Effects of Measuring Coil Imperfections on the Measured Field Parameters

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1. Introduction :

A measuring coil in practice may have several types of imperfections, which may affect the accuracy of field measurements. One class of imperfections relates to coil fabrication. Examples in this class are a *sag*, *bow*, a *twist* in the tangential coil, and a mismatch, or *offset* between the geometrical center of the coil and the rotation axis. Another class of imperfections relates to placement of the coil during actual measurements. Examples in this class are a *displacement* and a *tilt* of the coil axis with respect to the magnetic axis. Detailed analytical formulations are available to deal with the problem of displacement[1] and sag[2]. Out of all the imperfections listed above, the measured parameters are most dramatically affected by displacement. As a result, *centering* of measured parameters to eliminate the displacement effects is a routine feature in all data analysis. The other imperfections generally have negligible effects. Nevertheless, a quantitative estimate of the effects of other types of imperfections will be quite useful, for example, in deciding upon machining tolerances.

The effects of other imperfections noted above are discussed in this note. Analytical results are presented for each one of these, along with some typical numerical results. The formalism for a displacement of axes is basic to all analysis. Some useful results are reproduced here for ready reference. If $C(n)$ and $\alpha(n)$ are the amplitudes and phases of the harmonic fields with respect to a given origin, then these parameters in a displaced reference frame are given by[1]

$$\bar{C}(n)\exp\{in\bar{\alpha}(n)\} = \sum_{\ell=n}^{\infty} C(\ell)\left[\frac{(\ell-1)!}{(\ell-n)!(n-1)!}\right]\left(\frac{r_0}{R}\right)^{\ell-n}\exp[i\{\ell\alpha(\ell)-(\ell-n)\sigma\}] \qquad (1)$$

where $\bar{C}(n)$ and $\bar{\alpha}(n)$ are the coefficients in the displaced reference frame having its origin at polar co-ordinates (r_0, σ) in the undisplaced reference frame. Another useful result for this note is the voltage induced in a tangential coil, which is given by[3]

$$V(t) = \sum_{n=1}^{\infty} C(n)\left(\frac{R_c}{R}\right)^{n-1} 2LR_cN\omega\sin\left(\frac{n\Delta}{2}\right)\cos[n\{\omega t-\delta+\alpha(n)\}] \qquad (2)$$

where R_c=radius of coil, L=length of coil, N=number of turns, ω =angular speed of clockwise rotation, Δ=angle subtended by the coil, and δ=the coil center line angle at $t = 0$.

2. A 'Typical' Dipole Magnet :

It is seen from Eq.(1) that the strengths of various terms in the expansion are proportional to $C(\ell)$. Thus, apart from the amount of displacement, the effective coefficients also depend on the actual harmonic contents of the magnetic field. This is true for most of the imperfections to be dealt with in this note. In order to obtain quantitative results in a situation of practical interest, we shall consider a *typical dipole magnet* characterized by harmonic contents measured in an actual dipole, DSA207, picked arbitrarily. This is a short, 50mm SSC magnet. The magnetic field parameters in this magnet are given in Table I. The reference radius, R, is taken to be 1.0cm. The normal (b'_n) and skew (a'_n) coefficients are averages of up and down ramp measurements in a cold run. All the harmonic field parameters are calculated from these coefficients, assuming a dipole field of 2.5 Tesla. The relationship between (b'_n, a'_n) and $[C(n), \alpha(n)]$ is given by

$$b'_{n-1} = \frac{C(n)}{C(1)} \cos[n\alpha(n)], \qquad a'_{n-1} = -\frac{C(n)}{C(1)} \sin[n\alpha(n)] \tag{3}$$

Table I. Magnetic Field Parameters of a 'Typical' Dipole Magnet

n	$C(n)$ (Tesla)	$\alpha(n)$ (degrees)	b'_{n-1} (units)	a'_{n-1} (units)
1	2.5000	0.004	—	—
2	3.34×10^{-4}	44.207	0.037	-1.337
3	4.20×10^{-4}	1.469	1.674	-0.129
4	6.93×10^{-6}	28.910	-0.012	-0.025
5	9.08×10^{-5}	71.747	0.363	0.008
6	4.51×10^{-6}	48.240	0.006	0.017
7	4.78×10^{-6}	24.856	-0.019	-0.002
8	2.50×10^{-7}	11.250	0.000	-0.001
9	9.76×10^{-6}	39.674	0.039	0.002
10	2.50×10^{-7}	9.000	0.000	-0.001
11	3.01×10^{-6}	32.294	0.012	0.001
12	0.0000	0.000	0.000	0.000
13	2.50×10^{-7}	13.846	-0.001	0.000

The coefficients *as measured* by an imperfect coil may be in large error, but it may be possible to get rid of most of the error by centering, as we shall see in later sections. This, however, requires that a reliable criterion for centering be available. In Table I, the field parameters for $n = 12$ are made zero, and terms higher than $n = 13$ are also assumed to be zero. Though artificial, this provides a very reliable means of centering the numerically calculated data for the purpose of this note. In practice, high order terms may not always be so reliable. In particular, later coil cross sections are expected to give much smaller high

order terms. It may be pointed out here that recent results[4] on a *quadrupole configured dipole* suggest interesting possibilities for reliable centering in actual measurements of dipole magnets.

3. Effect of Sag in the Coil :

Although the effect of sag has been formulated earlier[2], it is included here mainly for the sake of completeness. A sag results from finite rigidity of the coil form, and is aggravated by the need to have a long coil with a small diameter. In analysis of sag, it is assumed that the coil has a curved shape due to its own weight. This means that as the coil rotates, the shape of the coil along its length does not change. At each axial position, the rotation axis coincides with the *local* geometrical axis of the coil form, but is different in terms of a *space fixed* reference frame. This is a valid assumption, specially in view of rather low rotation speeds. Sag is therefore a complex form of displacement, where the displacement parameter r_0 depends on axial position and σ is -90^0 (vertically downward displacement). It should be pointed out here that a *bow* in the coil is different from *sag*, as discussed later in Sec.9.

If the transverse profile of the sagging coil is known, the effective coefficients, $C_{eff}(n)$ and $\alpha_{eff}(n)$ may be obtained by integration along the length of the coil. Assuming a parabolic profile with zero displacement at the ends and a maximum displacement of h at the center of the coil, it has been shown[2] that

$$C_{eff}(n)\exp\{in\alpha_{eff}(n)\} = \sum_{\ell=n}^{\infty} C(\ell)\left[\frac{(\ell-1)!}{(\ell-n)!(n-1)!}\right]\left(\frac{h}{R}\right)^{\ell-n}\frac{[2(\ell-n)]!!}{[2(\ell-n)+1]!!} \times \exp[i\{(\ell-n)\frac{\pi}{2}+\ell\alpha(\ell)\}] \quad (4)$$

where $(2m)!! = 2.4.6\ldots 2m$, $(2m+1)!! = 1.3.5\ldots(2m+1)$ and $0!! = 1$. The differences between effective and real harmonic field amplitudes and phases are given in Tables II and III. Two different values of h are considered. One is a rather large sag of 0.030", and the other one is a 'moderate' sag of 0.010". The values in Tables II and III thus represent the *worst case* values, rather than *typical* values. The reference radius R was taken as 1.0cm. Amplitude errors in excess of 100% are also shown as 100% in Table II. As expected, the *uncentered* parameters have large errors, particularly for the unallowed n = even terms. However, after a centering correction is applied using $b_{12} \rightarrow b_{11}$ feed down, the errors are dramatically reduced. Even for the large sag of 0.030", almost all the amplitude and phase errors become negligible. The situation is evidently very comfortable with the 'moderate' sag of 0.010". The centering radius obtained in each case is very close to $(2h/3)$, which is the average displacement for a parabolic sag.

It can therefore be concluded that a *sagging* coil (within easily achievable limits) can be considered merely as a *displaced* coil with an average displacement of $(2h/3)$. This is *not* a serious problem in field measurements, provided a reliable means of centering is available.

Table II. Amplitude Errors due to Sag in a 'Typical' Dipole Magnet

n	$\Delta C(n)$ (%) for 0.030" Sag		$\Delta C(n)$ (%) for 0.010" Sag	
	Before Centering	After Centering	Before Centering	After Centering
1	−0.001	0.000	0.000	0.000
2	12.653	−0.002	4.226	0.000
3	−0.637	−0.067	−0.123	−0.007
4	100.000	0.322	83.760	0.034
5	1.436	0.041	0.421	0.005
6	32.595	−0.028	9.943	0.003
7	19.285	2.946	2.578	0.328
8	100.000	−0.779	100.000	−0.168
9	−5.481	−0.717	−0.867	−0.080
10	100.000	−0.166	100.000	−0.007
11	1.692	0.282	0.188	0.031
12	100.000	0.000	100.000	0.000
13	0.000	0.000	0.000	0.000

Table III. Phase Errors due to Sag in a 'Typical' Dipole Magnet

n	$\Delta\alpha(n)$ (mrad) for 0.030" Sag		$\Delta\alpha(n)$ (mrad) for 0.010" Sag	
	Before Centering	After Centering	Before Centering	After Centering
1	0.000	0.000	0.000	0.000
2	5.869	−0.009	2.124	−0.002
3	−0.174	0.022	−0.087	0.002
4	−85.431	−0.088	−55.079	−0.021
5	0.839	−0.007	0.291	−0.001
6	−18.799	0.023	−7.088	−0.003
7	1.356	0.220	0.237	0.025
8	−5.989	−0.152	−5.389	−0.043
9	0.090	0.026	−0.005	0.003
10	−7.102	−0.012	−5.576	−0.012
11	0.126	0.021	0.014	0.002
12	392.701	0.000	392.704	0.000
13	0.000	0.000	0.000	0.000

4. Effect of Twist in the Coil :

The wires of the coil are placed inside machined grooves in the coil form. The angular location of the coil is characterized by the parameter δ in Eq.(2). Inaccuracies in the groove locations along the length of the coil would mean a varying δ. It is assumed that the two grooves remain parallel to each other, so that Δ does not change. This imperfection will be referred to as a *twist*. Effect of errors in Δ will be discussed later in Sec.6.

Let us consider a general case where δ changes randomly along the length of the coil around a mean value, $\bar{\delta}$. It can be shown[5] that for small variations, the cosine term in Eq.(2) should be replaced by

$$\cos[n\{\omega t - \delta + \alpha(n)\}] \longrightarrow \left[1 - \left(\frac{n^2}{2}\right)\sigma_\delta^2\right]\cos[n\{\omega t - \bar{\delta} + \alpha(n)\}] \tag{5}$$

where σ_δ is the RMS variation in δ. Eq.(5) shows that the phases of the multipole fields, $\alpha(n)$, can still be obtained correctly if one uses the average value of δ in the calculations. The routine coil-calibration procedure should readily yield this average $\bar{\delta}$. On the other hand, the amplitudes are affected by a harmonic dependant factor. This result is opposite of what one might intuitively expect. The errors are larger for higher harmonics. If we set an upper limit on the allowable error in the highest harmonic of interest, Eq.(5) can be used to specify the RMS variation in δ. Assuming a maximum error of 1% for $n = 15$, σ_δ should be less than 9.4 mrad (0.54^0), which should be readily achievable in practice.

A special case is that of a *uniform twist*, where the grooves are straight and parallel to each other, but do not run parallel to axis of the coil. The angle δ in this case varies linearly from one end to the other. The twist angle, Θ is given by difference between δ values at the two ends of the coil. It can be shown[5] that σ_δ in this case is $\Theta/\sqrt{12}$. Thus, the limit on a *uniform* twist angle Θ for 1% accuracy in $C(15)$ is even more comfortable at 32.7 mrad or 1.9^0. With this limit, the amplitude errors up to 20-pole ($n = 10$) are less than 0.5%.

5. Systematic Error in δ :

It was shown in the previous section that random errors in δ are not too serious, as long as the average $\bar{\delta}$ is accurately known. In practice, there may be calibration errors in determining this $\bar{\delta}$. The effect of this systematic error is to change all phase angles by a fixed amount. This is the same as a rotation of reference frame. If the normal and skew coefficients are calculated in a *space fixed* reference frame, the errors can be calculated by differentiating Eq.(3) :

$$\Delta b'_n = [(n+1)a'_n]\epsilon_\delta\,, \qquad \Delta a'_n = [(n+1)b'_n]\epsilon_\delta \tag{6}$$

where ϵ_δ is the systematic error in δ. Assuming $(b'_n, a'_n) \sim 0.5$ unit, and permissible errors of 0.01 unit for $n \sim 10$, we get a limit of $\epsilon_\delta \sim 1$ mrad. In practice, these coefficients are calculated in a frame where $\alpha(1) = 0$, and not in a space fixed frame. In this case, there is

no error at all, since all phase angles, including $\alpha(1)$ are changed by the same amount, and phase angles relative to $\alpha(1)$ remain unaffected.

6. Random and Systematic Errors in Δ :

The treatment of random variation in Δ along the length of the coil is identical to the case of δ. Corresponding to Eq.(5), we have in this case[5] :

$$\sin\left(\frac{n\Delta}{2}\right) \longrightarrow \left[1-\left(\frac{n^2}{8}\right)\sigma_\Delta^2\right] \sin\left(\frac{n\bar{\Delta}}{2}\right) \tag{7}$$

It can be seen that the tolerance on the RMS variation of Δ can be a factor of two larger than for δ, and should be easily achieved in practice.

A systematic error in $\bar{\Delta}$ affects the amplitude differently. From Eq.(2), we get

$$\frac{\Delta C(n)}{C(n)} = \left(\frac{n}{2}\right)\cot\left(\frac{n\Delta}{2}\right)\epsilon_\Delta \tag{8}$$

where ϵ_Δ is systematic error in Δ. The fractional amplitude error reduces with n in this case. For a 1% accuracy in $C(1)$ with a $\Delta = 12^0$ coil, ϵ_Δ should be less than 2.1 mrad (0.12^0).

7. Random and Systematic errors in the Coil Radius :

Random errors in the coil radius are a result of machining errors – both in the coil form outer surface, as well as in the wire groove depths. Also, a typical multiturn coil, such as the tangential coil, has several layers. The different layers can be viewed as coils of different radii. The effect of these multiple layers is the same as a coil of varying radius. Once again, a calculation similar to that in the previous sections shows[5] that

$$\frac{\Delta C(n)}{C(n)} \approx \left[\frac{n(n-1)}{2}\right]\left(\frac{\sigma_{R_c}^2}{\bar{R}_c^{\,2}}\right) \tag{9}$$

where the average radius $\bar{R}_c$ is assumed to be known accurately. To keep this n dependant correction below 1% up to $n = 15$, we should have the RMS variation $\sigma_{R_c} \leq 0.005''$ in a coil of 0.5" radius.

Let us apply the result in Eq.(9) to the special case of a multilayered coil, where the only variation in R_c is assumed to be due to different layers. All other fabrication errors are neglected. Let there be N layers of a wire of diameter d. If R_1 is the radius of the innermost layer, subsequent layers will have radii $R_1 + d$, $R_1 + 2d, \ldots$. The mean, $\bar{R}_c$ and RMS variation in this case are[5]

$$\bar{R}_c = R_1 + \frac{(N-1)}{2}d, \quad \sigma_{R_c}^2 = \frac{d^2}{12}(N^2-1) \tag{10}$$

The fractional errors in various amplitudes are given by

$$\frac{\Delta C(n)}{C(n)} \approx \frac{n(n-1)}{24}(N^2-1)\left(\frac{d}{\bar{R}_c}\right)^2 \tag{11}$$

As expected, the errors given by Eq.(11) vanish if the coil has only one layer ($N = 1$). To obtain some numerical estimates, let us consider the tangential coil in the F-mole. This has five layers of a 0.006" diameter wire, and $\bar{R}_c = 0.482$". The amplitude errors in this case are 0.3% for $n = 5$ and 1.4% for $n = 10$.

If there is an error in knowing $\bar{R}_c$, then the fractional errors in the amplitudes are given by $\sim n(\Delta\bar{R}_c/\bar{R}_c)$. This error could be significant for large n. For example, an error of 0.001" in a coil of 0.5" radius would give a 3% error in $n = 15$.

8. Offset in Rotation Axis :

If the rotation axis of the coil does not coincide with the geometrical axis of the coil form, then Eq.(2) no longer correctly gives the voltage induced in the coil. Let (r_0, ψ_0) be the polar co-ordinates of the *geometrical center* of the coil form at time $t = 0$, measured in a reference frame having origin at the *center of rotation*. The parameters (r_0, ψ_0) are assumed to be constant along the length of the coil. In other words, the coil is perfectly straight, and not *bowed*.

Fig.1 illustrates a cross section of the coil where the locations of the wires are shown at various instants in one rotation. The triangles are formed by joining the rotation center, the coil form center and the center of the coil. The invariant vertex is obviously the rotation center. The small dashed circle is the path traced by the geometric center of the coil form.

The instantaneous flux through the coil can be easily calculated by transforming the field parameters to the geometrical center. The only complication in this is that the angular position, ψ of the coil form center changes with time as the coil rotates. Nevertheless, the transformation given in Eq.(1) remains valid at all instants. The expression for induced voltage can be obtained by differentiation. After some simple algebra, and a rearrangement of terms, it can be shown[6] that the effective coefficients in this case are given by :

$$C_{eff}(n)\exp\{in\alpha_{eff}(n)\}\sin\left(\frac{n\Delta}{2}\right) =$$

$$C(n)\sum_{\ell=1}^{n}\binom{n}{\ell}\left(\frac{r_0}{R_c}\right)^{n-\ell}\left[\frac{(n-1)!}{(n-\ell)!(\ell-1)!}\right]\sin\left(\frac{\ell\Delta}{2}\right)\exp[i\{n\alpha(n)-(n-\ell)(\psi_0-\delta)\}] \tag{12}$$

where δ is once again the angular position of the coil at $t = 0$, measured in a reference frame with origin at the *geometrical center* of the coil, and not at the rotation center.

Some interesting features of the summation in Eq.(12) should be noted. First of all, the effective coefficients for a given harmonic do not depend on other harmonics. In other words, there is no feed down due to this offset. Secondly, the offset r_0 is scaled by the radius of the coil, R_c, rather than the reference radius R. Finally, the summation goes from 1 to n, rather than from n to ∞. Thus, for the case of dipole field, $n = 1$, only one term contributes, and the summation reduces to the usual expression for the case without offset. The dipole field amplitude and phase are therefore not affected at all by offset. Another interesting feature is that a harmonic voltage does not vanish even if $\sin(n\Delta/2)$ is zero. As an example, a dipole buck winding ($\Delta = 180^0$) will also see a quadrupole field. Without an offset in rotation, a dipole buck winding would be insensitive to the quadrupolar field [see Eq.(2)]. This result can in fact be utilized to actually measure the amount of offset in a given coil.

Figs.2 and 3 show the effect of a 0.005" offset in rotation axis on the harmonic amplitudes and phases. The radius of the coil was assumed to be 15mm. Once again, this offset is perhaps larger than what can be easily accomplished. Typical amplitude errors are of the order of a few percent. The phase errors are typically about 1 mrad and do not depend much on the harmonic number. If terms corresponding to $\ell = n$ and $\ell = (n-1)$ only are considered in Eq.(12), then the errors are proportional to the offset. In order to keep the amplitude errors to below 1%, the offset should be less than 0.001". However, one can probably tolerate much more than 1%, since typical overall measurement accuracy may approach only a few percent in most cases. It may be a worthwhile idea to obtain the offset parameters as part of routine coil calibration procedure by using the dipole buck winding in a quadrupolar field, as explained earlier. These parameters can then be used to correct the measured field in any magnet, if at all necessary.

9. Bow in the coil :

The coil form in practice may not turn out to be perfectly straight. An *arched* coil may result, for example, due to stresses on the large outer machined surface of the coil form. As opposed to a sagging coil, which is flexible, a bowed coil is rigid. If we consider a transverse section of the bowed coil, it would rotate about a *space fixed* rotation axis, rather than the local geometrical center of the coil form. This is opposite of what happens in sag, as explained earlier in Sec.3.

Just as the formalism for a displacement of axes can be used to analyze the problem of sag (see reference 2), the formalism presented in Sec.8 for offset of rotation axis can be used to analyze the problem of bow. Such a detailed calculation, however, appears unnecessary in view of the small errors caused by these imperfections. For a given amount of bow, the effects will be smaller than those caused by the same amount of offset, for which estimates were presented in the previous section. In analogy with the case of sag, a bow of magnitude h may be considered as an offset of roughly $2h/3$ (see Sec.3). If measurement of offset is made a part of coil calibration procedure as suggested in Sec.8, the measurement would reflect overall offset parameters encompassing the effects due to an offset, as well as due to a bow in the coil.

10. Tilt in Placement of the coil :

The imperfections discussed so far in the earlier sections were essentially fabrication errors. Even with an otherwise perfect coil, the rotation axis in actual measurements may not coincide with the magnetic axis. In general, the coil rotation axis can have a displacement and a *tilt* with respect to the magnetic axis. The problem of displacement is well known and measured data are routinely centered. The tilt of rotation axis is generally neglected because long coils placed in small bore magnets with small radial clearance do not allow for any *significant* tilt. Once again, a quantitative treatment is still useful in deciding upon tolerances, particularly in dealing with large aperture magnets.

Let us consider a coil placed in a magnet such that the rotation axis is not parallel to the magnetic axis. We shall consider the simple case of pure tilt, where the average displacement of the coil is zero. Any general coil placement can be considered as a combination of pure tilt, and a pure displacement. If we look at a transverse section of the coil, the rotation axis will be displaced (and not offset) from the magnetic axis by (r, σ), which vary along the length of the coil. This is the same as in sag, discussed earlier. The difference lies in the manner in which (r, σ) vary along the length. In the case of tilt, the displacement r varies linearly. It is zero in the middle of the coil, and is maximum (say, r_0) at the two ends. The parameter σ can take any value, but is fixed for the first half of the coil (say, σ_0), and is $\sigma_0 \pm \pi$ for the other half. Integration along the length of the coil gives[7] the effective parameters as seen by the coil :

$$C_{eff}(n)\exp\{in\alpha_{eff}(n)\} = \sum_{\ell=n}^{\infty}{}' C(\ell)\left[\frac{(\ell-1)!}{(\ell-n)!(n-1)!}\right]\left(\frac{r_0}{R}\right)^{\ell-n}\frac{\exp[i\{\ell\alpha(\ell)-(\ell-n)\sigma_0\}]}{\ell-n+1} \quad (13)$$

The prime in the summation in Eq.(13) denotes that the summation is to be carried out only for values of ℓ such that $(\ell - n) =$ even. As defined earlier, (r_0, σ_0) are the displacement parameters at the ends of the coil. The unusual summation in Eq.(13) has interesting consequences as discussed in the following paragraphs.

Let us consider the case of a dipole magnet first. The symmetry of a dipole makes $n = 2, 4, 6, \ldots$ unallowed terms. These terms in an actual magnet will therefore be small, and thus most likely to be affected by feed down from higher harmonics. If we consider effect of tilt on an unallowed term, then Eq.(13) says that only *unallowed* terms contribute to the feed down. This, coupled with the fact that the feed down terms are at least of second order in (r_0/R), shows that one can neglect the effects of a modest tilt on unallowed harmonics. Similar arguments hold for the allowed terms, where feed down is from only the *allowed* terms. Numerical calculations for the 'typical' dipole with a $\sim 0.005''$ displacement of the coil at the ends gives amplitude errors of less than 0.1% and phase errors of less than 0.1 mrad for almost all the harmonics.

In the case of a quadrupole, the allowed terms from symmetry are only $n = 2, 6, 10, \ldots$. The only harmonics which are likely to be seriously affected by tilt are therefore $n = 4, 8, \ldots$ where we shall have an allowed term feeding down to an unallowed term, although only in

second order. Numerical calculations for the calibration "air magnet" confirm this. The effect is most prominent on $n = 4$, where a tilt of less than 0.5^0 can give rise to a measured amplitude of a few units, even if no octupole component is actually present.

11. Conclusions :

Various types of possible imperfections in a measuring coil have been studied in this note. The analytical results presented in Eqs.(4) to (13) can be used to estimate the measurement errors for a given imperfection, or to specify mechanical tolerances for a given accuracy. Numerical calculations for typical magnets of interest show that the errors should be negligible even with modest tolerances. The errors due to moderate sag can be corrected by centering. The most significant errors are due to use of a multilayered coil (Sec.7) , and offset in rotation axis (Sec.8) or a bow in the coil (Sec.9). Although very little could be done to reduce the construction errors beyond certain practical limits, the results from this work could be used to correct the data for most of the errors.

Acknowlegement :

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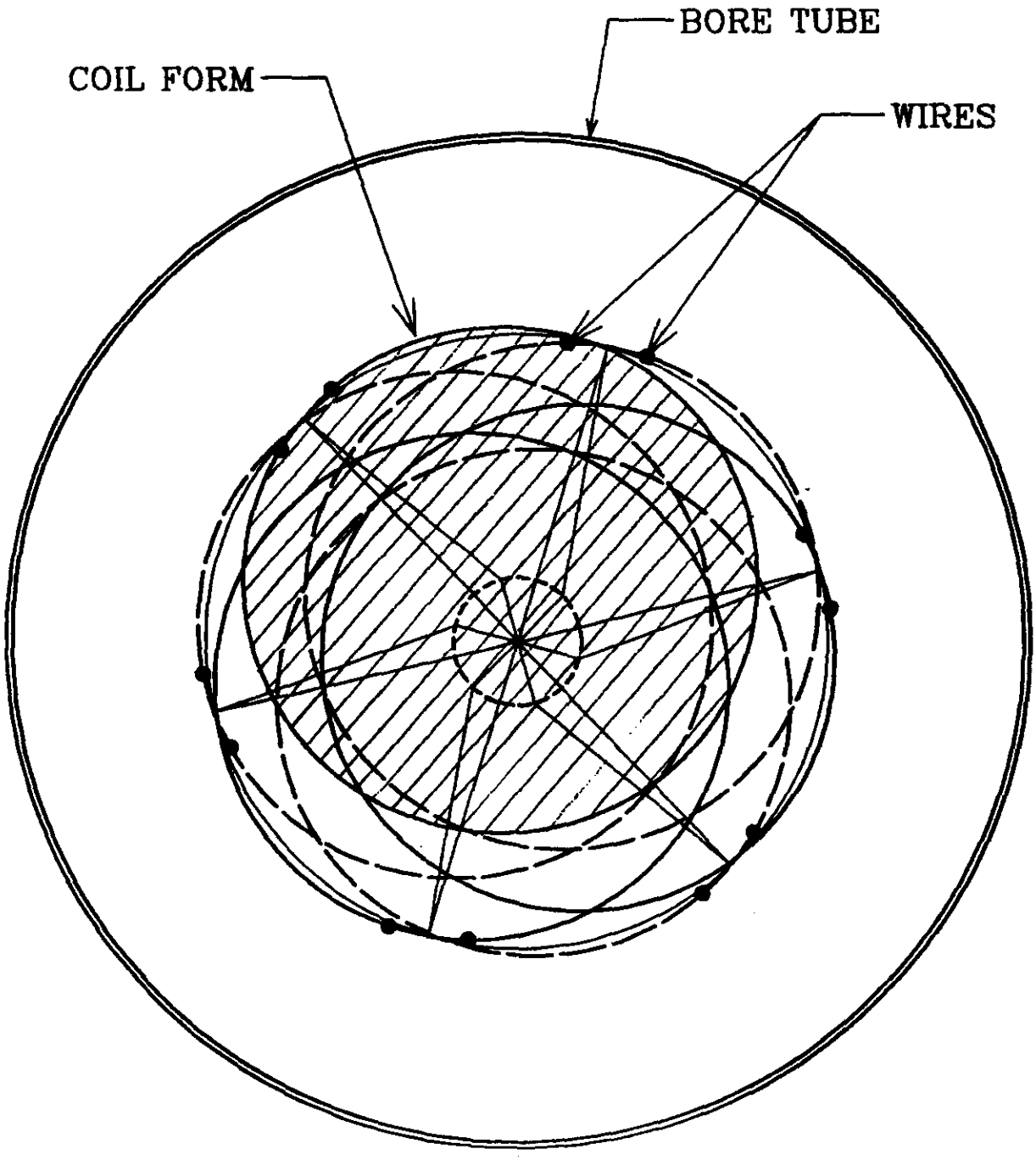

Figure 1: *Locations of coil wires as the coil form rotates about an axis offset from the geometric center. The small dashed circle is the path traced by the geometric center.*

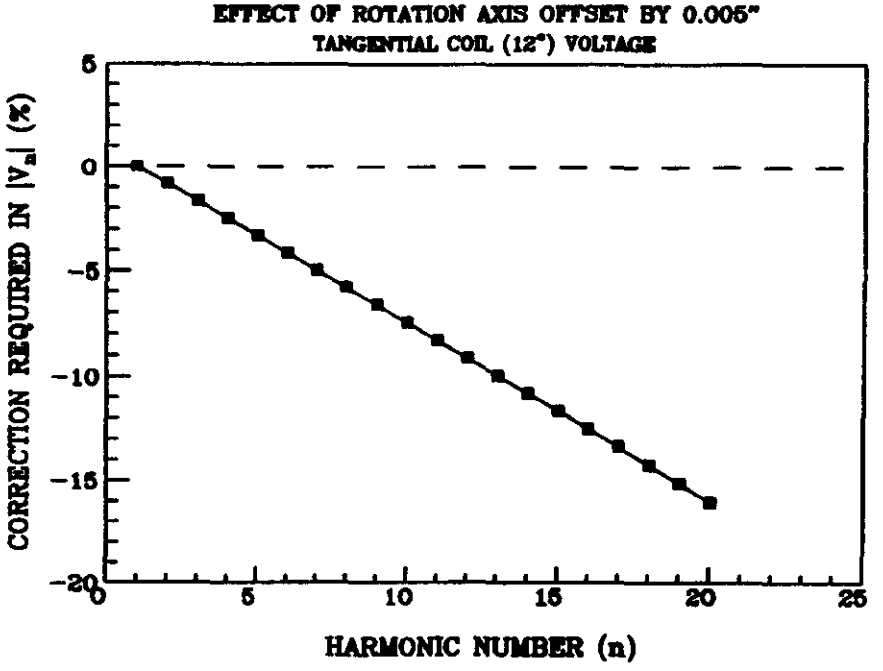

Figure 2: *Amplitude errors due to a 0.005" offset in the rotation axis of a tangential coil.*

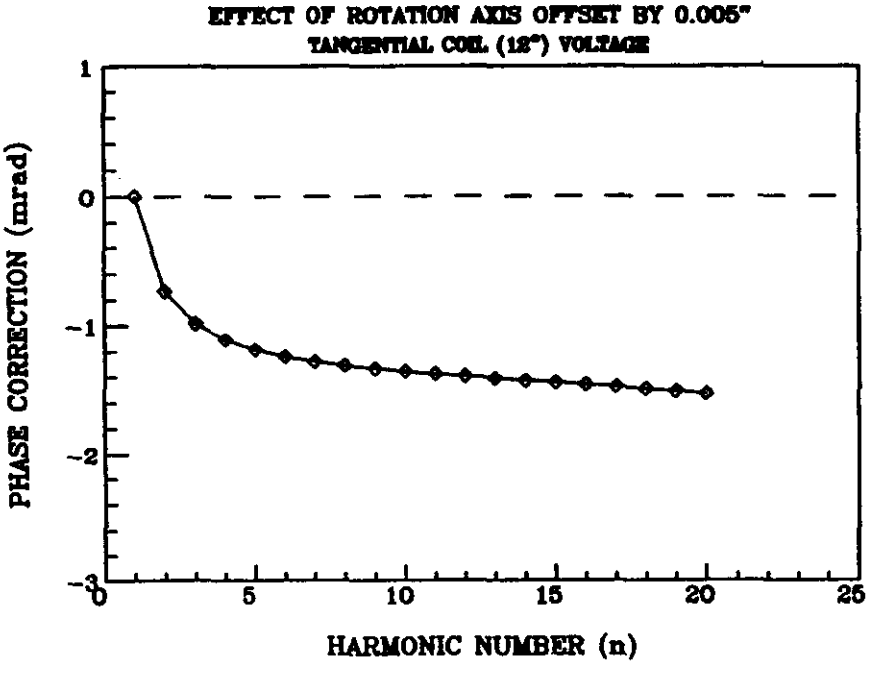

Figure 3: *Phase errors due to a 0.005" offset in the rotation axis of a tangential coil.*

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