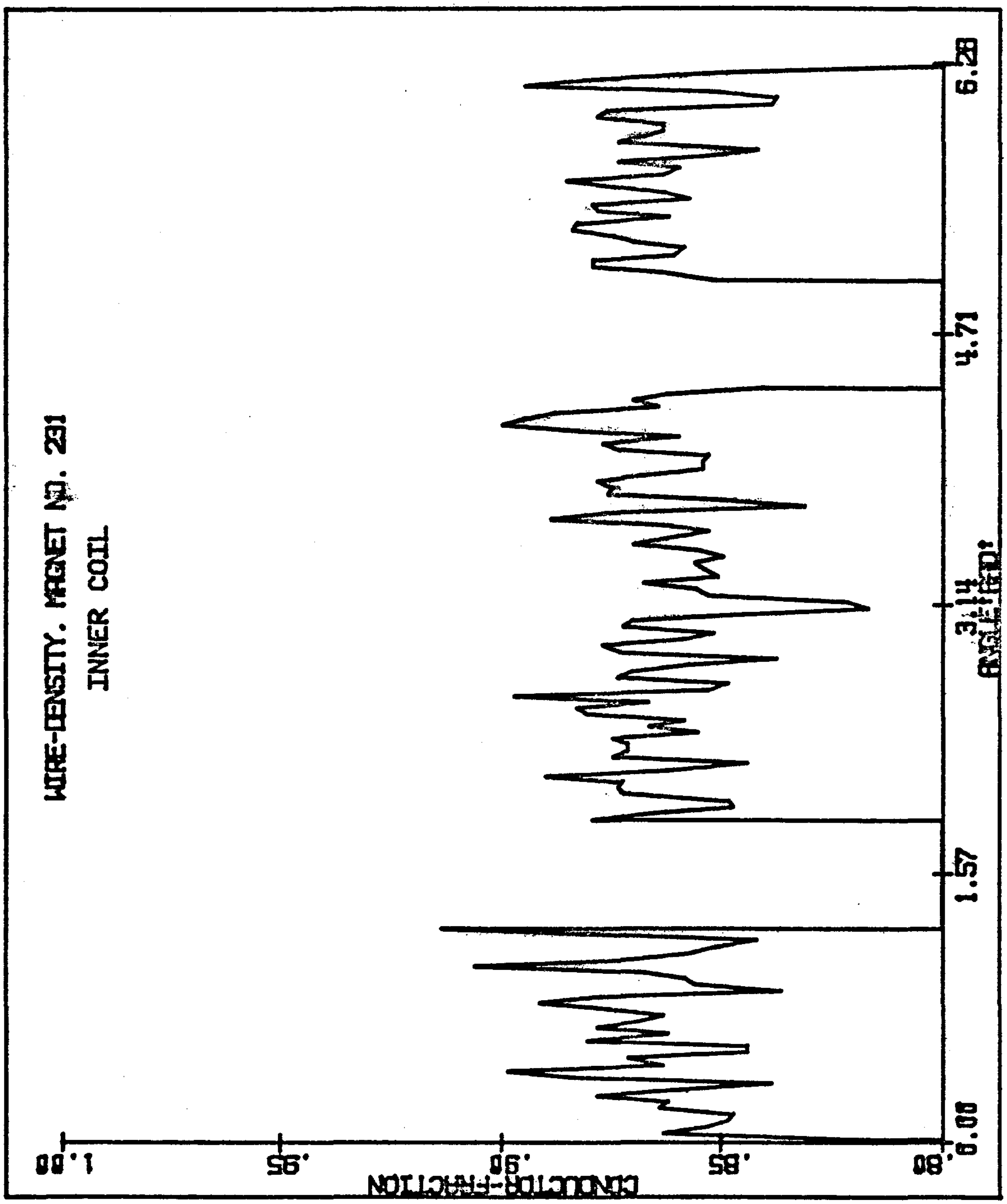

INSL. THICKNESS. MAGNET NO. 231
OUTER COIL
WIDTH (0.001 INCH)
0.00
5.00
10.00
15.00
20.00
WIRE-NO.
0.00
20.00
40.00
60.00
80.00
100.00
120.00
140.00
160.00
180.00
200.00

FIG. 7

FIG. 8


WIRE-DENSITY. MAGNET NO. 231
INNER COIL
CONDUCTOR-FRACTION
.80
.85
.90
.95
1.00
ANGLE(RAD)
0.00
1.57
3.14
4.71
6.28

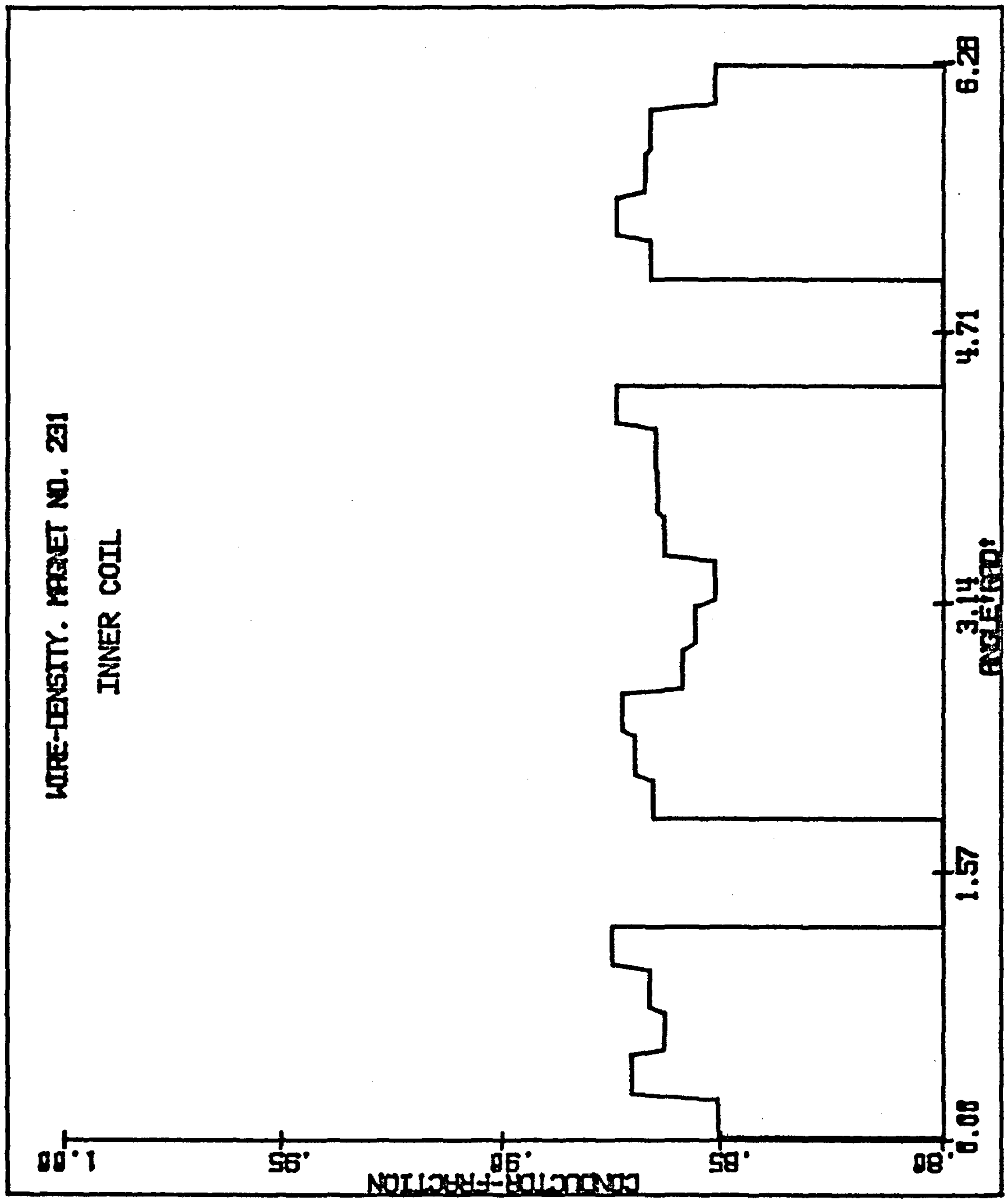
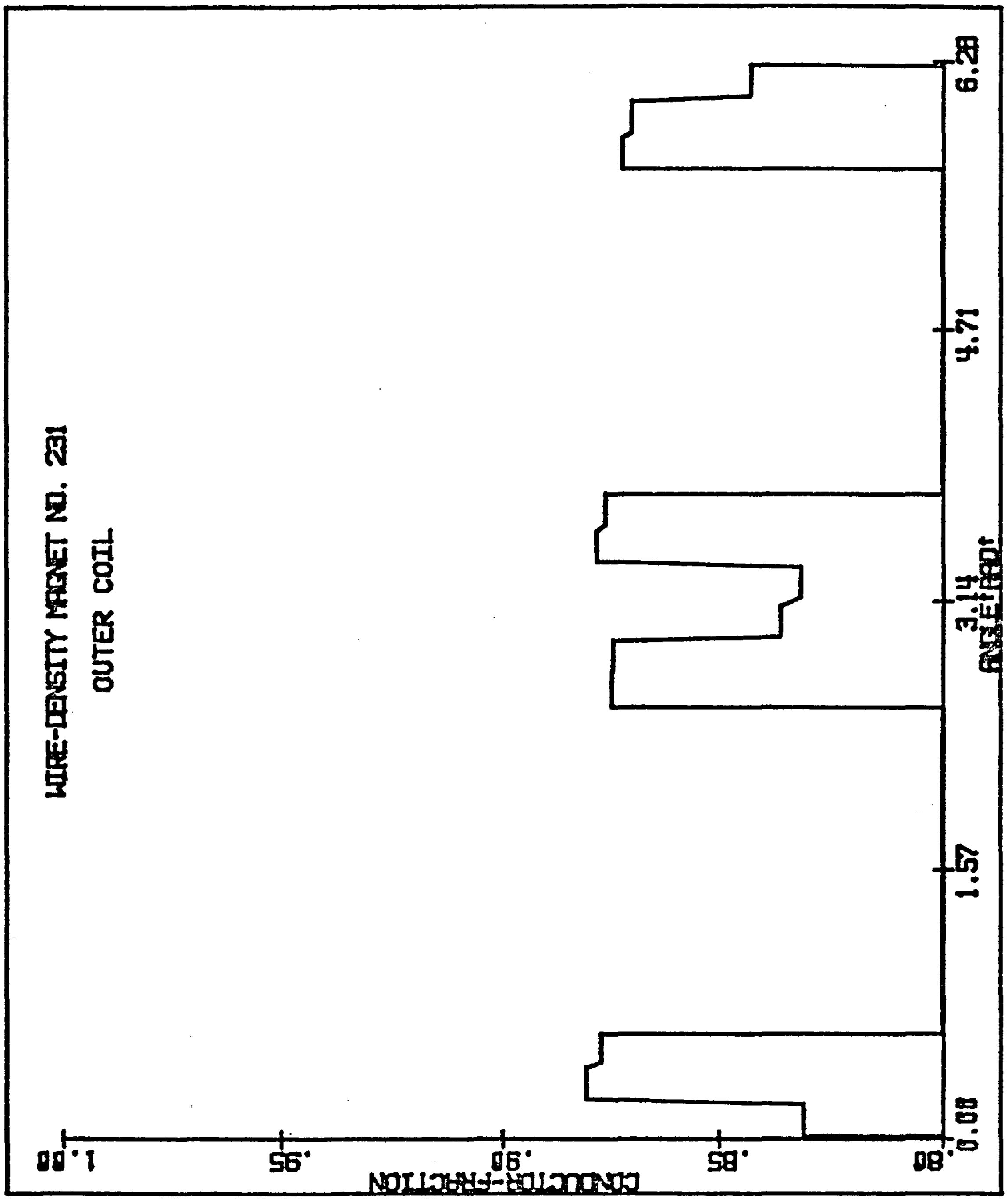

WIRE-DENSITY. MAGNET NO. 231
INNER COIL
CONDUCTOR-FRACTION
.80
.85
.90
.95
1.00
ANGLE(RAD)
0.00
1.57
3.14
4.71
6.28

FIG. 9



WIRE-DENSITY MAGNET NO. 231
OUTER COIL
CONDUCTOR-FRACTION
ANGLE(RAD)
.80
.85
.90
.95
1.00
0.00
1.57
3.14
4.71
6.28

FIG. 10

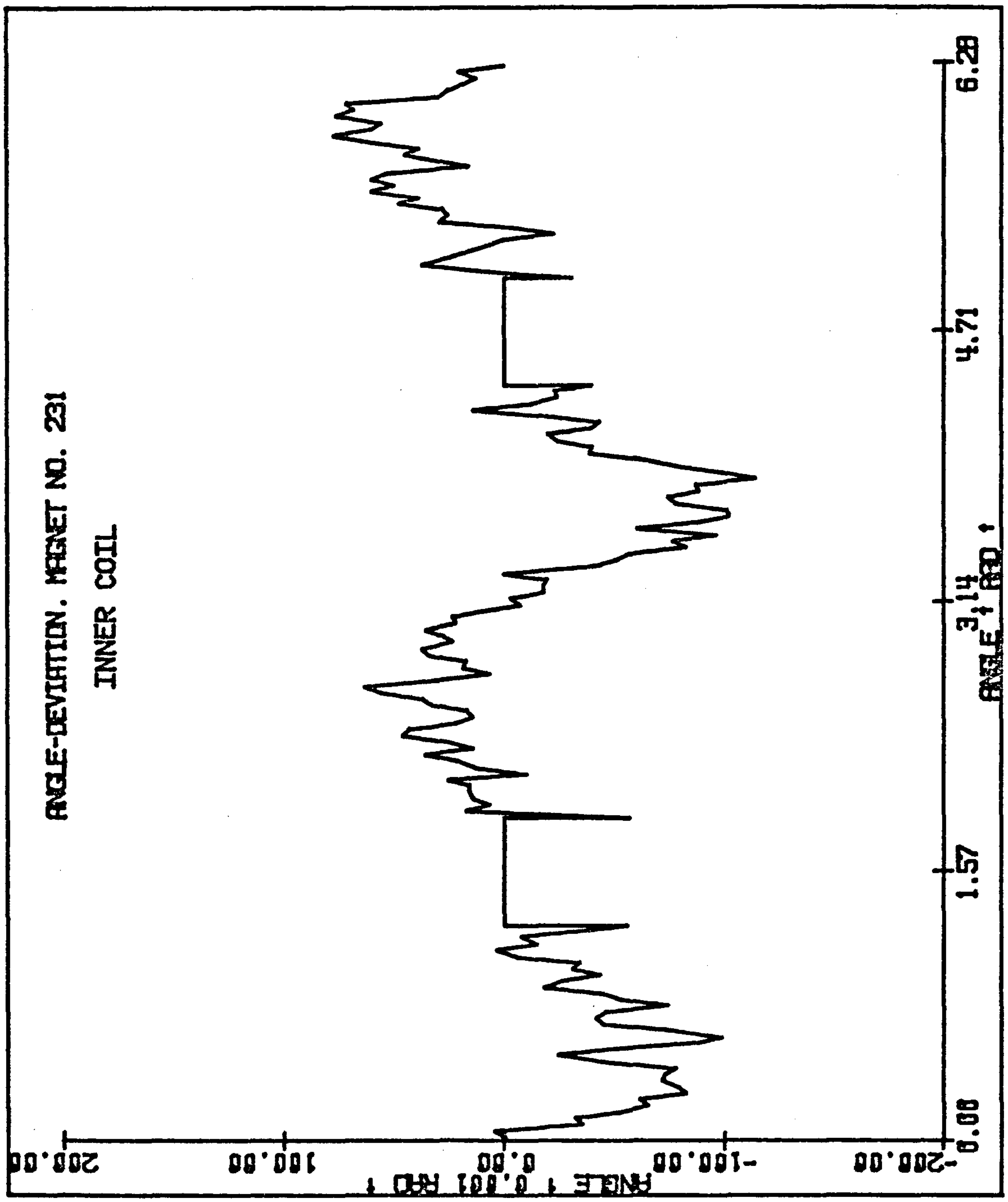

ANGLE-DEVIATION. MAGNET NO. 231
INNER COIL
ANGLE (RAD)
0.00
1.57
3.14
4.71
6.28
ANGLE (0.001 RAD)
200.00
100.00
0.00
-100.00
-200.00

FIG. 11

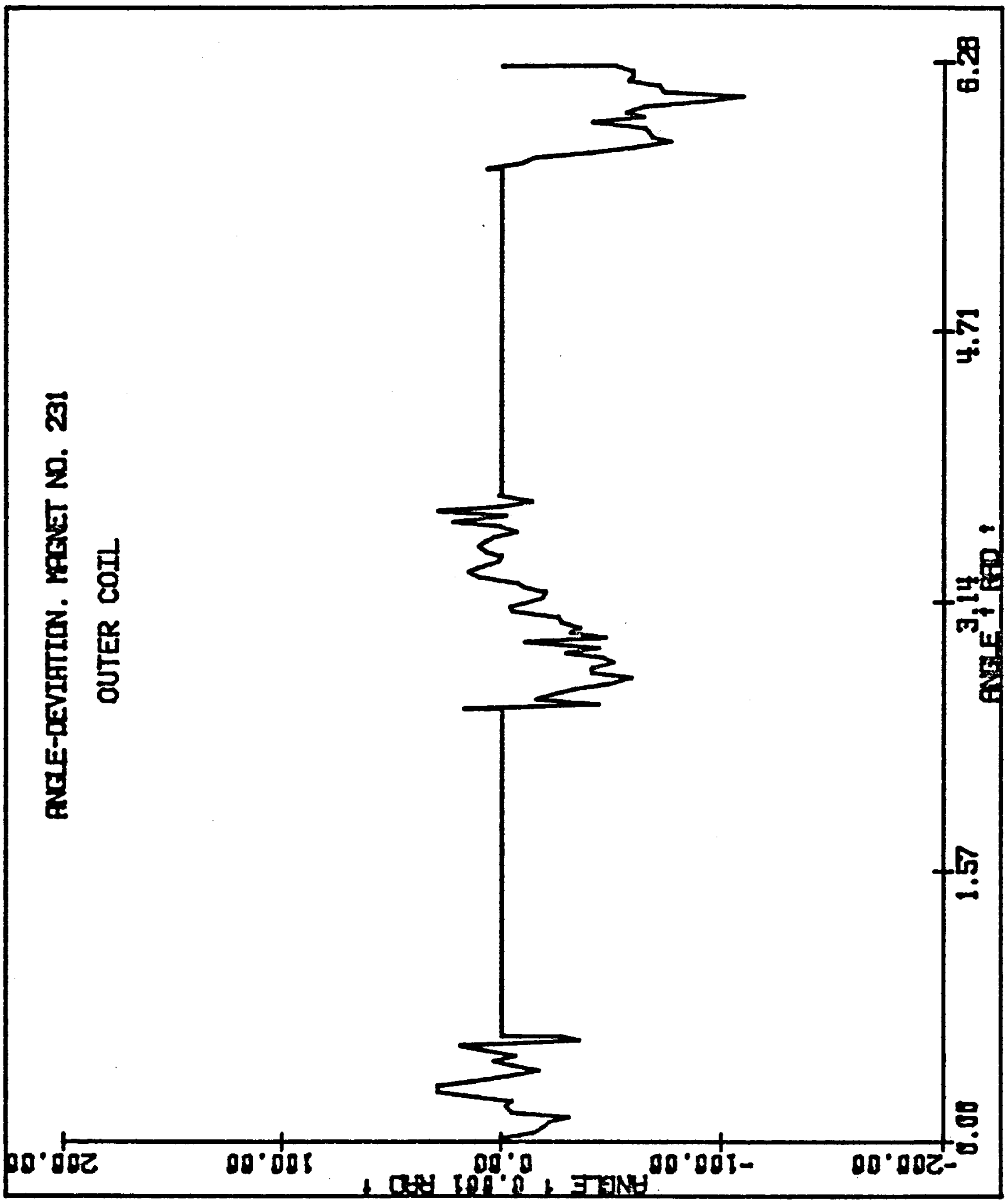

ANGLE-DEVIATION. MAGNET NO. 231
OUTER COIL
200.00
100.00
0.00
-100.00
-200.00
ANGLE (0.001 RAD)
0.00
1.57
3.14
4.71
6.28
ANGLE (RAD)

FIG. 12

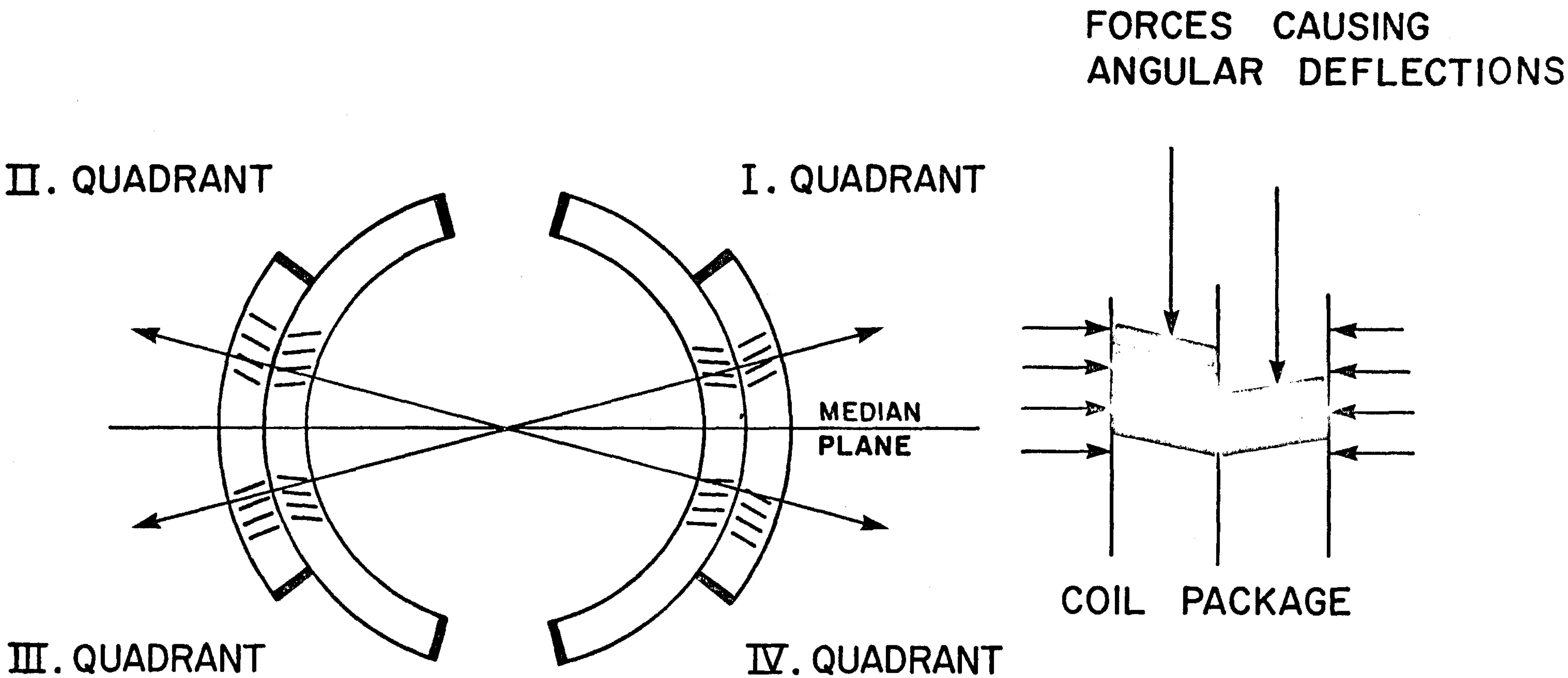


FIG. 13

ANGULAR DEVIATIONS OF
WIRES INSIDE COILS

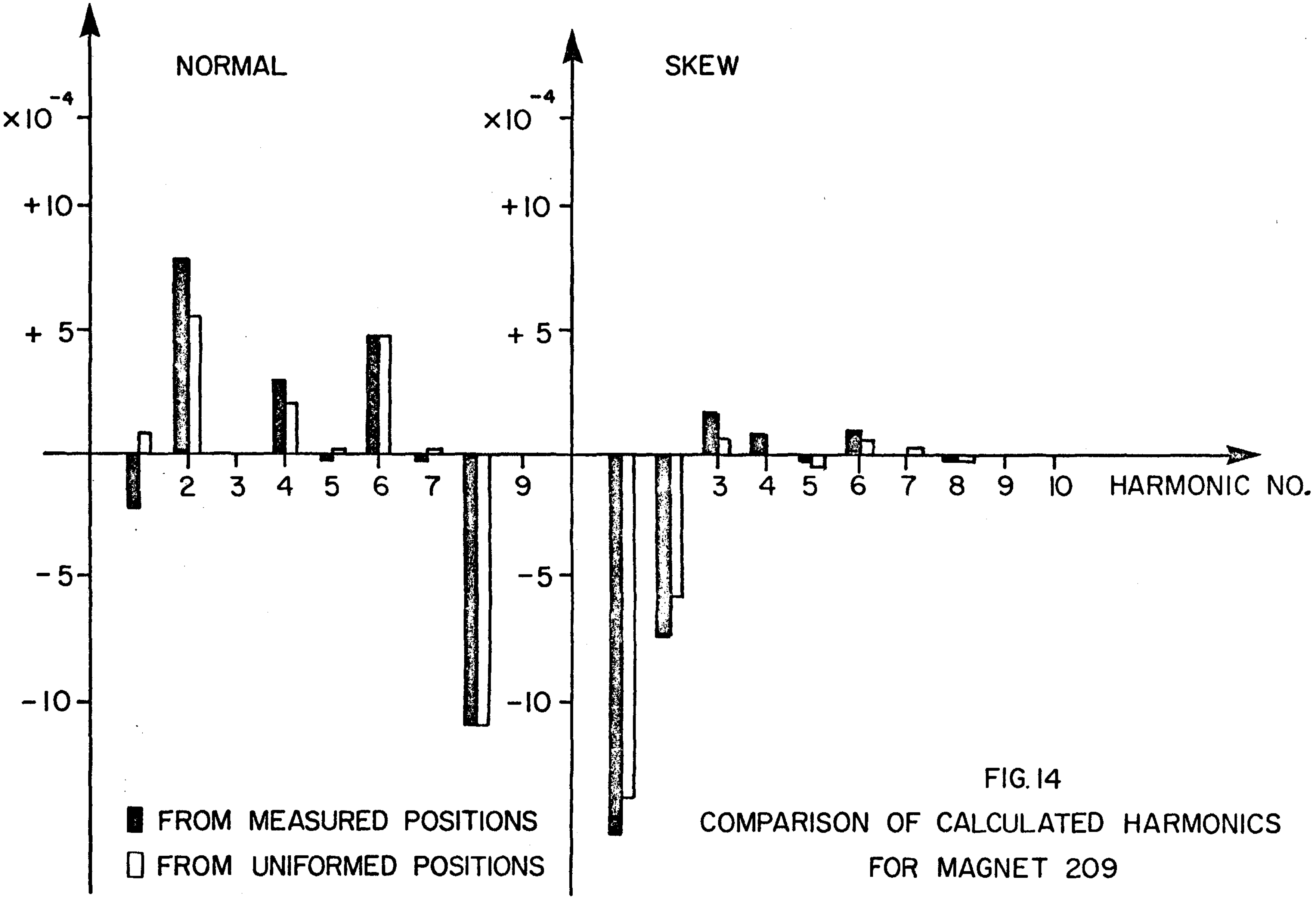


FIG. 14
COMPARISON OF CALCULATED HARMONICS
FOR MAGNET 209

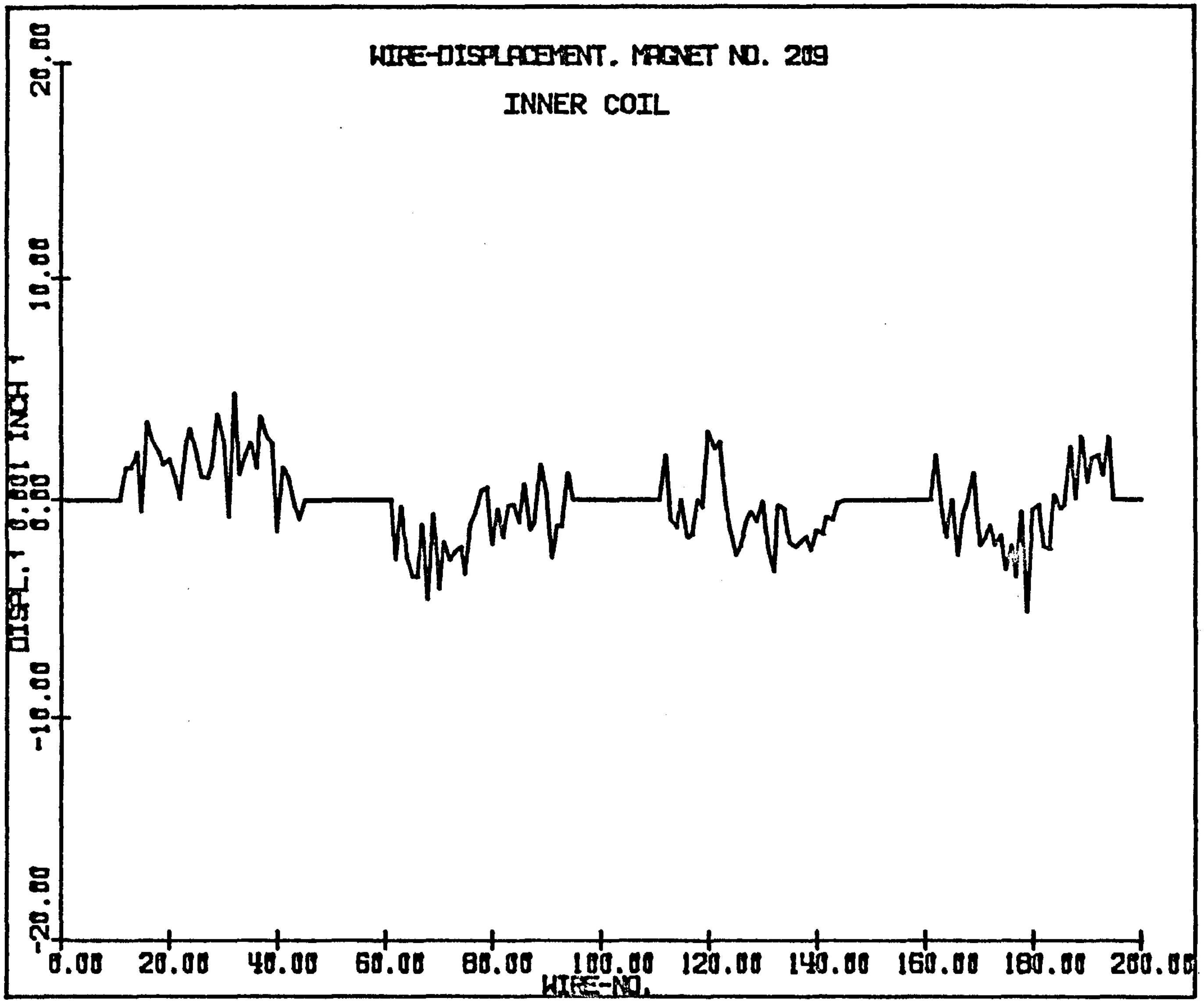

WIRE-DISPLACEMENT. MAGNET NO. 209
INNER COIL
DISPL. (0.001 INCH)
20.00
10.00
0.00
-10.00
-20.00
0.00
20.00
40.00
60.00
80.00
100.00
120.00
140.00
160.00
180.00
200.00
WIRE-NO.

FIG. 15

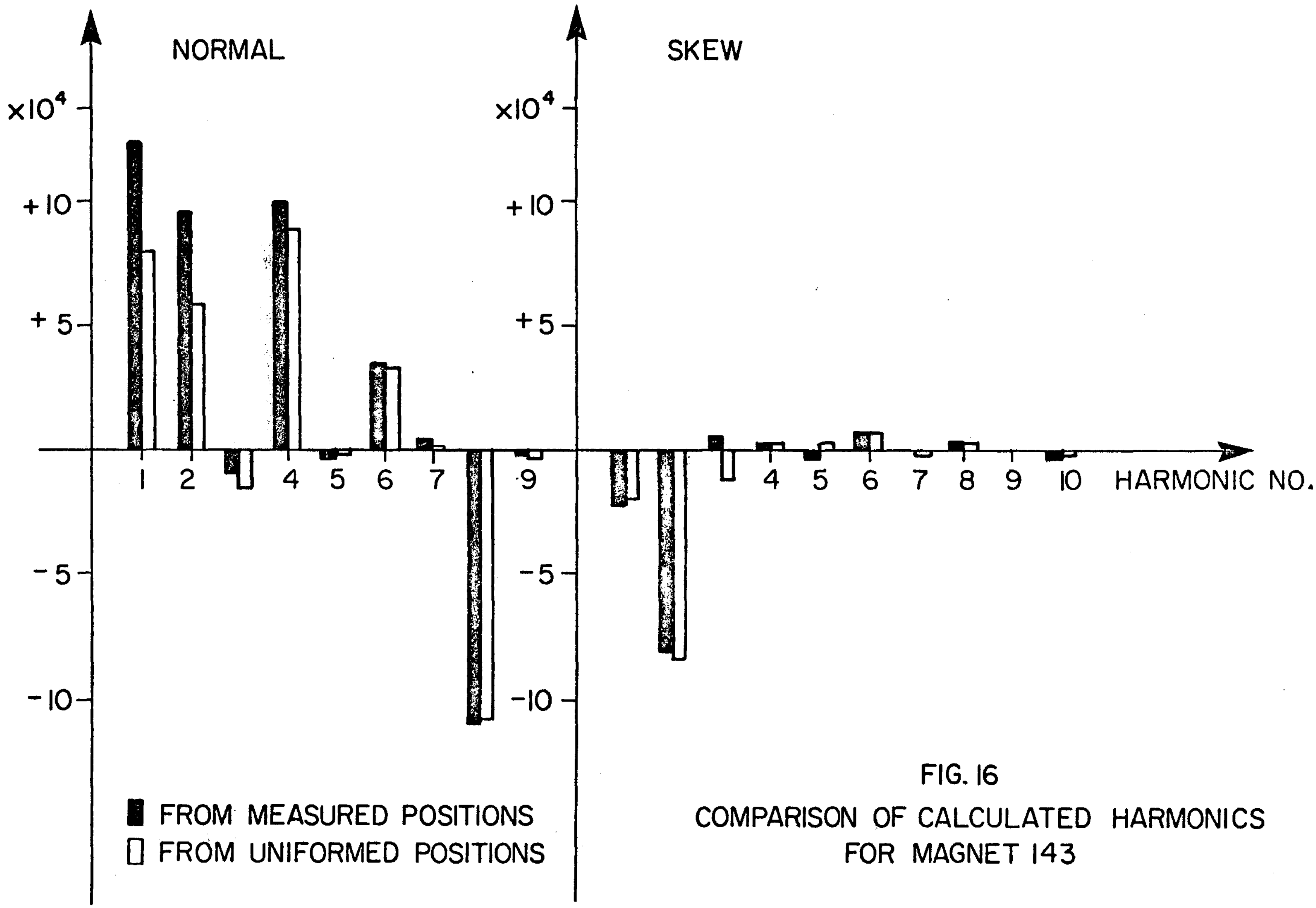


FIG. 16
COMPARISON OF CALCULATED HARMONICS
FOR MAGNET 143

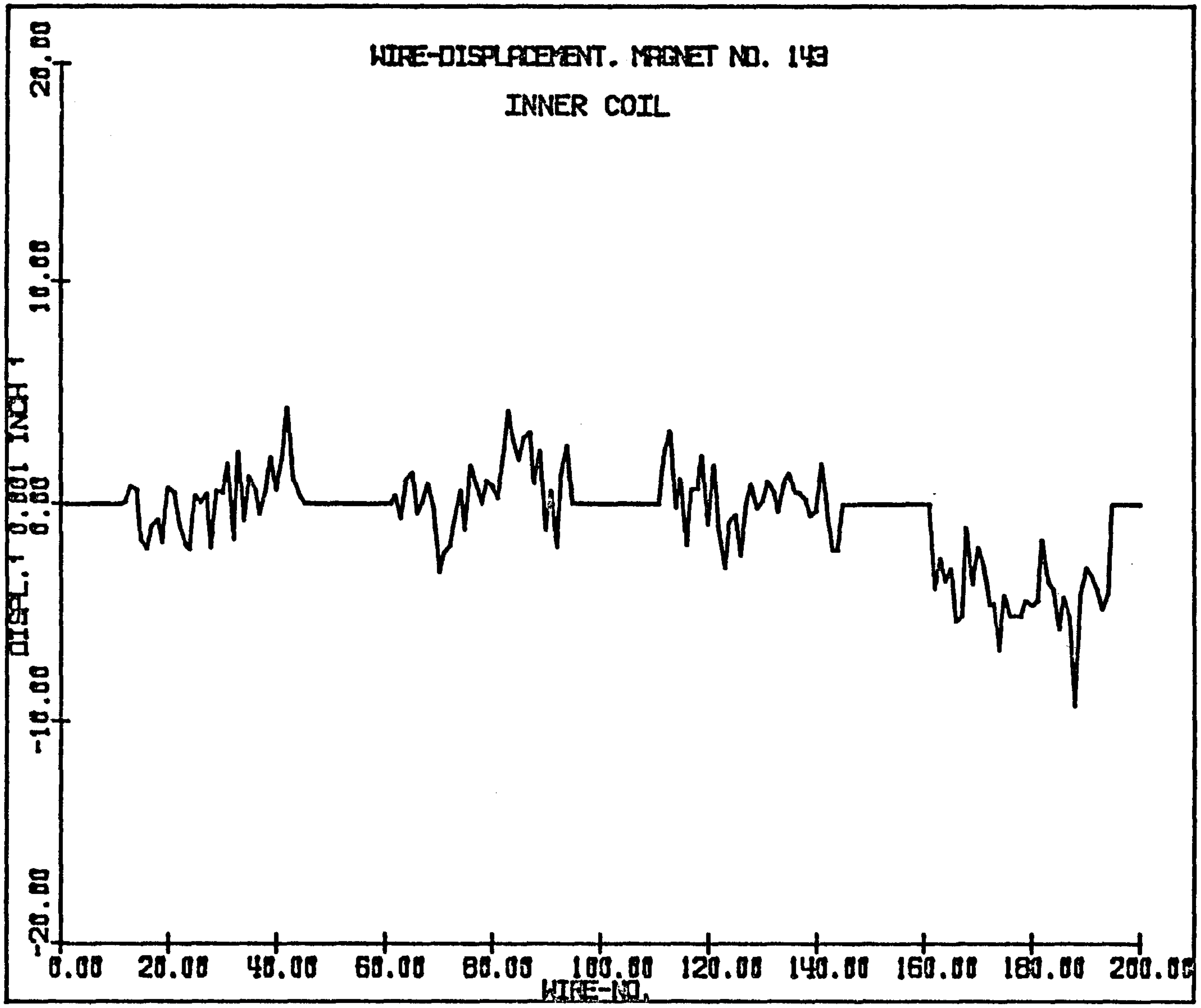

WIRE-DISPLACEMENT. MAGNET NO. 143
INNER COIL
DISPL. (0.001 INCH)
20.00
10.00
0.00
-10.00
-20.00
0.00
20.00
40.00
60.00
80.00
100.00
120.00
140.00
160.00
180.00
200.00
WIRE-NO.

FIG. 17