Non-Invasive Measurement of Current for Dosimetry

Final Report

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Abstract

Minimally-perturbing, resistive, non-ferrous probes were developed for measuring the current induced in personnel exposed to electromagnetic fields, with particular emphasis on the pulsed fields in EMP simulations. Each of these probes has an non-ferromagnetic toroid that passes around the leg or other body member, and a coil formed from high-resistance line, that is evenly distributed over the full length of the toroid. A metal electrostatic shield is used to limit capacitive coupling. Active elements were not used in the probe circuitry so that the probes would have maximum ruggedness for use in high intensity EMP fields. These probes have sufficient bandwidth for time domain measurements in EMP simulations. The probes are compatible with the low-impedance (50 Ohms) fiber-optics transducers typically used for data acquisition in EMP simulations.

The primary significance of this project to the Air Force is that possible hazards, from exposure of personnel to electromagnetic fields, may be better characterized and understood.

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1. Objective

The objective of this project was to develop minimally-perturbing probes for measuring the current induced in workers exposed to electromagnetic fields, with particular emphasis on the pulsed fields in EMP simulations. The primary significance of this project to the Air Force is that possible hazards, from exposure of personnel to electromagnetic fields, may be better characterized and understood.

In order to achieve our objective, it was necessary to make major changes in the design of minimally-perturbing current probes which we had developed previous to this project. The earlier probes were designed for fixed-frequency measurements [Hagmann and Babij, 1988, 1990a, 1990b; Babij and Hagmann, 1988], so they are loaded by diode detectors, and the rectified output is connected to (high-impedance) readout electronics by resistive line. By contrast, time domain measurements are required in EMP simulations, so the probe must have a much larger bandwidth, and the time-dependent (unrectified) output of the probe should be compatible with a low-impedance (50 Ohms) fiber-optics transducer for data acquisition. Additional circuitry with active components is not recommended because of the high intensity of the EMP fields. It was necessary to make major changes in the design of our earlier current probes in order to obtain greater bandwidth and ruggedness, and to decrease the output impedance, RFI susceptibility, and sensitivity.

2. Background, with Previous Work by Others

Clamp-on AC ammeters are commonly used to measure electrical current without interrupting a circuit, and high-frequency current probes are used for the same purpose in RF applications as well as in EMP simulations [Miller, 1986; Ricketts et al., 1976]. These commercial instruments use a ferromagnetic core to couple the magnetic flux produced by the current to a coil, and the voltage induced in this coil is measured in order to evaluate the current (See section 12 of this report, "Theoretical Analysis of Current Probes"). If the current is induced in an object by ambient fields (rather than current driven through a wire by a source of emf), then the commercial instruments would not be appropriate since the ferromagnetic core, wire coil and metal shield would alter the fields, and hence change the current.

Gronhaug has made theoretical and experimental studies of the currents induced in personnel exposed to the fields of EMP simulators [Gronhaug, 1983, 1986, 1988]. He measured the current in the (horizontal) arms of human volunteers exposed with a horizontally polarized dipole (HPD) simulator [Gronhaug, 1986], and the current in the legs for exposure with a vertically polarized dipole (VPD) simulator [Gronhaug, 1988]. The maximum values of peak current, which were measured in the ankles for VPD exposure, were 4.3 A with bare feet and 2.7 A with the feet insulated by standing on a dry wooden board using rubber-soled shoes [Gronhaug, 1988].

Gronhaug used a commercial current probe having a four inch diameter aperture (Ailtech 94456-2), which was the largest size available to him, in all of his measurements [Gronhaug, 1988]. This probe has a ferromagnetic core, a wire coil and a metal shield, so it would cause significant perturbations to the electromagnetic fields. Commercial current probes have also been used by others to measure the current induced in the legs of human subjects under fixed-frequency conditions [Allen, 1988].

3. Description of Our Earlier Current Probes

Previous to this project, we developed minimally-perturbing current probes for fixed-frequency measurements [Hagmann and Babij, 1988, 1990a, 1990b; Babij and Hagmann, 1988]. A block diagram for these devices is shown in Appendix I of this report. Each of these probes has an air-core toroid that passes around the leg or other body member, and high-resistance line is used to form a coil that is evenly distributed over the full length of the toroid. The transfer impedance of these current probes (ratio of output voltage to measured current) is typically about 6 Ohms at 1 MHz, and increases by 20 dB per decade of frequency. In each of these probes the signal is rectified by a diode located at the terminals of the winding, and resistive line is used to connect the DC output of the probe to (high-impedance) readout electronics.

High-permeability cores are not used in our current probes since we have shown analytically (See section 12 of this report, "Theoretical Analysis of Current Probes"), as well as by experiment, that a probe can function properly (output proportional to the total current passing through the aperture, and independent of the spatial distribution of the current) without them. We have shown that when a ferromagnetic core is not used, it is necessary to have the coil winding distributed over the full length of a toroidal core. It is also required that the product of the number of turns per unit length of the winding and the cross sectional area of the toroid must be kept constant over the full length of the coil. Use of a low-permeability core has the disadvantage that it reduces the transfer impedance (sensitivity) but it reduces field perturbations, permits greater bandwidth, and avoids errors due to nonlinearity and possible saturation of the core since the permeability is an exact constant.

Open field tests were made previous to this project, in which our current probes were used for fixed-frequency measurements with a man-sized phantom at the Naval Aerospace Medical Laboratory (NAMRL) in Pensacola, Florida [Hagmann and Babij, 1988; Babij and Hagmann, 1988]. The phantom was positioned so it was standing on a metal ground plane 1 m from a 10 m vertical monopole antenna, and a power of 1 kW at 29.9 MHz was fed to the antenna. A Bowman temperature probe was used to determine the local SAR (specific absorption rate, the rate of energy deposition per unit mass) at a point 27 cm above the ground plane on the axis of one leg of the phantom. One of our current probes was used to simultaneously measure the current in the leg. This experiment was made for both the arms raised (SAR = 4.4W/kg, current = 517mA), and the arms lowered (SAR = 2.8 W/kg, current = 448 mA). Using published values for the dielectric properties of the phantom, the SAR calculated from the measured currents differs from the value determined with the Bowman probe by -9.1 percent for the arms raised, and +7.1 percent for the arms lowered.

The current probes used in the fixed-frequency measurements at NAMRL are toroidal in shape, with an aperture radius of 9 cm and an outer radius of 11 cm (tube radius of 1 cm). The winding of 150 turns of high-resistance line is evenly distributed over the full length of the toroid, the total resistance being 500 k-Ohms. At frequencies below the coil resonance (100 MHz), the output of these probes is related to the time derivative of the measured current by V (volt) = 94.2 dI/dt (A/ns).

The minimally-perturbing current probes for fixed-frequency measurements, which we developed previous to this project, are not suitable for time-domain measurements in EMP simulations. Major design changes were required to produce the following changes in operating characteristics:

1. Increased Bandwidth; Much larger bandwidth is required so that the time-dependent (unrectified) output can be used to determine the instantaneous value of current.

2. Increased Ruggedness; Greater electronic ruggedness is required because of the high intensity of EMP fields.

3. Decreased Output Impedance; The time-dependent (unrectified) output of the probe should be compatible with a low-impedance (50 Ohms) fiber-optics transducer for data acquisition, rather than high-impedance readout electronics.

4. Decreased RFI Susceptibility; Improved shielding is required because of the high intensity of EMP fields.

5. Decreased Sensitivity; Calculations suggest that the peak current induced in man due to exposure to 100 kV/m EMP with a vertically polarized dipole (VPD) may be as large as 500 A [Guy, 1989]. The peak value of the rate of change of current in the human leg was reported as 2.1 A/ns for VPD exposure (Gronhaug, 1988). The current probes we used at NAMRL have a sensitivity of 94.2 volts per A/ns, so the unrectified output of a probe would be approximately 200 V which would overload the fiber-optics transducer.

4. Estimation of Required Bandwidth

Others have used conventional metallic current probes to measure the current induced in human volunteers exposed to the fields of EMP simulators. While we expect that the minimally-perturbing current probes we are developing in this project will provide greater accuracy in measuring induced currents, the data obtained with the metallic current probes may be used as a guide for determining the requirements for bandwidth.

Gronhaug has reported waveforms for the time-dependent current induced in human volunteers by EMP simulators [Gronhaug, 1988]. The waveforms obtained by theoretical modeling, and measurements with metallic current probes, both suggest that for vertical polarization, the current induced in the leg has a dominant frequency of approximately 30 MHz. With horizontal polarization, the current induced in the horizontal arm has a dominant frequency of approximately 60 MHz. All current waveforms appear limited in spectral content. The frequency dependence of the induced currents is quite different from that of the incident fields, which may be attributed to the resonant behavior of the human body.

Guy used numerical modeling to obtain waveforms similar to those presented by Gronhaug for currents induced by vertically-polarized EMP simulators [Guy, 1989]. A frequency-domain plot presented for the current in Guy's calculations has 3dB points at approximately 0.7 and 40 MHz, and 10db points at 0.2 and 60 MHz.

5. Calibration Procedures

Early in this project it was recognized that carefully defined calibration procedures are essential for characterizing a particular current probe, as well as determining the effects of various design parameters for probe optimization. We had several conversations with engineers at the Eaton Corporation to determine the methods used to calibrate commercial current probes, and have used these procedures with each of the new probes. We have also developed new shielded test fixtures which we consider to be more practical and give higher accuracy than those used previously by others. We have also used loop test fixtures, and have found that they can detect anomalous probe responses which are missed using the standard shielded test fixtures.

Standard Shielded Test Fixtures

We have followed the procedures used to calibrate commercial current probes at the Eaton Corporation in characterizing each of the new current probes. We fabricated shielded test fixtures similar to those at Eaton, and verified that our calibrations of three commercial current probes agree with measurements made by the manufacturer.

These shielded test fixtures are rectangular metal boxes with a coaxial connector at the center of the top and base, and a metal cylinder joining the center pins of the two connectors. The box and center conductor form a coaxial transmission line, and a current probe is placed in the box with the center conductor passing through the probe window. A signal generator, and a 50 Ohm load are connected to the test fixture, and the voltage across the load is measured to determine the current. At a fixed frequency, the transfer impedance of the probe is calculated by dividing the voltage output of the probe by the current. Engineers at Eaton recommend that the VSWR of a loaded test jig be less than 2.0.

New Shielded Test Fixtures

We have developed new shielded test fixtures that are more practical to use with our current probes than the standard shielded test fixtures described in the previous section of this report. The new test fixtures consist of two flat metal sheets, each with a coaxial connector at the center, and a metal cylinder joining the center pins of the two connectors. The two metal sheets are placed across the top and base of the aluminum shield of a current probe, and the metal cylinder and the inner surface of the shield form a coaxial transmission line. The diameter of the metal cylinder is chosen such that the characteristic impedance is approximately 50 Ohms.

The characteristic impedance of the shielded test fixtures is determined by the ratio of the diameter of the center conductor to 1) the diameter of the aperture of the current probe in the new fixtures, and 2) the size of the metal box in the standard fixtures. Objects placed in a Crawford cell should be smaller than one-third the cross section of the cell to limit perturbations of the field distribution and an unacceptable increase in the VSWR. We believe that a similar specification should be followed with shielded test fixtures because they are TEM devices closely related to the Crawford cell. If the box in a standard test fixture is large enough to meet this specification for a current probe then in general, a center conductor which will fit though the window of the probe is too small for a characteristic impedance of 50 Ohms. Thus we find that a VSWR of less than 1.1 (0.4 to 110 MHz) may be obtained with the new shielded test fixtures, as compared to a value of 2.0 for the standard shielded test fixtures.

The lower weight and smaller size of the new shielded test fixtures should be appreciated in field tests with the relatively large (30.4 cm OD) current probes designed for placement on the human thigh.

Loop Test Fixtures

Two types of loops have also been used as test fixtures with the new current probes. One is a simple loop in which the center conductor of a section of 50 Ohm coaxial cable is bent so that it returns to make electrical contact with the outer conductor through a 50 Ohm resistor. The second is a shielded loop in which the entire coaxial cable is bent so that it returns on itself, and both the center and outer conductor at the end of the cable are soldered to the outer conductor. A gap is made in the outer conductor at the center of the circular loop. Both types of loops are made as small as possible, while interlacing through the aperture (window) of the current probe, to increase the upper usable frequency for the system to approximately 100 MHz.

We use the two types of loops to detect possible changes in the sensitivity of a current probe when the source current is at different locations in the probe window. The two types of shielded test fixtures described in the previous sections give an integrated measurement of the sensitivity.

We believe that calibrations with shielded test fixtures may not properly represent the conditions under which current probes are used, and recommend that the loops or other unshielded test fixtures be used to supplement the calibration data. We have found anomalous responses in several commercial current probes when they are tested with the loops, even though we were able to duplicate the calibration curves from the manufacturer by using our shielded test fixtures (See Appendix II). The magnetic field in a shielded test fixture is primarily due to the current in the conductor passing through the probe window. The electrostatic shield of a current probe limits the sensitivity to electric fields. Thus, a current probe in a shielded test fixture responds primarily to the magnetic field produced by the current passing through the probe window. A more complex field pattern, more closely related to common usage of the probes, is presented by the loop test fixtures.

6. <u>RFI Susceptibility</u>

Early in this project it was recognized that methods for determining RFI susceptibility must be carefully defined before characterizing a particular current probe, or determining the effects of various design parameters for probe optimization. We have developed our own methods for determining RFI susceptibility of current probes because our test results suggest that the procedures used to test commercial current probes are often inadequate.

We have evaluated the RFI susceptibility of the new current probes as well as several commercial current probes using 1) loop test fixtures that do not interlace the probes, 2) a Crawford cell, and 3) a simple parallel plate fixture.

Decreasing RFI Susceptibility of the New Probes

Pickup through the electrostatic shield may be eliminated by using care in the fabrication of the shield. It is necessary to inspect for flaws in the shield, and to use care in designing the circumferential gap.

RFI susceptibility is mostly due to cable pickup, and this may be minimized by reducing the length of the cable and using ferrite beads to increase attenuation on the outside of the braid of the cable. Double shielding of the coaxial cable has also been found to help.

The toroidal winding in each of the new current probes is a symmetrical device, so that balanced loading is required to minimize extraneous responses of the probe. When using the probe with a detector having an unbalanced input, such as a fiber-optic transducer in field tests, or an oscilloscope in bench top testing, each terminal of the winding must be connected to a separate channel of the detector. The electrostatic shield of the current probe is connected to the cable shields, and hence to the ground of the detector. In some models of the new current probes we have used twinax cable, in place of two separate cables, and have found that this reduces the effects of cable pickup.

RFI Susceptibility of Commercial Current Probes

We tested an Eaton model 93686-4 current probe, and found it to be highly susceptible to RFI. When this probe was placed in a Crawford cell, and exposed to approximately TEM fields but no current, the ratio of probe output to the current input to the cell exceeded the specified transfer impedance at frequencies greater than 30 MHz. This anomalous response of the probe was not apparent in calibration using a shielded test fixture. We found an apparent design error in the current probe. The paint on the electrostatic shield was not removed beneath the type N connector, and there is a gap between the connector and the shield. The RFI susceptibility of the probe was decreased by about two orders of magnitude by closing this gap with pressure-sensitive copper tape. The results of our tests with the commercial current probe were described in a memorandum, a copy being attached as Appendix II to this report.

7. Optimization of the Electrostatic Shield

An electrostatic shield is essential to limit capacitive coupling so that the current probes operate properly. When one of the current probes is tested without a electrostatic shield, the probe has an output due to the TEM fields of a Crawford cell, even though no current passes through the probe window. An unshielded probe also responds to a loop test fixture, even when the loop does not interlace the probe. Also the output from the probe is changed by bringing the hand near the probe during measurements. These extraneous responses are eliminated by using the electrostatic shield.

It would be ideal to use a resistive shield in order to minimize the field perturbations caused by a current probe. We tested probes using several materials including Teledeltos paper and carbon loaded plastic for resistive shields, but found that these materials have specific resistivities that are too high to provide adequate RFI susceptibility for use in EMP simulations, so we have chosen to use metal shields instead.

The electrostatic shield, which is the outer aluminum container of the current probe, must be carefully sealed to limit capacitive coupling and RFI. Copper or aluminum pressure-sensitive tape is used to seal all gaps in the shield, except for the circumferential gap on the inner surface of the probe which must be kept open at all times to permit coupling to the magnetic field produced by the source current.

8. Optimization of Coil Resistance

We have used distributed resistive loading to decrease the quality factor of the coil in each current probe to obtain greater bandwidth. A number of probes were constructed with different values of coil resistance, and we determined the effects of coil resistance on some of the characteristics of the probes. The final probes have a coil resistance of 30 to 40 k-Ohms which is a compromise providing 1) adequate bandwidth, and 2) low enough attenuation that the output of the probe is not sensitive to the position of the current within the probe aperture.

Since the coil is resistively loaded, there is some attenuation in propagation on this coil, so the output of a probe is greatest if the current is near the end of the probes where the terminals are located. The dependence of probe output on location of the current is only pronounced when the current is close to the metal shield, so this undesirable effect may be minimized by using a spacer of styrofoam or other low-density low-loss dielectric to keep the leg, or other current-carrying part at least 1 to 2 cm from the inner surface of the shield. We have evaluated the dependence of probe output on location of the current by using the loop test fixtures described in the section of this report on calibration.

We have formed the resistive winding for each probe by using a large number of carbon resistors connected in series, so that there is approximately one per turn. The model 12 series probes use 150 Ohm 1/8 Watt, carbon film resistors (Probe with serial number 1 has 200 turns and total resistance of 33.2 k-Ohms; Probe with serial number 2 has 225 turns and total resistance of 36.6 k-Ohms). We have used resistance wire and carbon-loaded plastics in some coils, but find that they are not practical for the value of Ohms per unit length that is optimum for the probes (e.g. too small a diameter of wire and too large a diameter of carbon-loaded plastic).

If a conductive coil were used in place of a resistively loaded coil the field perturbation would not be measurably increased, because the coil is contained in a metal electrostatic shield. The coil and shield act as a coaxial transmission line so in principle, broad bandwidth could be obtained with a conductive coil, if this line was matched by loads at both ends of the coil.
We have made several tests which suggest that it may be possible to obtain adequate bandwidth without resistive loading.

The output impedance of the probe was specified to be 50 Ohms to match the input of the fiber optic systems used for data acquisition in EMP measurements. We have found it is possible to decrease the characteristic impedance of the coil/shield transmission line (See section 12 of this report, "Theoretical Analysis of Current Probes") to approximately 50 Ohms by using a metal tape helical toroid winding with a closely-spaced shield. The VSWR for the modified probe, loaded by 50 Ohms, is less than 1.2 from 0.4 to 110 MHz. This design offers a number of advantages over the probes we have used so far, but it is still in a developmental stage so probes with resistive windings were furnished by us on the present contract.

9. Methods for Increasing Bandwidth

We have chosen to use no active elements (amplifiers, active filters, etc.) in order to decrease the possibility of burnout in the intense fields of an EMP simulator. From Faraday's law of induction, it may be seen that at frequencies below coil resonance (100 MHz) the output of a current probe is approximately proportional to frequency. The effects of coil resonance have been damped by resistive loading, and the flatness of response has been improved by adding a low-pass filter.

The low-pass filter used with the current probes consists of a shunt capacitor, in combination with the series resistance of the coil. This filter causes the response to be relatively flat from the cutoff frequency of the filter, f_c, to about 100 MHz, by decreasing the sensitivity at higher frequencies to that at f_c. We have chosen to use a shunt capacitor of 220 pF, which is a compromise between bandwidth and sensitivity. The manual for the probes, which is Appendix III of this report, has tables and figures giving the transfer impedance as a function of frequency both with and without the shunt capacitor. The shunted probes have a transfer impedance of 10 to 20 m-Ohms, which is considered to be adequate for use in EMP simulations, because the peak current induced in man due to exposure to 100 kV/m is approximately 500 A [Guy, 1989].

10. Description of the Completed Probes

The manual supplied with the new current probes, which is Appendix III of this report describes the completed probes, and provides calibration data as well as instructions for the calibration and use of these probes.

The new current probes are designed for non-invasive measurement of current in personnel exposed to electromagnetic fields, with particular emphasis on the pulsed fields in EMP simulations. The model 12 series probes are toroidal in shape, with an inner radius of 10.8 cm, outer radius of 15.2 cm, and a height of 4.8 cm. This size is suitable for placement on the human thigh, even with most endomorphic or mesomorphic people.

11. Insertion Impedance of Current Probes

We have shown by analysis and experiments that both the ferromagnetic core and the grounded metal shield of a current probe modify the circuit in which the probe is used by introducing an insertion impedance, thus changing the current being measured. The ferromagnetic core introduces a series inductance into the circuit, and the grounded metal shield introduces a capacitive shunt to ground.

The magnitude of the insertion impedance, and hence the errors in current measurements, are greatest when a large fraction of the probe aperture (window) is filled, such as in measurements with the human body, but the errors are small in measurements with wires, for which the probes are intended.

Our observations of errors in current measurements were described in the paper "Inaccuracy of Measurements of RF Current in the Human Body with Commercial Clamp-on Probes," at the June, 1990 meeting of the Bioelectromagnetics Society in San Antonio, Texas. A copy of the abstract for this paper is attached as Appendix IV for this report, and a copy of the slides is attached as Appendix V.

Subsequent to our presentation at the BEMS meeting we observed that the ferromagnetic core of a current probe is also responsible for an increase in the circuit resistance; the insertion impedance being primarily resistive at frequencies below 100 MHz. It appears that the depth of current flow in a conductor is reduced by the presence of the ferromagnetic core, thus causing the circuit to have increased resistance. Our new current probes, not having ferromagnetic cores, appear to cause significantly less insertion impedance than the commercial current probes which we have tested.

12. Theoretical Analysis of Current Probes

Commercial Current Probes

Commercial current probes use a ferromagnetic core to couple the magnetic flux produced by the current to a coil, and the voltage induced in this coil is measured in order to evaluate the current. A derivation showing how these probes function is given in Appendix VI of this report. This derivation may be summarized as follows:

The ferromagnetic core has a permeability much greater than that of the surrounding medium, so the boundary relations for magnetic fields require that the magnetic flux within the core is independent of azimuthal location. The permeability and cross sectional area A of the core are constant, so the magnetic field intensity H has a constant magnitude within the core and is oriented azimuthally. Thus Ampere's Law requires that this value of H is equal to the total current passing through the aperture of the core, divided by the circumference of the core. Therefore the magnetic flux, and hence the voltage output of the probe is independent of the distribution of current within the aperture. Note that the coil may be located anywhere on the core because the flux is independent of azimuthal location. Furthermore it is not necessary that the axis of the core be circular in shape. Inspection of the equations shows that neither the cross sectional area nor the permeability need be constant, but their product must be constant over the length of the core.

Non-Ferromagnetic Probe with Axial Current

High-permeability cores are not used in our current probes. Appendix VII of this report has a derivation which shows that it is possible to build a toroidal coil which will have a voltage output proportional to the current, if the current is on the axis of the coil. This derivation may be summarized as follows:

Since a ferromagnetic core is not used, it is no longer possible to use boundary relations as in the previous derivation, to show that the magnetic flux within the core is independent of azimuthal location. However, if the current is in a filament on the axis of the toroid, then Ampere's Law requires that the value of H has constant magnitude (the current divided by the circumference of the core) within the coil and is oriented azimuthally. If the coil winding is distributed over the full length of a toroidal core, and the number of turns per unit length and the cross sectional area A are constant, then the potentials from each increment in length of the coil may be summed to give an equation relating voltage output to current that is the same as in the previous derivation for a ferromagnetic core. Inspection of the equations shows that neither the number of turns per unit length nor the cross sectional area need be constant, but their product must be constant over the length of the coil.

Non-Ferromagnetic Probe with Off-Axis Current

Appendix VIII of this report has a derivation showing that it is possible for a non-ferromagnetic toroidal coil to have the same relationship of voltage output to input current, regardless of the location of a current filament within the aperture of the coil. The same equation is obtained as in the earlier derivation in Appendix VI (for commercial current probes) where a ferromagnetic core is assumed, and this equation is appropriate for any distribution of current within the aperture.

Since a ferromagnetic core is not used, it is not possible to use boundary relations to show that the magnetic flux within the core is independent of azimuthal location, as in Appendix VI. Indeed the magnetic flux is not constant from point to point within the coil. Since the current filament is not on the axis of the coil, unlike the derivation in Appendix VII, the value of H is not constant in magnitude within the coil and is not oriented parallel to the axis of the coil. The derivation in Appendix VIII may be summarized as follows:

In the derivation in Appendix VIII, first the potential induced in an increment in the length of the coil is evaluated. Since the current filament is not on the axis of the coil, this potential is dependent on the azimuthal position of the increment. Integration is used to obtain the voltage output by summing the potentials induced in each increment of the winding. If the coil winding is distributed over the full length of a toroidal core, and the number of turns per unit length and the cross sectional area A are constant, then the voltage output is given by the same equation as in the derivation in Appendix VI for a ferromagnetic core. This surprising result has been confirmed by numerical solutions. In addition, we have verified experimentally that the output is independent of the location of the current within the aperture, and insensitive to currents located outside of the aperture.

Inspection of the derivation in Appendix VIII shows that neither the number of turns per unit length nor the cross sectional area need be constant, but their product must be constant over the length of the coil. Furthermore, it is possible to extend the derivation to show that the axis of the coil need not be circular in shape.

The derivations in Appendices VI-VIII are only valid at low frequencies under conditions for which dielectric loss is negligible. In general it is necessary to allow for retarded times and attenuation during propagation from the source current to the coil, and for delays and attenuation during propagation on the coil. Some of the effects due to propagation on the coil will be treated in the following part of this section.

Probe Coil/Shield as a Transmission Line

Since the new current probes do not have ferromagnetic cores, the coil winding must be distributed over the full length of a toroid, instead of using a short coil such as in the commercial probes. Thus, the induced voltage is distributed over the full length of the coil, rather than being a localized source. It was necessary to use a distributed voltage source in the derivations for Appendices VII and VIII referred to in the previous two parts of this section. The continuous distribution of induced voltage over the length of the coil may be approximated by a finite number of discrete sources as shown in Appendix IXa. The coil and shield form a coaxial transmission line, and the voltage is induced in the coil which is the inner conductor of this line.

The response of the new current probes may be evaluated by determining how the distributed voltage source is combined to yield the output of the probe. In the derivations for Appendices VII and VIII it was assumed that the output is a simple summation of increments of the distributed voltage source, but this approximation is only valid at low frequencies. At high frequencies it is necessary to allow for the effects of the coil/shield transmission line on this summation.

The characteristics of a uniform transmission line may be determined using an equivalent circuit [Kraus, 1984] consisting of four distributed quantities; 1) the series resistance R Ohm/m, 2) the series inductance L Henrys/m, 3) the shunt capacitance C Farads/m, and 4) the shunt conductance G Siemens/m. It is possible to determine how the distributed voltage source is combined to yield the output of a current probe by adding the RLCG models to Appendix IXa, to represent sections of the coil/shield transmission line coupling the discrete voltage sources, thus forming Appendix IXb.

Appendix IXc is the final model which we have used to analyze the new current probes. This model differs from Appendix IXb in that it shows that 1) R and L are due to the resistively-loaded coil, 2) C is due to the capacitance between the coil and the shield, 3) G may be neglected because low-loss dielectrics are used, and 4) the discrete voltage sources are located in the coil. Values of the distributed quantities R, L, and C may be measured for a current probe, and used to evaluate the (complex) characteristic impedance, phase velocity and attenuation [Kraus, 1984]. We have found this procedure to be useful in explaining the frequency response of the new current probes, and in the optimization of these probes. In commercial current probes the shield is only needed to limit capacitive coupling, but in the new probes the shield is a part of a coaxial transmission line, and is essential to the operation of the devices at high frequencies.

13. Suggestions for Future Work

In section eight of this report, "Optimization of Coil Resistance," it was stated that we have made and tested several current probes with conductive coils, in which the characteristic impedance of the coil/shield transmission line is approximately 50 Ohms. These probes offer the promise of greater bandwidth without resistive loading, but they are still in a developmental stage so probes with resistive windings were furnished by us on the present contract. We plan to continue the development of current probes with conductive coils, and hope that this can be funded at a later date.

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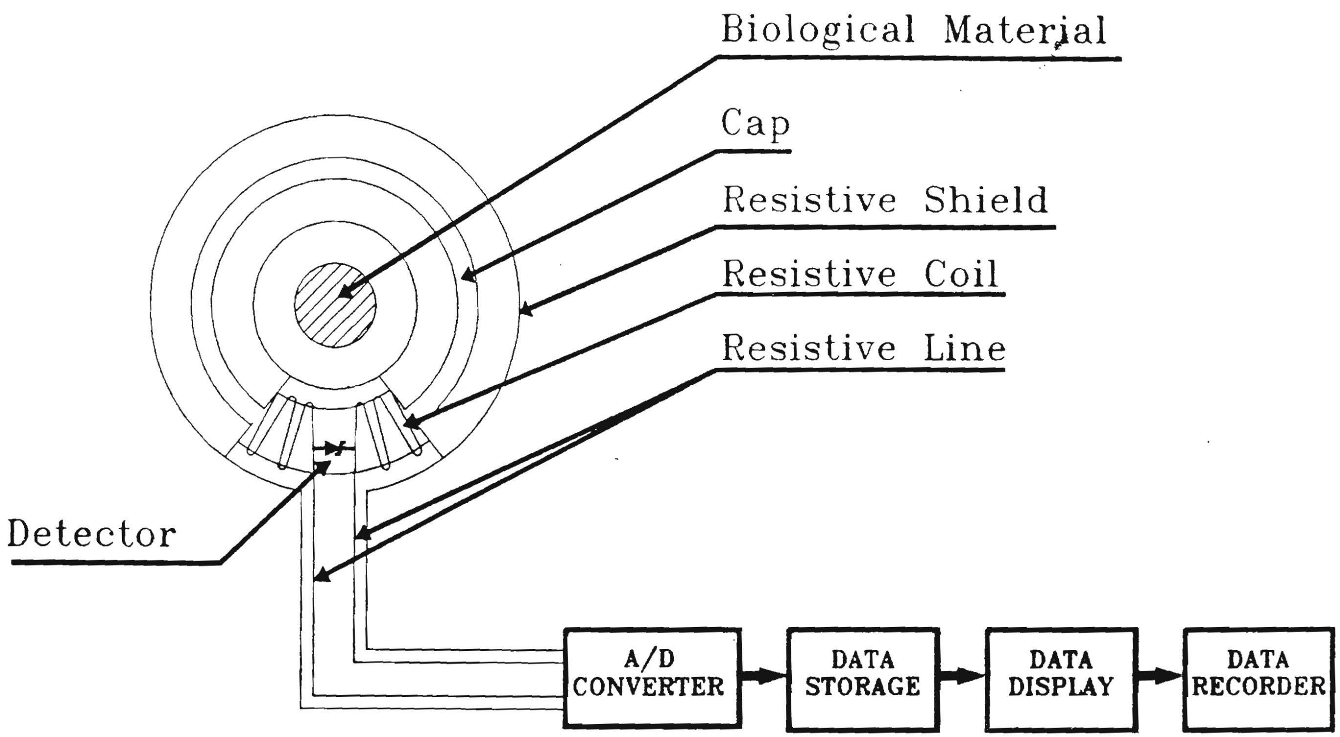

APPENDIX I. BLOCK DIAGRAM OF NEW CURRENT PROBES

APPENDIX II

MEMORANDUM

TO: Mr. R. Richard Bixby, Radiation Physics Branch, Radiation Sciences Division, USAF School of Aerospace Medicine (AFSC), Brooks Air Force Base, Texas 78235-5301.

FROM: Mark J. Hagmann and Tadeusz M. Babij, Dept of Electrical Engineering, Florida International University, Miami, Florida 33199.

SUBJECT: Anomalous Response of Commercial Current Probes

DATE: April 4, 1990

Testing summarized in this memo was done as a part of our comparisons of the new current probes, under development for EMP applications, with commercial current probes. The new probes differ from commercial probes in that they minimize perturbation of electromagnetic fields to increase accuracy in measuring currents induced in lossy dielectric objects. Thus it was anticipated that the new probes would give similar results when measuring current in a low-impedance load connected to a signal generator.

Two different test fixtures have been used to calibrate the new current probes. One is a simple loop in which the center conductor of a section of 50 Ohm coaxial cable extends past the shield, and is bent to connect back to the shield through a 50 Ohm resistor. The second is a shielded loop in which a section of 50 Ohm coaxial cable is bent so it returns on itself, with a gap in the shield at the center of this loop. In the shielded loop, at the point where the cable returns to itself both shields are soldered together, and connected to the center conductor of the cable end through a 50 Ohm resistor. In both test fixtures the loop is made as small as possible, while interlacing through the aperture (window) of the current probe, to increase the upper usable frequency to approximately 100 MHz.

In our measurements the loop, or other test fixture, is connected directly to a signal generator. The current input to the test fixture is determined by using an oscilloscope to measure the voltage on a 1 Ohm resistor connected across a gap in the coaxial shield near the test fixture. The output of the current probe is measured with an oscilloscope, and a 50 Ohm termination with a T adapter is used to load the input to the oscilloscope. Only single-shielded 50 Ohm coaxial cable is used, without ferrite beads.

An Eaton model 93686-4 current probe was tested and found to be highly susceptible to RFI. At frequencies greater than 30 MHz, when either of our test loops is brought near the probe (zero current through the window since the loop does not interlace the probe) the probe output is comparable to that when the loop interlaces the probe. When the probe is placed in a TEM (Crawford) cell, so that the probe is exposed to approximately TEM fields but not current, the ratio of probe output to the current input to the cell exceeds the specified transfer impedance at frequencies greater than 30 MHz.

We described the tests with the Eaton model 93686-4 current probe in phone conversations with Don Radimacher and Larry Toller of the Eaton Corporation. They were surprised by our results, and sent a description of the shielded test fixtures they use for calibration (copy attached). In subsequent testing we found an apparent design error in the probe. The paint on the Faraday shield was not removed beneath the type N connector, and there is a gap between the connector and the shield (photographs attached). The RFI susceptibility of the probe is decreased by about two orders of magnitude by closing this gap with pressure-sensitive copper tape.

An Eaton model 91550-1 current probe was also tested, and we found that the RFI susceptibility is almost two orders of magnitude below that of the (uncorrected) 93686-4 probe. There is no visible gap between the type N connector and the Faraday shield on the 91550-1 probe, but we anticipate that the RFI susceptibility could be increased by removing the paint at this location on the shield.

We have constructed shielded test fixtures similar to those used by Eaton. In a shielded test fixture, only the current in the conductor passing through the probe window produces a magnetic field at the probe. The Faraday shield on a current probe limits the sensitivity to electric fields. Thus, a current probe in a shielded test fixture responds only to the magnetic field produced by current passing through the probe window. We have found that each of the two Eaton probes has a transfer impedance that is relatively flat from 1 to 100 MHz, as claimed by the manufacturer, when tested with our shielded fixtures. Both probes have quite different characteristics (including considerable frequency dependence) when they are tested with either of our two loops. It appears that differences in our results using shielded and unshielded test fixtures are not from RFI (cable pickup, etc.), but are due to the increased complexity of the fields with the unshielded (loop) fixtures.

In our EMP project it is necessary to measure currents induced in man, or phantom models simulating man, under open-field conditions. We believe that calibrations with shielded test fixtures may not properly represent the conditions of our measurements. We intend to use both shielded and unshielded test fixtures, and we will describe calibrations made with shielded fixtures as the "sensitivity to current". Differences between the results of these tests, and of tests with unshielded fixtures, will be described as the "anomalous response" of the probes. We recommend that others consider using unshielded test fixtures if the conditions under which measurements will be made are significantly different from the shielded configuration.

APPENDIX III

Manual for Non-Ferrous Current Probes Model No. 12, and Test Fixture Model 10

Prepared for Georgia Institute of Technology
Subcontract No. B-10-A10-S1
FIU Project No. 571808200

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October 19, 1990

Non-Ferrous Current Probes Model 12, Serial Numbers 1 and 2, and Test Fixture Model 10, Serial Number 1 were delivered with this manual.

Abstract

Minimally-perturbing, resistive, non-ferrous probes were developed for measuring the current induced in workers exposed to electromagnetic fields, with particular emphasis on the pulsed fields in EMP simulations. Each of these probes has an air-core toroid that passes around the leg or other body member, and a coil formed from high-resistance line, that is evenly distributed over the full length of the toroid. A metal Faraday shield is used to limit capacitive coupling. Active elements were not used in the probe circuitry so that the probes would have maximum ruggedness for use in high intensity EMP fields. These probes have sufficient bandwidth for time domain measurements in EMP simulations. The probes are compatible with the low-impedance (50 Ohms) fiber-optics transducers typically used for data acquisition in EMP simulations. Calibration data and instructions for use of the probes and test fixture are included.

1. Background

Clamp-on AC ammeters are commonly used to measure electrical current without interrupting a circuit, and high-frequency current probes are used for the same purpose in RF applications as well as in EMP simulations [Miller, 1986; Ricketts et al., 1976]. These commercial instruments use a ferromagnetic core to couple the magnetic flux produced by the current to a coil, and the voltage induced in this coil is measured in order to evaluate the current. If the current is induced in an object by ambient fields (rather than current driven through a wire by a source of emf), then the commercial instruments would not be appropriate since the ferromagnetic core, wire coil and metal shield would alter the fields, and hence change the current.

2. Description of the New Current Probes

The new current probes are designed for non-invasive measurement of current in personnel exposed to electromagnetic fields, with particular emphasis on the pulsed fields in EMP simulations. Our model 12 series probes are toroidal in shape, with inner radius = 10.8 cm, outer radius = 15.2 cm, and height = 4.8 cm. This size is suitable for placement on the human thigh, even with most endomorphic or mesomorphic people. The new probes were prepared by making major design changes in devices developed previous to this project for use at constant frequencies [Hagmann and Babij, 1988, 1990a, 1990b; Babij and Hagmann, 1988].

The new current probes differ from commercial probes in that they do not have ferromagnetic cores. Thus they cause less perturbation of electromagnetic fields, and less insertion impedance, than the commercial devices. We have shown analytically, as well as by experiment, that a current probe will function properly (output proportional to the total current passing through the aperture, and independent of the spatial distribution of the current) without a ferromagnetic core, if the coil winding is evenly distributed over the full length of the toroidal core. Use of a low-permeability core reduces the transfer impedance (sensitivity) but reduces field perturbations and insertion impedance, increases the ratio of maximum frequency to probe size, and avoids errors due to nonlinearity and possible saturation of the core since the permeability is an exact constant.

We have used distributed resistive loading to decrease the quality factor of the coil for greater bandwidth. We have used a coil resistance of 30 to 40 k-Ohms which is a compromise providing 1) adequate bandwidth, and 2) low enough attenuation that the output of the probe is not sensitive to the position of the current within the probe aperture. The resistive winding for each probe consists of a large number of 150 Ohm 1/8 Watt, carbon film resistors connected in series, so that there is approximately one resistor per turn. The probe with ser. no. 1 has 200 turns, with a total resistance of 33.2 k-Ohms, and the probe with ser. no. 2 has 225 turns, with a total resistance of 36.6 k-Ohms.

An electrostatic shield is essential to limit capacitive coupling so that the current probes operate properly. When one of the current probes is tested without a Faraday shield, the probe has an output due to the TEM fields of a Crawford cell, even though no current passes through the probe window. Also the output from the probe is changed by bringing the hand near the probe during measurements. These extraneous responses are eliminated by using the electrostatic shield.

The Faraday shield is the outer aluminum container of the current probe. If the shield is opened for any reason, it is essential that copper or aluminum pressure-sensitive tape be used to seal all gaps in the shield, except the circumferential gap on the inner surface of the probe which must be kept open at all times.

3. Operation of the New Current Probes

Each model 12 current probe has two type N connectors, one for each end of the internal coil. Since the new current probes have a symmetrical output, balanced loading is required to minimize RFI and other extraneous responses of the probe. When the probe is used with a detector having an unbalanced input, such as a fiber optic transducer in field tests, or an oscilloscope in bench top testing, it is best to connect each terminal of the probe to a separate channel of the detector. The Faraday shield of the current probe is connected to the cable shields, and hence to the ground of the detector.

Both outputs of a model 12 current probe should be matched by 50 Ohm loads. The probes are designed to be compatible with low-impedance (50 Ohms) fiber optic transducers typically used for data acquisition in EMP simulations. When a probe is used with an oscilloscope it is necessary to have a T with a 50 Ohm shunt at both inputs of the oscilloscope for proper matching to the probe. When a single channel detector must be used, then a 50 Ohm load should be connected to the unused output of the probe. If a current probe is not properly loaded, mismatch causes a change in both the frequency response and the sensitivity.

RFI susceptibility with the new current probes is mostly due to cable pickup. As with commercial probes, this problem may be minimized by using 1) short cables, 2) ferrite beads to load the cable shield, 3) double-shielded cable, and other standard procedures. Balanced loading also reduces RFI susceptibility with the new current probes. If the user wishes to evaluate the RFI susceptibility of the new current probes, we recommend the use of 1) Crawford cells, or 2) loop test fixtures, described in the section of this manual on calibration, made so they do not interlace the probes.

Since the internal coil is resistively loaded, there is some attenuation in propagation on this coil, so the output of a probe is greatest if the current is near the end of the probe where the two type N connectors are located. The dependence of probe output on location of the current is only pronounced if the current is close to the metal shield, so this effect may be minimized by using a spacer of styrofoam or other low-density low-loss dielectric to keep the leg, or other current-carrying part at least 1 to 2 cm from the inner surface of the shield. If the user wishes to evaluate the dependence of probe output on location of the current we recommend the use of loop test fixtures described in the section of this manual on calibration.

The new current probes, like commercial probes, are only sensitive to current passing axially through the aperture, and do not measure currents having azimuthal or radial orientation. Another limitation of all current probes is that they are sensitive to displacement current, as well as to conduction current, so a null reading is not obtained when the probe is isolated in air. If the electric field is approximately parallel to the surface of the body, then a sizable air gap between the surface of the probe and the body does not cause appreciable errors due to the displacement currents within the gap. This experimental result may be understood since 1) boundary relations for tangential polarization require that the magnitudes of the electric field intensity inside and outside the body are equal, and 2) the magnitude of the complex permittivity of tissues is large, so the current density within the body is much greater than the displacement current density in the air gap.

4. Calibration of the New Current Probes

We have supplied one Model 10 Test Fixture for calibration of the new current probes. This fixture consists of two flat metal sheets, each with a BNC connector at the center, and a metal cylinder joining the center pins of the two connectors. The two metal sheets are placed across the top and base of the aluminum shield of a current probe, and the metal cylinder and the inner surface of the shield form a coaxial transmission line. The diameter of the cylinder is chosen such that the characteristic impedance of the probe-containing fixture is approximately 50 Ohms.

After the test fixture is placed on a current probe, 50 Ohm coaxial cable is used to connect one terminal to a signal generator and the other to a detector such as an oscilloscope. It is necessary to match the detector to the fixture, so if an oscilloscope is used, then it is necessary to have a T with a 50 Ohm shunt at the scope. The voltage across the load is measured to determine the current through the probe aperture. At a fixed frequency, the transfer impedance of the probe is calculated by dividing the total voltage output of the probe (sum of both outputs) by the current.

Calibration data which we have obtained for Current probes Model 12, serial numbers 1 and 2, with Test Fixture Model 10, serial number 1, are given at the end of this manual. Tables I and II give the transfer impedance as a function of frequency with no shunt, and with a 220 pF capacitive shunt (as supplied) for the two probes. Plots of these data are presented in Figs. 1-4. It is recommended that these calibration data be verified by the user.

Shielded test fixtures which are generally used to calibrate commercial current probes consist of a metal box, in which the probe is placed, and a center conductor which passes through the aperture of the probe. These test fixtures are (TEM) coaxial transmission lines. Due to the large size of our new current probes, it is not possible to have a large enough center conductor to obtain a 50 Ohm characteristic impedance with the box-type fixtures, so a high VSWR results. By contrast, the VSWR is typically less than 1.1 (0.4 to 110 MHz) when the new current probes are used with the model 10 shielded test fixtures. It is for this reason, as well as the reduced size and weight, that we recommend the Model 10 test fixture.

The Model 10 test fixture is not appropriate for testing commercial current probes, since these probes are generally painted, and good electrical contact must be made between the two metal plates and the probe shield. It is also inappropriate to use this fixture with current probes having a different size than the Model 12, because the characteristic impedance of the probe-containing fixture will no longer be 50 Ohms, so a high VSWR may result. It is recommended that the VSWR be less than 1.5 for all calibrations.

We have also used two types of loops as test fixtures, but are not supplying them because it would be simple for the user to fabricate them if they were needed. One is a simple loop in which the center conductor of a section of 50 Ohm coaxial cable is bent so that it returns to make electrical contact with the outer conductor through a 50 Ohm resistor. The second is a shielded loop in which the entire coaxial cable is bent so that it returns on itself, and both the center and outer conductor at the end of the cable are soldered to the outer conductor. A gap is made in the outer conductor at the center of the circular loop. Both types of loops are made as small as possible, while interlacing through the aperture of the current probe, to increase the upper usable frequency for the system to approximately 100 MHz.

Calibrations with shielded test fixtures often fail to properly represent the conditions under which current probes are used, so we recommend that the loops or other unshielded test fixtures be used to supplement the calibration data. We have found anomalous responses in several commercial current probes when they are tested with the loops, even though we were able to duplicate the calibration curves from the manufacturer by using our shielded test fixtures.

5. Field Modifications to Change Bandwidth and Sensitivity

We have chosen to use no active elements (amplifiers, etc.) in the Model 12 current probes in order to decrease the possibility of burnout in the intense fields of an EMP simulator. Filtering has been used to obtain a relatively flat response.

Both current probes have been supplied with internal 220 pF capacitive shunts. A larger capacitor would increase the bandwidth and decrease the sensitivity. A smaller capacitor would increase the sensitivity and decrease the bandwidth. These effects are shown in Tables I and II, and Figs. 1 and 2 at the end of this manual.

The relatively low sensitivity of a current probe with a 220 pF shunt may be adequate for use in EMP measurements. Calculations suggest that the peak current induced in man due to exposure to 100 kV/m EMP simulated with a vertically polarized dipole (VPD) may be as large as 500 A [Guy, 1989]. The peak value of the rate of change of current in the human leg was reported as 2.1 A/ns for VPD exposure (Gronhaug, 1988).

If the capacitive shunt is changed, then the new capacitor must have small size (such as a disc ceramic) and the leads should be kept short. Care must also be used in resealing the Faraday shield. Use copper or aluminum pressure-sensitive tape to seal all gaps in the shield, except the circumferential gap on the inner surface of the probe which must be kept open at all times.

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Table I
Calibration of Non-Ferrous Current Probe
Model 12, Serial Number 1

	Transfer Impedance (Ohms)	
f MHz	No Shunt	220 pF
2		.0045
3		.0055
4		.0070
6		.0090
7		.010
8		.011
9		.011
10	.027	.012
20	.060	.014
30	.087	.012
40	.12	.014
50	.12	.016
60	.11	.012
70	.11	.012
80	.16	.012
90	.25	.016
100	.28	.022
110	.32	.046
120	.32	.026
130	.28	.018
140	.25	.014
150	.22	.013

Non-Ferrous Current Probe Model 12, Ser. No. 1 has 200 turns, and resistance = 33.2 k-Ohms
All current probes are supplied with a 220 pF shunt.

Table II
Calibration of Non-Ferrous Current Probe
Model 12, Serial Number 2

	Transfer Impedance (Ohms)	
f MHz	No Shunt	220 pF
2		.0040
3		.0055
4		.0075
6		.010
7		.012
8		.012
9		.014
10	.027	.014
20	.063	.018
30	.097	.015
40	.13	.016
50	.13	.018
60	.12	.018
70	.12	.016
80	.17	.018
90	.31	.023
100	.33	.042
110	.38	.072
120	.38	.058
130	.35	.048
140	.32	.040
150	.28	.035

Non-Ferrous Current Probe Model 12, Ser. No. 2 has 225 turns, and resistance = 36.6 k-Ohms
All current probes are supplied with a 220 pF shunt.

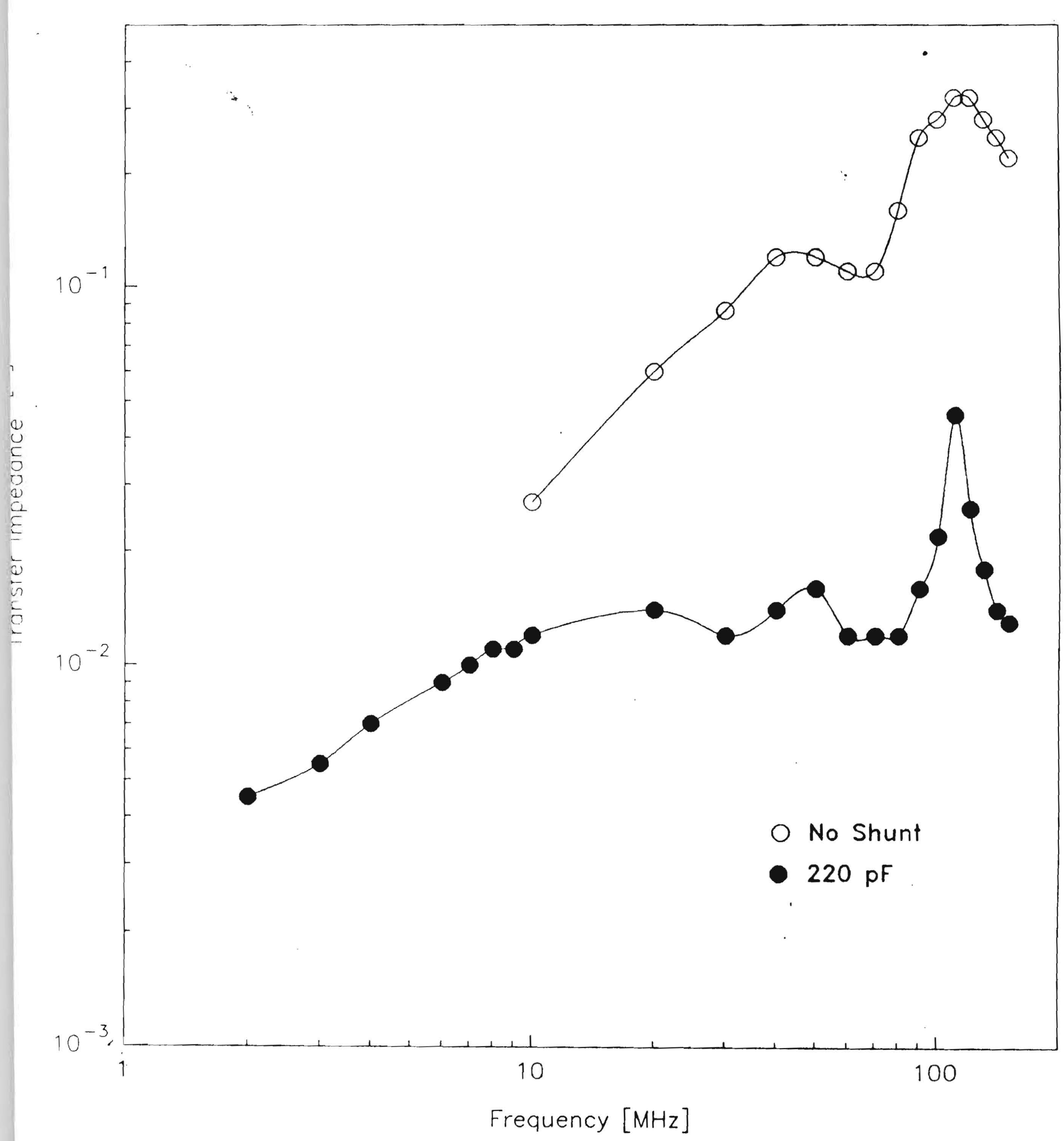

Fig. 1. Calibration of Non-Ferrous Current Probe

Model 012, Serial Number 001

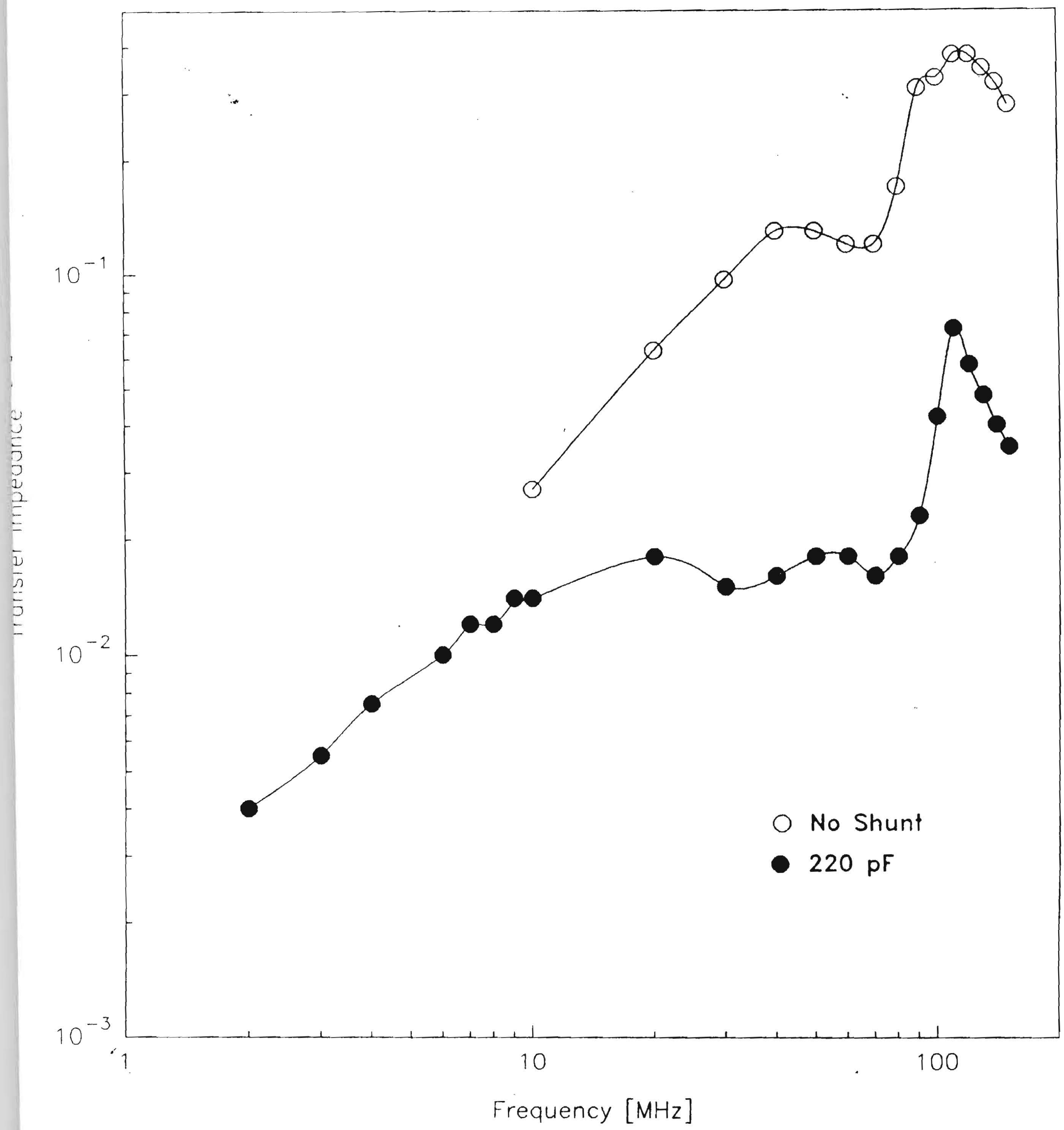

Fig. 2. Calibration of Non-Ferrous Current Probe

Model 012, Serial Number 002

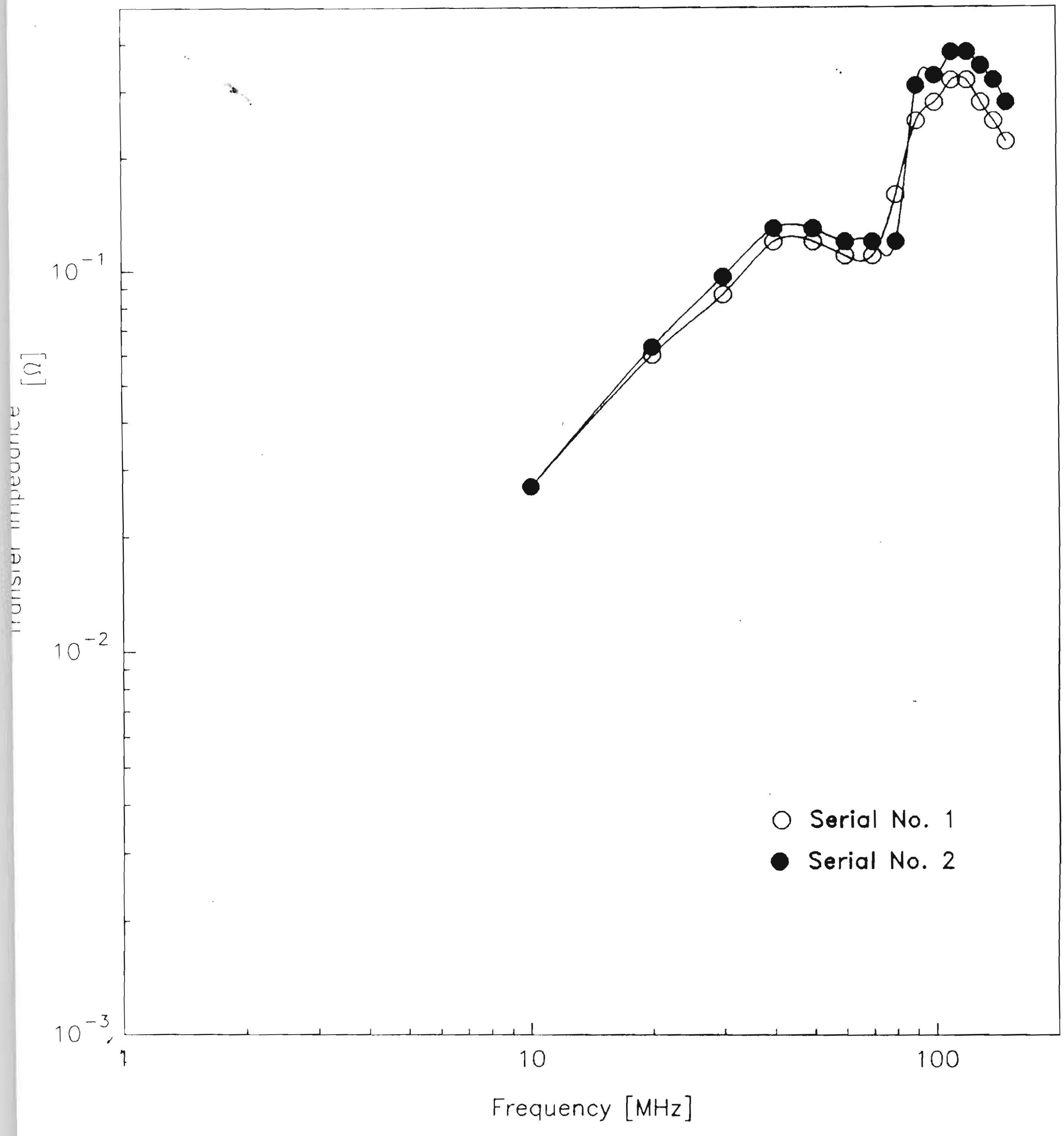

Fig. 3. Calibration of Non–Ferrous Current Probe
Model 012, without Shunt Capacitor

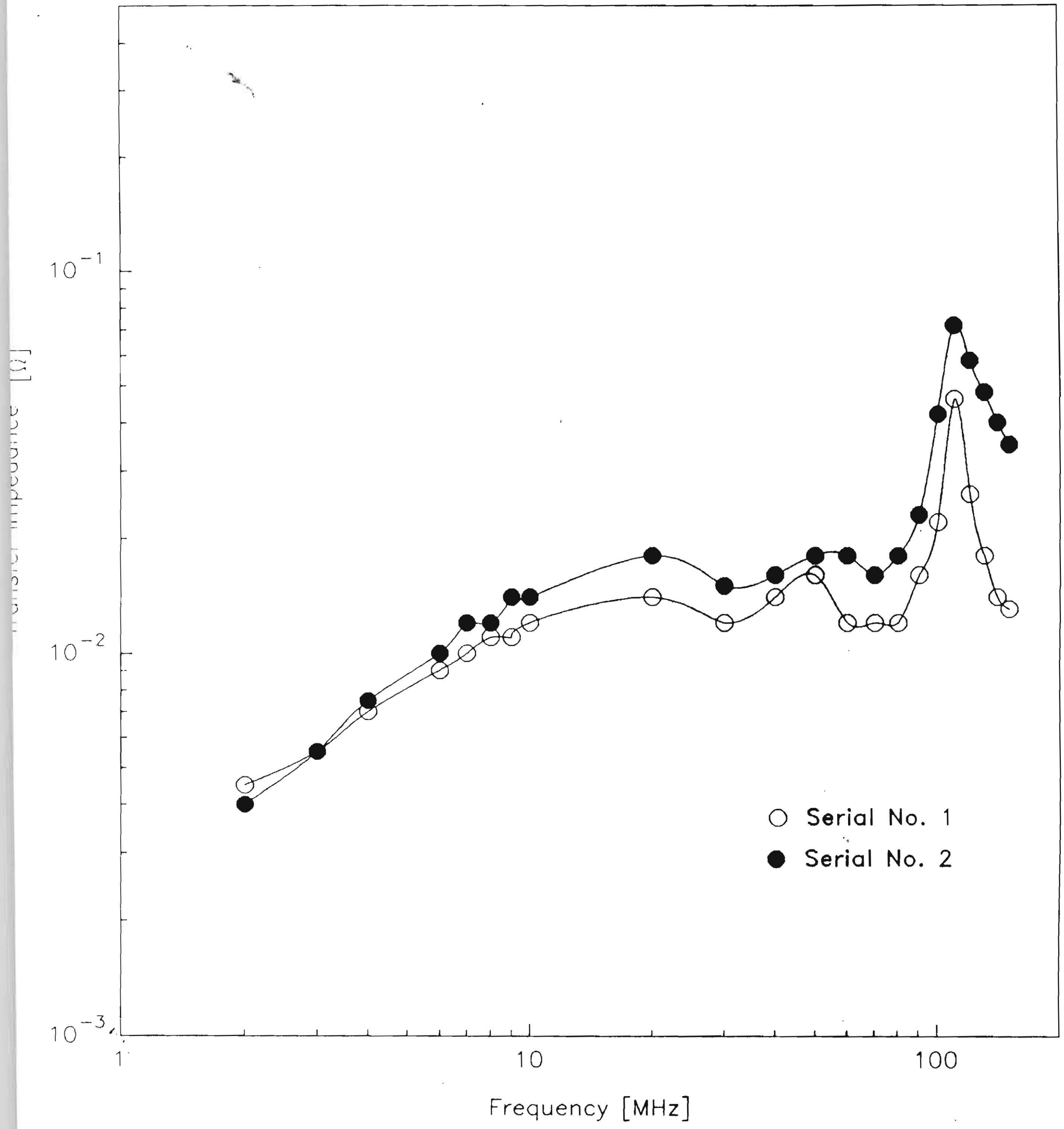

Fig. 4. Calibration of Non–Ferrous Current Probe
Model 012, with 220 pF Shunt Capacitor

APPENDIX IV

Inaccuracy of Measurements of RF Current in the Human Body with Commercial Clamp-on Probes

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Clamp-on ammeters and probes are commonly used to measure time-dependent currents in electrical circuits. These commercial instruments use a ferromagnetic core to couple the magnetic flux produced by the current to a coil, and the voltage induced in this coil is measured to evaluate the current. Recently these commercial instruments have been used by others to measure currents induced in the human body by EMP simulators as well as CW sources.

We have previously described minimally-perturbing current probes in the BEMS annual meetings for 1988 and 1989, and consider these new probes to be more appropriate for measurements of currents induced in the human body. Our new probes do not contain ferromagnetic or other metallic materials.

We have shown by analysis that the ferromagnetic core in a commercial current probe introduces a series inductance into the circuit to which it is applied. In biological applications this inductance may be as much as 1 mH since a large fraction of the aperture is filled, but the effect is often negligible with a wire conductor (for which the probes were intended).

We have shown by analysis that the grounded conductive shield of a commercial current probe introduces a capacititive shunt to ground. In biological applications this capacitance may be as much as 100 pF since the shield is close to the body, but the effect is often negligible with a wire conductor (for which the probes were intended).

At frequencies above 100 MHz, the size of a commercial current probe is large enough that the above circuit analysis is not appropriate. We model the section of the human body (or wire) in which the current is measured with a transmission line, and effect of the probe on the current may be analyzed as a discontinuity in the impedance of this transmission line. The effects of this discontinuity are often negligible with a wire conductor (for which the probes were intended), but the effects are significant in biological applications, since a large fraction of the probe aperture is filled so that the discontinuity in impedance is more pronounced.

Experiments will be described which illustrate the inaccuracy of measurements with commercial clamp-on current probes.

This research is sponsored by the USAF School of Aerospace Medicine under subcontract B-10-A10-S1 from Georgia Institute of Technology.

Abstract of a paper presented at the twelfth annual meeting of the Bioelectromagnetics Society in San Antonio, TX, June 1990.

APPENDIX V

Inaccuracy of Measurements of RF Current in the Human Body with Commercial Clamp-on Probes

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INTRODUCTION

Clamp-on ammeters and current probes are commonly used to measure time-dependent currents in electrical circuits. In these commercial instruments a ferromagnetic core couples the magnetic flux produced by the current to a coil, and the potential induced in this coil is measured to evaluate the current. A grounded metal shield is required to limit capacitive coupling (Fig. 1).

Others have used commercial current probes to measure current in the human body with both CW [1] and pulsed [2]-[3] sources. We have made minimally-perturbing current probes [4]-[5] for this purpose. The present paper shows that the ferromagnetic core and grounded metal shield in commercial current probes can significantly modify currents in the human body. Additional inaccuracies due to non-ideal components in the probe are not considered.

METHODS OF ANALYSIS

I. Changes in the Equivalent Circuit of an Antenna

Antenna theory has been used previously to determine the SAR for models of man in free-space as well as with ground and reflector effects [6]. In the present paper a current probe was added to find the effects of the probe on antenna reactance.

Figure 2 shows a vertical cylindrical monopole antenna, with a current probe, above ground. Changes in the equivalent circuit of the antenna due to the current probe are shown in Fig. 3. Definitions of terms in Figs. 2 and 3 are given in Table I. The length of the monopole, H = 175 cm, the height of a standard man, and the radius, R1 = 11.3 cm, for a volume corresponding to 70 kg of tissue.

The ferromagnetic core in a commercial current probe introduces a series inductance L, into the circuit to which it is applied. The value of this inductance was determined by 1) using the total current, conduction plus displacement, with Ampere's law to calculate the magnetic field intensity, 2) integrating to find the total magnetic energy, and 3) relating the total magnetic energy to inductance and current. Our calculations have shown that in biological applications this inductance may be as much as 1 mH since a large fraction of the aperture is filled, but the effect is often negligible with a wire conductor (for which the probes were intended).

The grounded metal shield introduces a capacitive shunt to ground. This capacitance was determined with the expression for a coaxial transmission line, so the value is underestimated unless the gap between the probe and the antenna is much smaller than the length of the probe. Our calculations have shown that in biological applications the value may be as much as 100 pF when the shield is close to the body, but the effect is often negligible with a wire conductor (for which the probes were intended).

The series inductance and the capacitive shunt to ground are both distributed over the length of the probe, but this is approximated by the circuit shown in Fig. 3. Resistance and inductance in the path to ground from the capacitor were not considered in the present analysis. The reactance of the antenna was determined using the approximation of open ended tapered two-wire transmission line, and changes in reactance due to the current probe were calculated. Examples in Tables II-IV suggest that a current probe can cause a significant change in the resonant behavior of the antenna, and hence of man.

II. Transmission Line Model

At frequencies above 100 MHz, the length of a commercial current probe is large enough that the above analysis with lumped circuit elements is not appropriate. The transmission line model (Fig. 4) consists of 1) an open-ended section of tapered two-wire section with length H -Z -S/2, 2) a coaxial section with length S, and 3) a tapered two-wire section with length Z -S/2.

The impedance of the coaxial section was determined using the values of inductance per unit length and capacitance per unit length from the previous section of this paper. The velocity of propagation in the coaxial section is modified by the effective relative permeability, RPE, which is typically less than 10 percent of the relative permeability of the ferromagnetic core.

Preliminary calculations using this method have shown that the effects of the probe are often negligible with a wire conductor (for which the probes were intended), but suggest that the effects may be significant in biological applications, since a large fraction of the probe aperture is filled so that the discontinuity in impedance is more pronounced.

EXPERIMENTAL RESULTS

An aluminum cylinder 3.1 cm in diameter and 28 cm long was connected to a Hewlett Packard 4193A Vector Impedance Meter with two wire transmission line, and the impedance of this circuit was measured from 0.5 to 110 MHz. The data in Table V show that significant changes in impedance occur when a commercial current probe is placed on the cylinder. The Eaton model 93686-4 has a larger diameter, so less of the aperture is filled by the cylinder, but this probe is more massive than the 91550-1; hence the two probes have similar effects on the circuit. At frequencies near resonance, the impedance (and hence the current) in this circuit is typically changed by approximately one order of magnitude when either current probe is placed on the cylinder. We observed that the effects of two probes are not additive, which may be explained by capacitive shunting of the probe nearer ground.

This research is sponsored by the USAF School of Aerospace Medicine under subcontract B-10-A10-S1 from Georgia Institute of Technology.

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Table I, Definitions of Terms

R1= Outer radius of the monopole, cm.
R2= Inner radius of the probe, cm.
R3= Outer radius of the probe, cm.
RP= Relative permeability of the probe core.
S= Length of the probe, cm.
H= Length of the monopole, cm.
Z= Height of center of the probe above ground, cm.
C= Shunt capacitance with probe, pico Farads.
L= Series inductance with probe, micro Henrys.
RPE= Effective relative permeability.

Table II, Example with Antenna Equivalent Circuit

R1= 11.3 cm. S= 2.0 cm.
R2= 12.3 cm. H= 175. cm.
R3= 14.3 cm. Z= 24. cm.
RP= 4,000.
Added capacitive shunt, C= 13.1 pico Farads.
Added series inductance, L= 2.41 micro Henrys.
Effective relative permeability, RPE= 221.

	Dipole Reactance in Ohms	
f MHz	Without probe	With probe
1.	-j8,955.	-j8,924.
5.	-j1,772.	-j1,619.
10.	-j855.3	-j542.9
15.	-j535.7	-j45.18
20.	-j364.6	+j340.6
25.	-j251.8	+j745.3
30.	-j167.1	+j1,319.
35.	-j97.02	+j2,669.
40.	-j34.20	+j213,462.
45.	+j26.23	-j1,890.
50.	+j88.48	-j510.2
55.	+j157.3	+j49.49
60.	+j239.5	+j417.2
65.	+j347.4	+j728.4
70.	+j507.9	+j1,051.
75.	+j797.5	+j1,479.
80.	+j1,561.	+j2,366.
85.	+j13,656.	+j14,574.
90.	-j2,045.	-j1,020.
95.	-j920.9	+j204.8
100.	-j565.8	+j657.1

Resonances without probe are at 43 and 86 MHz.
Resonances with probe are at 16, 40, 54 and 86 MHz.

Table III, Example with Antenna Equivalent Circuit

R1= 11.3 cm.   S= 2.0 cm.
R2= 14.3 cm.   H= 175. cm.
R3= 16.3 cm.   Z= 24. cm.
RP= 4,000.
Added capacitive shunt, C= 4.73 pico Farads.
Added series inductance, L= 2.09 micro Henrys.
Effective relative permeability, RPE= 191.

	Dipole Reactance in Ohms	
f MHz	Without probe	With probe
1.	-j8,955.	-j8,928.
5.	-j1,772.	-j1,640.
10.	-j855.3	-j590.3
15.	-j535.7	-j133.1
20.	-j364.6	+j182.4
25.	-j251.8	+j449.7
30.	-j167.1	+j703.8
35.	-j97.02	+j965.3
40.	-j34.20	+j1,253.
45.	+j26.23	+j1,592.
50.	+j88.48	+j2,023.
55.	+j157.3	+j2,635.
60.	+j239.5	+j3,661.
65.	+j347.4	+j6,016.
70.	+j507.9	+j21,553.
75.	+j797.5	-j8,514.
80.	+j1,561.	-j1,647.
85.	+j13,656.	+j12,033.
90.	-j2,045.	-j2,908.
95.	-j920.9	-j1,319.
100.	-j565.8	-j638.3

Resonances without probe are at 43 and 86 MHz.
Resonances with probe are at 17, 72, 82 and 86 MHz.

Table IV, Example with Antenna Equivalent Circuit

R1= 11.3 cm.	S= 4.0 cm.
R2= 12.3 cm.	H= 175. cm.
R3= 16.3 cm.	Z= 24. cm.

RP= 4,000.
Added capacitive shunt, C= 26.2 pico Farads.
Added series inductance, L= 8.97 micro Henrys.
Effective relative permeability, RPE= 411.

	Dipole Reactance in Ohms	
f MHz	Without probe	With probe
1.	-j8,955.	-j8,842.
5.	-j1,772.	-j1,171.
10.	-j855.3	+j760.3
15.	-j535.7	-j18,430.
20.	-j364.6	-j551.1
25.	-j251.8	+j416.6
30.	-j167.1	+j991.7
35.	-j97.02	+j1,454.
40.	-j34.20	+j1,869.
45.	+j26.23	+j2,260.
50.	+j88.48	+j2,640.
55.	+j157.3	+j3,019.
60.	+j239.5	+j3,405.
65.	+j347.4	+j3,813.
70.	+j507.9	+j4,271.
75.	+j797.5	+j4,855.
80.	+j1,561.	+j5,912.
85.	+j13,656.	+j18,298.
90.	-j2,045.	+j2,887.
95.	-j920.9	+j4,301.
100.	-j565.8	+j4,944.

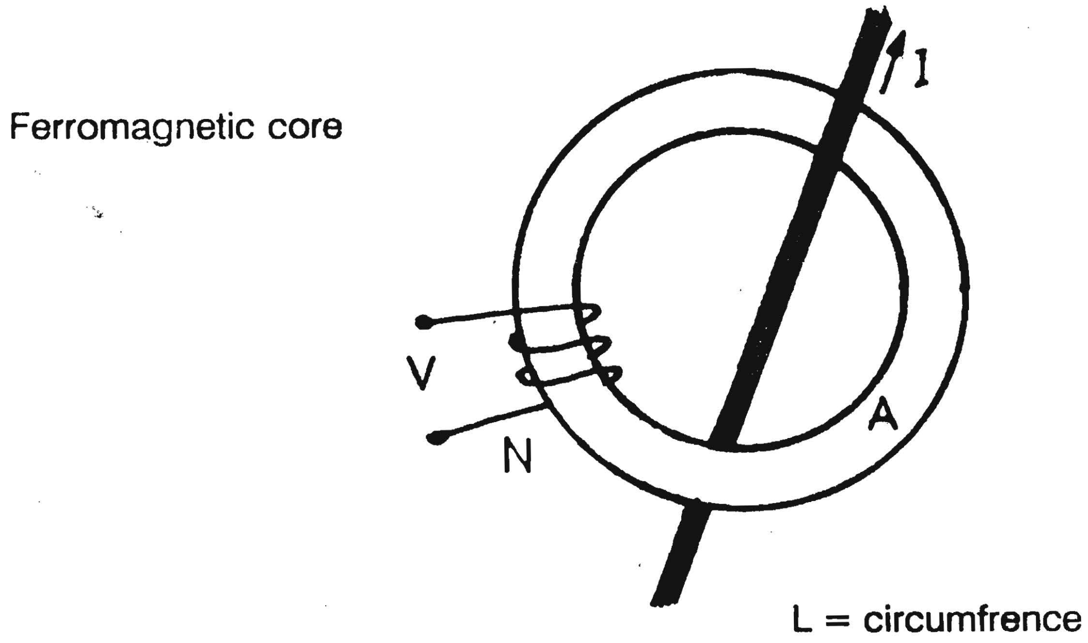
Resonances without probe are at 43 and 86 MHz.
Resonances with probe are at 8, 15, 22 and 86 MHz.

Table V, Measurements of Impedance

	No Probe	Eaton 91550-1	Eaton 93686-4
First Resonance	51.53 MHz	49.76 MHz	50.42 MHz
	5.3 k Ohm	3.7 k Ohm	3.7 k Ohm
Second Resonance	77.03 MHz	74.24 MHz	73.38 MHz
	34. Ohm	28 Ohm	26 Ohm
Third Resonance	92.49 MHz	92.70 MHz	92.31 MHz
	1.7 k Ohm	2.0 k Ohm	2.1 k Ohm

A Hewlett Packard 4193A Vector Impedance Meter was used to measure the impedance of a circuit consisting of a 3.1 cm o.d., 28 cm long aluminum cylinder with two wire transmission line. Eaton models 91550-1 and 93686-4 current probes, with aperture diameters of 3.5 and 6.5 cm, respectively, were placed on the aluminum cylinder.

APPENDIX VI. DERIVATION FOR FERROMAGNETIC CURRENT PROBES



Ampere's law

$$\oint \vec{H} \cdot d\vec{l} = I$$

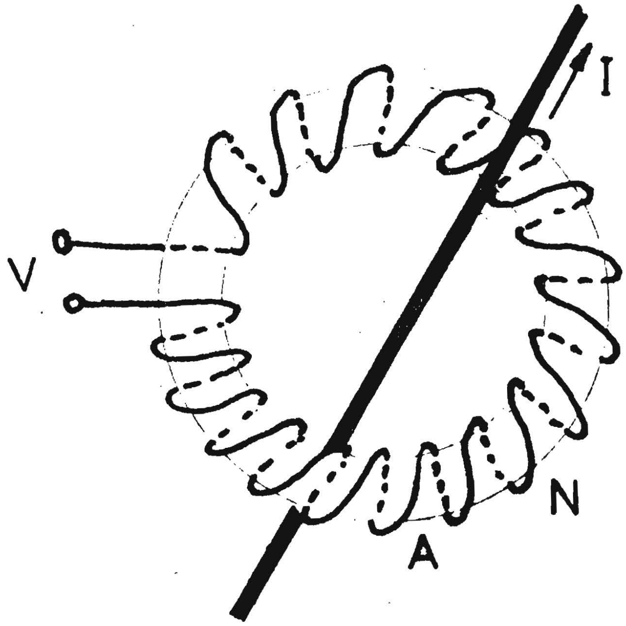
$$\Phi = \frac{\mu A I}{L}$$

$$v = -\frac{j \omega \mu N A I}{L}$$

Coil may be anywhere on the core

APPENDIX VII. DERIVATION FOR NON-FERROUS CURRENT PROBES

Non-ferrous core



At any azimuthal location on the coil

$$\Phi = \mu A \vec{H} \cdot \hat{l}$$

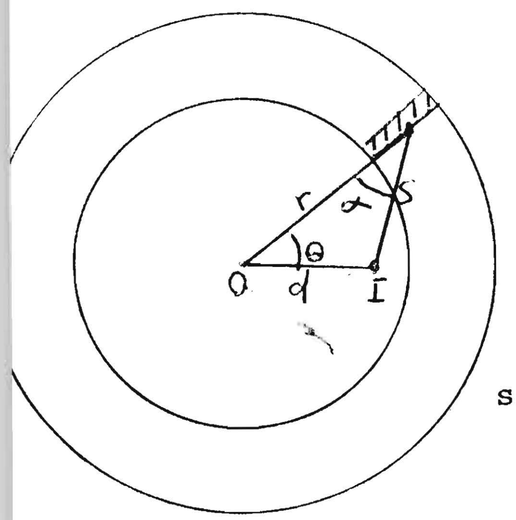
$$dv = -j\omega\Phi\left(\frac{N}{L}dl\right) = -\frac{j\omega\mu NA}{L}\vec{H}\cdot d\vec{l}$$

$$v = -\frac{j\omega\mu NA}{L}\oint\vec{H}\cdot d\vec{l}$$

Using Ampere's law

$$v = -\frac{j\omega\mu NAI}{L}$$

Turns per unit length x area = Constant



APPENDIX VIII. DERIVATION FOR NON-FERROUS CURRENT PROBES WITH OFF-AXI CURRENT

Non-ferromagnetic Core Low Frequency Analysis with an Off-Axis Current Filament

$$s^2 = r^2 + d^2 - 2rd\cos\theta$$

$$\frac{s}{\sin\theta} = \frac{d}{\sin\alpha}$$

Then $\cos\alpha = \sqrt{1 - \frac{d^2}{s^2}\sin^2\theta}$

$$s\cos\alpha = \sqrt{r^2 + d^2 - 2rd\cos\theta - d^2\sin^2\theta} = r - d\cos\theta$$

Then $\frac{\cos\alpha}{s} = \frac{r - d\cos\theta}{r^2 - 2rd\cos\theta + d^2}$

$H = \frac{I}{2\pi s}$ but H perpendicular to the increment of winding

$$= \frac{I\cos\alpha}{2\pi s} = \frac{I}{2\pi}\left[\frac{r - d\cos\theta}{r^2 - 2rd\cos\theta + d^2}\right]$$

Number of turns on increment of winding is $dn = \frac{n\,d\theta}{2\pi}$

Voltage on increment of winding $dv = \frac{\mu_0}{2\pi}\left[\frac{r - d\cos\theta}{r^2 - 2rd\cos\theta + d^2}\right]\left(\frac{dI}{dt}\right)A\,dn$

Total voltage $V = \frac{\mu_0 nA}{(2\pi)^2}\left(\frac{dI}{dt}\right)\int_0^{2\pi}\left[\frac{r - d\cos\theta}{r^2 - 2rd\cos\theta + d^2}\right]d\theta$

$$V = \frac{\mu_0 n A}{\ell} \left(\frac{dI}{dt}\right) \int_0^{2\pi} \left[\frac{1 - \frac{d}{r}\cos\theta}{1 - \frac{2d}{r}\cos\theta + \frac{d^2}{r^2}} \right] \left(\frac{d\theta}{2\pi}\right)$$

$$\text{The integral } = 1 \text{ for } \frac{d}{r} < 1$$

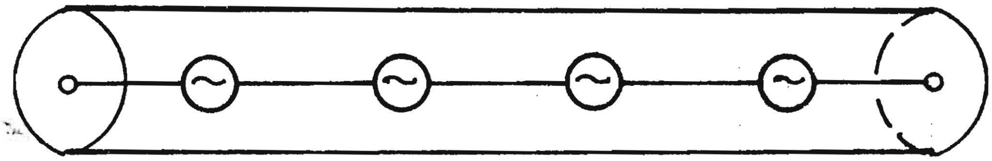
$$\frac{1}{2} \text{ for } \frac{d}{r} = 1$$

$$0 \text{ for } \frac{d}{r} > 1$$

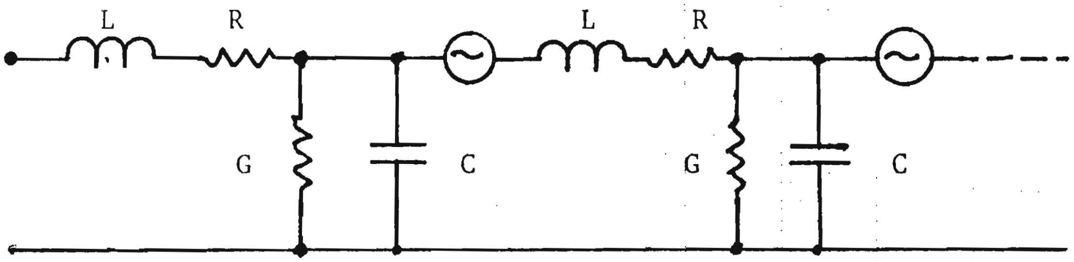
Thus $V = \dfrac{\mu_0 n A}{\ell} \; \dfrac{dI}{dt}$ if the current source is within the aperture

APPENDIX IX. TRANSMISSION LINE MODEL OF THE PROBE COIL/SHIELD

A



B



C