MONITORING TRANSVERSE BEAM PROFILE WITH NONUNIFORMLY-WOUND TOROIDAL COILS

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Abstract

Others have shown that the voltages induced on one uniformly-wound toroidal coil and two sinusoidally-wound toroidal coils may be used to determine the current in a single filament and its coordinates. We have extended this technique to show that the voltages measured on a group of sinusoidally-wound toroidal coils may be used to approximate the transverse distribution of the current that passes through their common aperture. This is possible because each measured voltage is proportional to the product of unique functions of the radial and azimuthal coordinates of each increment of the current. We have developed matrix methods to determine the transverse distribution of the current and determined the sensitivity of these calculations to measurement errors. Shielded sinusoidally-wound coils with a precision of 0.02 cm have been prepared using rapid prototyping, and methods to prepare the next generation of these coils, which will have a precision of 0.001 cm, by using an engraving tool with the 4th axis of a vertical milling machine have been defined.

INTRODUCTION

A number of different techniques have been used to monitor the transverse distribution of the beam current in accelerators, including secondary emission monitors, wire scanners, multi-wire chambers, gas curtains or jets, residual gas monitors, scintillator screens, scrapers and measurement targets, synchrotron radiation, and Laser-Compton scattering [1], as well as optical transition radiation [2] and the deflection of a probe beam of electrons [3].

A Rogowski Coil is a non-ferrous current probe which is generally wound as a toroid, but may also be made by bending a uniformly wound helical coil to follow a closed curve having arbitrary shape [4-6]. A time-dependent current passing through the aperture of a Rogowski Coil induces a voltage on the coil, and for an ideal coil this voltage would be independent of the location of the current within the aperture, and zero for currents outside of the aperture.

Great care is taken to limit the deviations from a perfectly uniform winding because these errors cause a Rogowski Coil to have "position sensitivity" so that the induced voltage depends on the location of the current within the aperture and may be non-zero when the current is outside of the aperture [7-8]. However, others have shown that the position sensitivity of non-uniformly wound coils may be used advantageously to determine the location of a single current that passes through the aperture [9-11].

SUMMARY OF THE ANALYSIS

We have previously derived exact closed-form expressions for the open-circuit voltage that is induced on a non-ferrous toroidal coil by a time-dependent current passing through the aperture when the turn density of the coil varies sinusoidally as a function of θ, which is the angle about the axis of the toroid [12-13]. To illustrate the configuration, Fig. 1 is a design drawing that was used in fabricating one of our toroids which has a total of 268 turns in which N'(θ), the number of turns per unit length at the mean radius R_1, is proportional to sin(θ). Thus, it may be seen that there is a reverse in the direction of the winding at the midpoint of the coil.

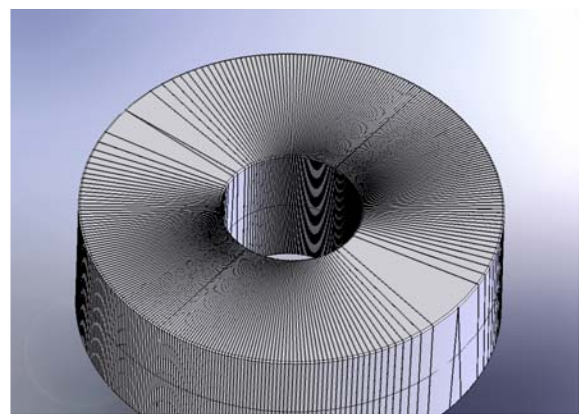

Fig. 1. Design drawing for sin(θ) toroid.

Each coil has a rectangular cross-section with height h, inner radius r_1, and outer radius r_2. To begin with we determine the open-circuit voltage induced on the coil by a filament of current I_0 which is located at the coordinates (R_2, Φ) where $R_2 < r_1$ to be inside of the aperture. The current is assumed to have harmonic time-dependence of $e^{j\omega t}$, but Fourier analysis may be used to extend the analysis to pulses or other functions of time. If the turn density is given by N_0', $N_{JC}\cos(J\theta)$, or $N_{JS}\sin(J\theta)$, it may be shown that the open-circuit voltage is given respectively, by the following three expressions:

$$V_{OC} = j\omega\mu_0 hR_1N_0{}'I_0\ln\left(\frac{r_2}{r_1}\right) \qquad (1A)$$

$$V_{OC} = \frac{j\omega\mu_0 hR_1N_{JC}{}'I_0\cos(J\Phi)}{2J}\left[\left(\frac{R_2}{r_1}\right)^J - \left(\frac{R_2}{r_2}\right)^J\right] \qquad (1B)$$

$$V_{OC} = \frac{j\omega\mu_0 hR_1N_{JS}{}'I_0\sin(J\Phi)}{2J}\left[\left(\frac{R_2}{r_1}\right)^J - \left(\frac{R_2}{r_2}\right)^J\right] \qquad (1C)$$

For the special case of a thin toroid, where $r_2 - r_1 << R_1$, these three expressions simplify to give those which were reported earlier [12-13]. Nonuniformly wound coils are also sensitive to other currents which may be located outside of the aperture so it is necessary to shield the coils to limit the effects of this interference.

We have previously reported simulations which show that a group of sinusoidally-wound toroidal coils may be used to approximate the transverse distribution of the current that passes through their common aperture [12], or the current and position of one or two filaments [13]. This may be understood because Eqs. (1A), (1B), and (1C) show that the voltage measurements are related to the distribution of the current through orthogonal sine and cosine functions of the azimuthal angle θ, as well as radial functions which are unique for each coil in the group.

EXPERIMENTAL COILS

Three different coils have been fabricated for laboratory measurements; a 300 turn coil with a uniform winding, a 268 turn coil with a turn density proportional to sin(θ), and a 264 turn coil with a turn density proportional to sin(2θ). Each coil was wound on a toroidal form with the dimensions $r_1 = 4.0$ cm, $r_2 = 12.0$ cm, and $h = 8.0$ cm.

The coil forms were prepared by rapid prototyping through stereo lithography (SLA) in which 0.10 mm thick layers of DMX-SL100 resin (similar to ABS plastic) are deposited with a specified tolerance of 0.050 mm. Data files were prepared to define the location and shape for grooves to hold the wire, but the tolerance was not met on the vertical faces of the coil forms where the minimum center-to-center spacing of the wires is as small as 0.60 mm. Thus, it was necessary to prepare inserts for the inner and outer vertical faces of the coil forms.

Each coil was wound from a single piece of wire with no splices, by passing a spool through the aperture. The coils were made of No. 30 tin-plated copper wire (O.D. = 0.254 mm) to provide some additional rigidity for the small wire and also simplify connections to the coil. The total resistance of each coil is approximately 30 Ω. Kapton tape was used to hold the coil in each groove.

Each toroidal form was made in two parts, with a groove for an additional turn that passes along the center of the tube of the toroid. This turn is connected in series with the toroidal coil as a compensating turn to correct for the effects of the single turn that the coil itself makes in the toroidal winding [8]. Figure 2 is a design drawing that shows the bottom half of the coil form, including the groove which holds the compensating turn.

Each coil has a metal shield to limit interference by currents that may be outside of the aperture as well as electric fields. Figure 3 is a design drawing that shows the coil with a uniform winding, including the plastic ribs on the coil form which are used to hold the coil in place within the shield. Figure 4 is a design drawing showing the shield, in which the top and base were machined from a single piece of aluminum. The two halves are in electrical contact at the outer surface, but there is a circumferential gap on the inner surface to allow the coil to be sensitive to the effects of currents that are within the aperture. All of the construction of each current probe is non-ferrous.

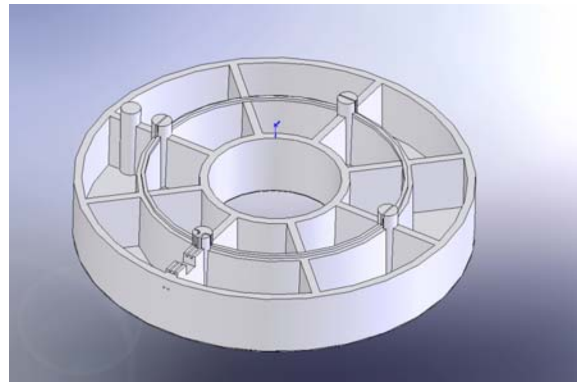

Fig. 2. Design drawing showing the inside of the bottom half of the coil form.

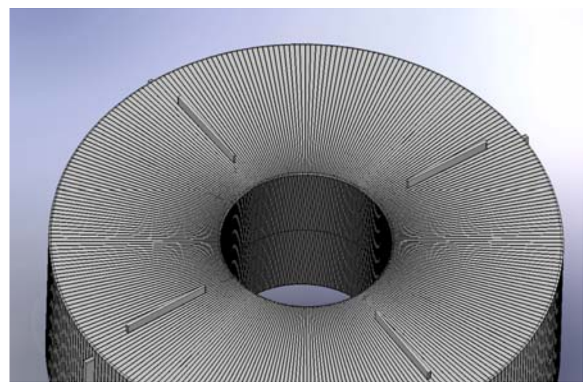

Fig. 3. Design drawing showing the coil with a uniform winding, including the ribs which secure the coil.

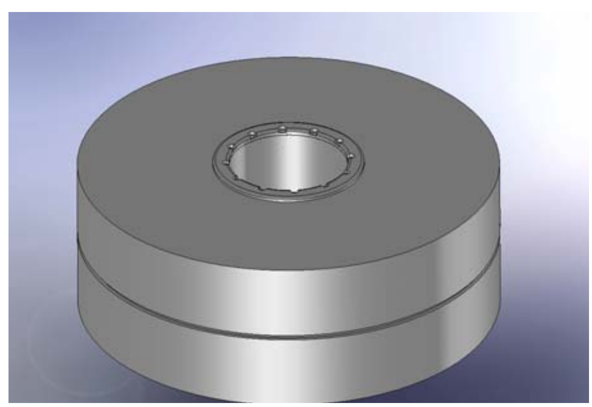

Fig. 4. Design drawing showing a coil with a shield.

The precision of the winding on these coils, which have been prepared by rapid prototyping supplemented by machined inserts, is approximately 0.02 cm, and we are prepared to make the next generation of coils, which will have a precision of 0.001 cm, by using an engraving tool with the 4th axis of a vertical milling machine. A test fixture has been prepared which will enable highly accurate measurements to be made in order to determine the precision that is required for the coils to be used for determining the transverse distribution of the current that passes through their common aperture.

DESCRIPTION OF TEST FIXTURE

A Rogowski coil is generally calibrated by placing it in a metal box and passing a wire with a known current through the aperture. However, the box must be much larger than the coil and the box must also be much smaller than the wavelength to prevent higher modes. In order to simplify the calibration and make it possible to use higher frequencies we have generally used the metal shield for the coil as the outer conductor to form a coaxial calibration cell [6]. Metal plates cover the top and base of the shield, and coaxial connectors in these plates are connected to a metal cylinder which serves as the inner conductor of the cell. The ratio of the inner radius of the shield to the radius of the cylinder is equal to 2.30 so the coaxial calibration cell has a characteristic impedance of 50 Ω. A signal generator and a 50 Ω load are attached to the two coaxial connectors to complete the test circuit.

Figure 5 illustrates the concept for the precision test fixture which is used to calibrate and measure the position sensitivity for these coils. Two plates with coaxial connectors are used with a central cylinder to provide a coaxial calibration cell as was done earlier [6]. However, now two track systems are used to slide the current probe relative to the cylinder in order to scan the position of the current through the full area of the aperture. Two gauges are used to measure this movement along two axes to an accuracy of 0.001 inch (0.0254 mm).

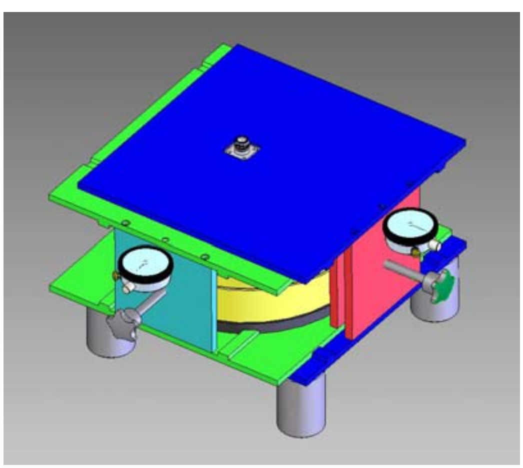

Fig. 5. Concept for the test fixture.

Figures 6 and 7 are photographs of the completed test fixture with one of the three shielded toroids. We have verified the accuracy of positioning with the test fixture and also determined that it has a low standing-wave ratio, and we believe that similar instruments would be useful to others for determining the position sensitivity of Rogowski coils as well as other types of current probes. However, measurements with our three current probes having uniform, sin(θ) and sin(2θ) turn densities are still in progress.

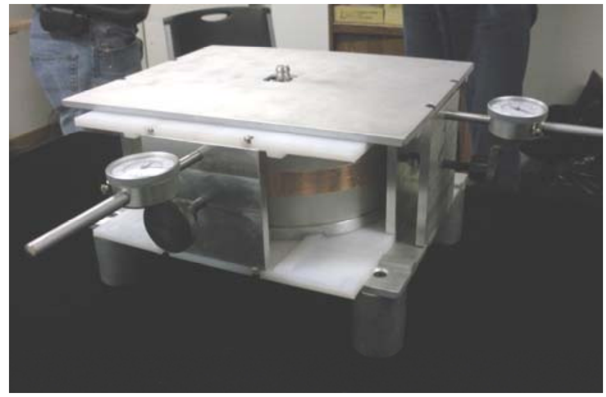

Fig. 6. First picture of the test fixture with a current probe.

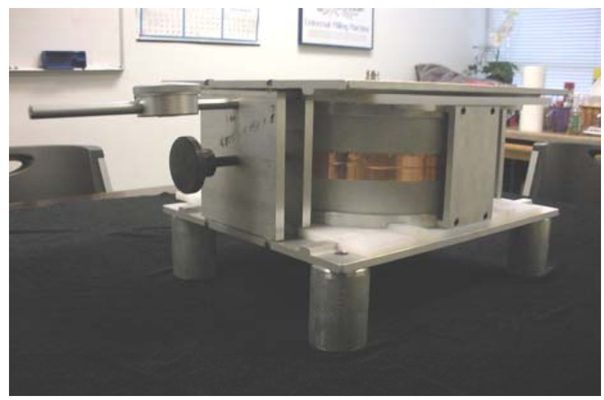

Fig. 7. Second picture of test fixture with a current probe.

SUMMARY AND CONCLUSIONS

- Exact closed-form expressions have been derived for the open-circuit voltage induced on a non-ferrous toroidal coil by a time-dependent current when the turn density of the coil varies sinusoidally as a function of the angle θ about the axis of the toroid.

- These expressions show that the voltages that are measured on a group of such coils are related to the distribution of the current through orthogonal sine and cosine functions of θ, as well as radial functions that are unique for each coil.

- Simulations show that it is possible to determine the traverse distribution of a current, or the current and position of one or two filaments, by this method.

- We have fabricated three different precision toroidal coils having turn densities that are uniform, and proportional to sin(θ) and sin(2θ), as well as a test fixture which can be used to determine the response of these coils to currents at precise locations within their apertures.

- We have verified the accuracy of positioning the current within the test fixture and also determined that this fixture has a low standing-wave ratio.

- Simulations suggest that the three coils have sufficient precision to enable determining the transverse distribution of a current, or the current and position of one or two filaments. Measurements with the three current probes are still in progress.

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