Using Image Planes on DC Motors to Filter High Frequency Noise

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***Abstract*—Traditionally, DC motors have only been filtered for narrow frequency bands of interest, such as the AM and FM bands. However, as more electronic devices are implemented in consumer applications such as automobiles, requirements now demand filtering from kilohertz to several gigahertz. Capacitors, inductors, and ferrites characteristically are used to filter narrow frequency bands. They are limited by their size and parasitics for broadband performance and are cost prohibitive in many DC motor applications that require broadband performance. The purpose of this paper is to investigate an alternative cost effective approach for broadband filtering performance. Image planes have been shown to provide good results on PCB applications for reducing radiated emissions. This paper examines the possibility of using image theory for filtering DC motors.**

Keywords-Image Planes; filtering; Radiated Emissions; cancellation; X2Y®;

I. INTRODUCTION

A point charge (q+) a distance (h) above a perfect conducting plane causes a dispersal of the E-field at the surface. Image theory explains this phenomenon by claiming that an oppositely charged point charge (q-) exists the same distance (h) below the conducting plane (Fig. 1) [1].

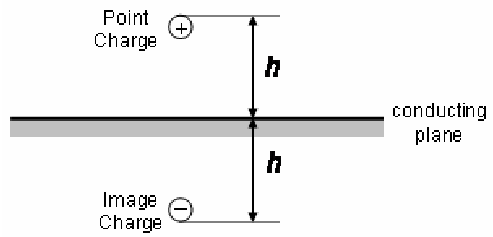

Figure 1. A point charge and its image in a conducting plane.

Further, Weeks [1] claims that the fundamental conservation of charge equation,

$$\nabla \cdot \mathrm{J} + j\omega\rho = 0 \tag{1}$$

where **J** is the total current density and ρ is the volume density of electric charge, incurs that time varying electric currents above an electric conductor also have images. In addition, the dual solution of Maxwell's Equation immediately concludes that magnetic currents above a magnetic conductor have images.

Fig. 2 shows electric and magnetic currents and their images in a perfect electric/magnetic conductor. For a perfect electric conductor, the normal component of an electric current adds while the tangential components cancel (Fig. 2a).

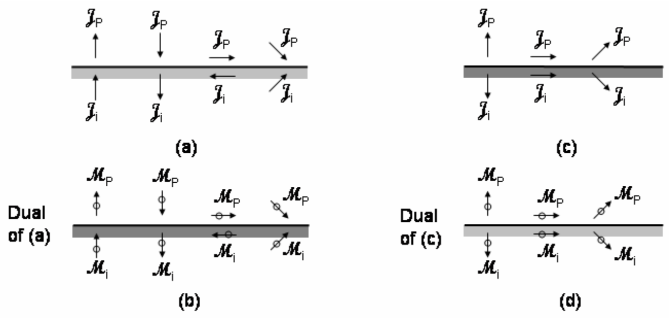

Figure 2. (a) Electric currents and their images in a perfect electric conductor. (b) Magnetic currents and their images in a perfect magnetic conductor. (c) Electric currents and their images in a perfect magnetic conductor. (d) Magnetic currents and their images in a perfect electric conductor.

German, Ott, and Paul in [2] used image theory on a printed circuit board (PCB) to reduce ground-noise voltage and radiated emissions. Their approach was to place a conductive plane (image plane) close to and beneath a conducting trace. In addition, by correctly attaching cables to the image plane, radiated emissions from the cables were also reduced (Fig. 3).

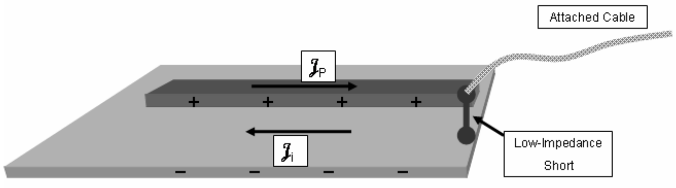

Figure 3. German, Ott, and Paul's approach to use image theory on PCB and attached cables to reduce radiated emissions.

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Other research [3] questioned the validity of using image theory to explain the phenomenon described by German, Ott, and Paul because of the PCBs finite dimensions which in certain instances do not hold true. However, Fessler, Whites and Paul in [4] investigated to what degree image theory is valid for a PCB by investigating the effect a conducting (image) plane has on radiated emissions and documenting the geometry ratio between the trace and plane for image theory to be valid.

For the purposes of this paper, the questions to be investigated herein are what constitutes an ideal image plane, how that applies to DC motors, and can radiated emissions from the power cables of a DC motor be reduced through the concept of image theory?

II. CONSTRUCTING AN IDEAL IMAGE PLANE

When using an image plane to cancel image charges and currents in an application, how can an infinitely large image plane be constructed? Assuming that the application is finite in size and conducting geometry, examining a spherical capacitor and a cylindrical capacitor can help define the answer.

A spherical capacitor is made up of two concentric spherical shells each with a radii of ‘a’ and ‘b’ (Fig. 4). The capacitance between the two spheres is defined by Equation (2) [5].

$$C = 4\pi\varepsilon_O \frac{ab}{b-a} \tag{2}$$

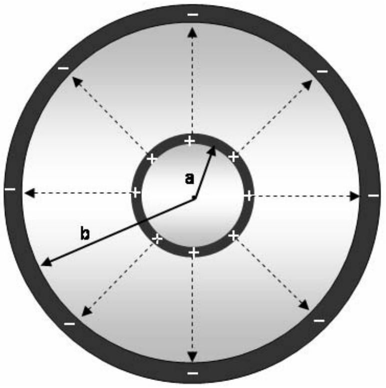

Figure 4. Cross-section of a spherical capacitor.

When a positive charge is applied to the inner conductor, a negative image charge appears on the outer conductor. The idea is the same as the image plane, but stated more accurately, it is an image sphere. An image plane only couples one-half the point charge whereas the image sphere encompasses it, coupling in all directions. If the charge has a velocity then the current direction is 3-dimensional as shown in Fig. 2. Therefore from the perspective of the center sphere, the image sphere (outer sphere) can be called infinitely large in all directions.

The benefit of an infinitely large image sphere is the additive nature of the normal component of the current as stated in Fig. 2. No matter which direction the normal component is directed in the sphere, the same normal current is occurring on the opposite side of the sphere creating a 180° phase difference. Thus, the normal components also cancel.

Assuming that an image sphere is ideal, how does this apply to DC motors? DC motors are usually cylindrical in shape. A cylindrical capacitor is formed by two coaxial cylinders of radii ‘a’ and ‘b’ with a length of ‘L’ (Fig. 5). If L is much greater than b, then the effect of edge fringing is negligible, otherwise end caps are required to contain the E-field. Assuming that L is much greater than b, the capacitance is defined by Equation (3) [5].

$$C = 2\pi\varepsilon_O \frac{L}{\ln\left(\frac{b}{a}\right)} \tag{3}$$

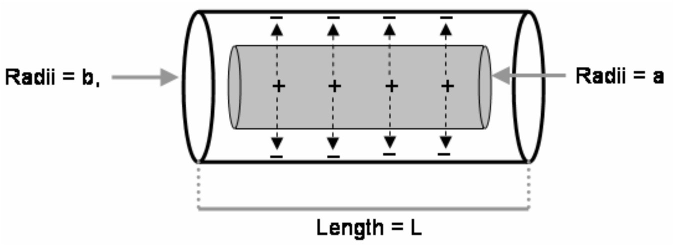

Figure 5. Depiction of a cylindrical capacitor.

Although image sphere may be the ideal, cylindrical capacitors have similar properties. A positive charge on the inner cylinder will result in a negative image charge on the outer. If the length (L) is much greater than the radii of the outer cylinder (b) then the outer cylinder fully encompasses the coupling in all directions and can be said to appear infinitely large.

III. DEFINING THE DC MOTOR STRUCTURE

A DC motor is constructed of six basic components: an armature wound with wire, brushes, commutator, shaft, polarized magnets, and a housing of magnetic steel (Fig. 6).

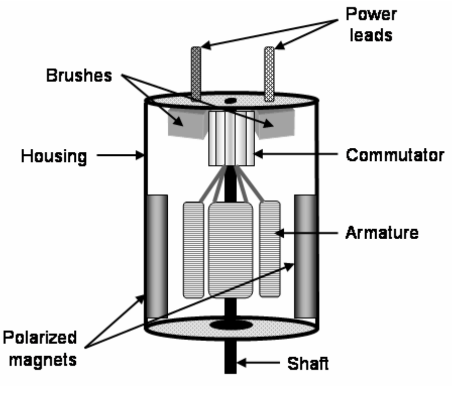

Figure 6. The structure and components of a DC motor.

The first step to applying image theory is to identify the conducting components of the application. When a positive and negative DC supply is attached to the power leads, current flows through the armature circuit via the leads, the brushes, the commutator, and finally the wire coil wound around the armature stack. The resulting H-field from the wire (current loop) is attracted and/or repelled by the polarized magnets causing the armature to rotate with the interaction of the magnetic fields. The conducting path ("conducting application") internal to the housing is the brushes, commutator, and wire wrapped around the armature. The fields generated are continually reversing creating a spinning antenna or mode-stir effect internal to the housing.

The second step is to identify the image sphere. The housing is the natural choice because it is DC isolated from and encompasses the "conducting application". (Note: as discussed in Fig. 5, the ratio of length to radii of the housing is important in determining effectiveness of the image sphere.) By defining the DC motor structure in this way, obvious parallels can be drawn to a cylindrical capacitor.

IV. APPLYING IMAGE THEORY TO DC MOTORS TO REDUCE RADIATED EMISSIONS FROM THE CABLES

DC motors needs direct current to operate. Any time-varying or alternating (AC) current is not desired because it may result in radiated emissions from the power cables. The approach in [2] showed that proper attachment of cables to an image plane can reduce radiated emissions. For DC motors both the positive and negative power cables need to be attached to the DC motor housing with a DC isolated connection.

Capacitors are the natural selection to perform this function. However, if the filtering frequency ranges of interest is from kHz to GHz, standard capacitors are limited in their frequency range of effectiveness by parasitics. Multiple parallel capacitors introduce trace or via parasitics that become limiting factors for broadband performance.

To address the broadband filtering requirements currently required for DC motors an X2Y® component can be used. The X2Y® Technology provides low-impedance from a few kHz out to several GHz in a single device (Fig. 7) [7]. In addition, X2Y® components in a Circuit 1 configuration work in differential bypass. (Note: Circuit 1 configuration has been defined by the manufacturers and inventor of the X2Y® Technology [8].) This allows a single component to provide a low-impedance for both the (+) and (-) power leads while referenced to the housing at the same time.

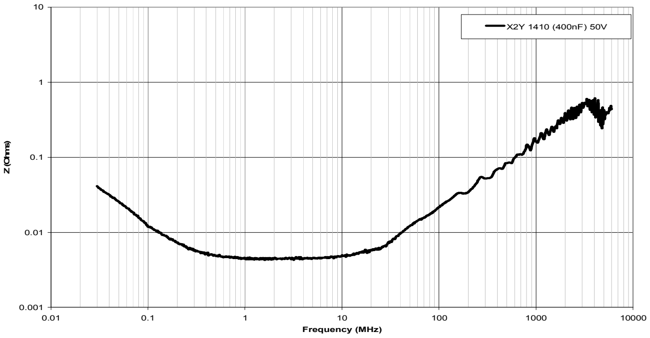

Figure 7. Impedance magnitude plot of a 1410 (400nF) 50v X2Y® component in a Circuit 1 configuration.

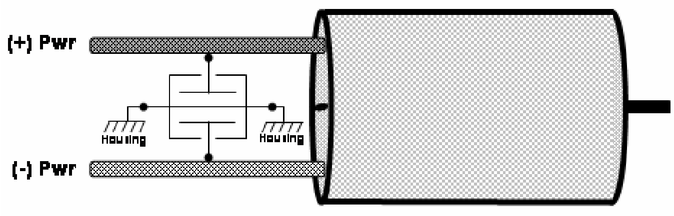

Figure 8. X2Y® Circuit 1 configuration applied to a DC Motor.

The critical parameters for applying X2Y® components on a DC motor is trace length to the component and location. Trace length should be minimized to reduce impedance and components should be located at exit point (inside or outside housing) at the power leads. (An in-depth discussion on applying X2Y® components in DC motors is found in [6], [9]-[11].)

V. MEASURED RADIATED EMISSIONS ON A DC MOTOR

For this section, three different production washer-pump motors, courtesy of Johnson Electric, Inc., will be used to evaluate radiated emissions. The first motor is an unsuppressed version of the washer-pump motor used as a baseline to compare the other two motors (Fig. 9a). The second version uses (2) capacitors and (2) inductors in traditional shunting and blocking roles (Fig. 9b); and the third uses X2Y® as a shorting device in an image sphere approach (Fig. 9c).

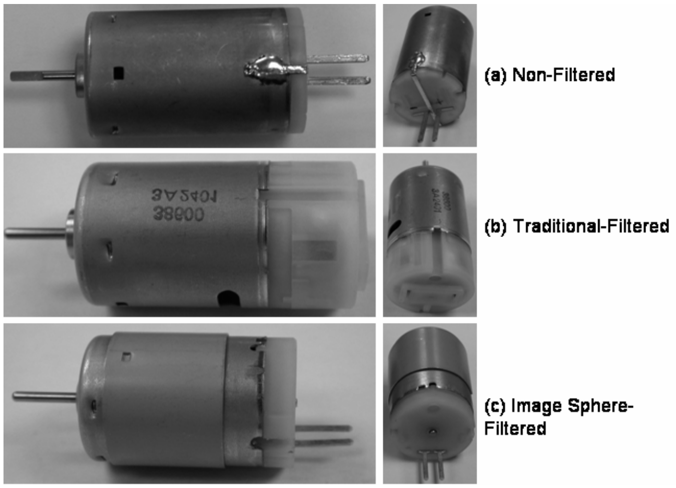

Figure 9. Washer pump motors used as DUTs to measure radiated emissions from power cables.

Each motor was connected to a 3 meter power cable inside a GTEM to measure the radiated emissions from the power cable (Fig. 10).

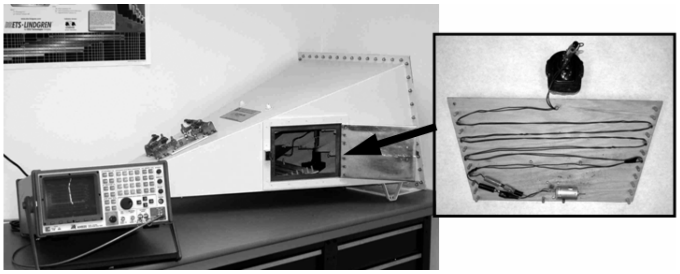

Figure 10. Radiated emissions from a 3 meter cable connected to a washer pump motor were messured in a GTEM.

Fig. 11 shows the results of the radiated emissions for all three production washer-pump motors. The image sphere approach over tradition filtering consistently shows a 10 to 20dBuV reduction in radiated emissions.

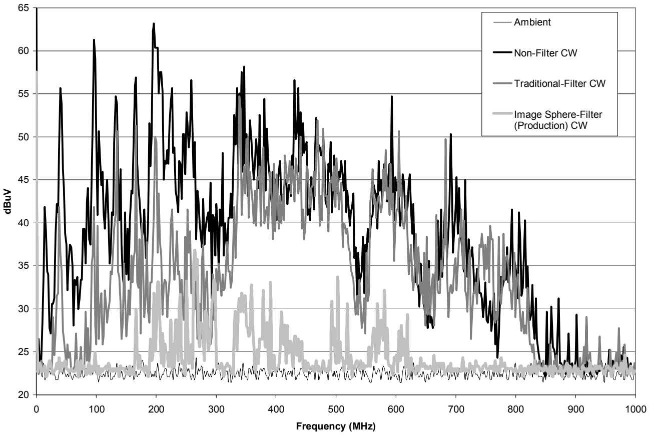

Figure 11. Radiated emissions of a DC motor from 9kHz to 1GHz using peak hold, 3 sweeps.

To highlight the importance of location and trace length of the X2Y® component when using the image sphere approach to filter, the unsuppressed motor was prototyped externally with an X2Y® component (Fig. 12). The distance of the G1/G2 trace to the housing is now 3 times that of the production X2Y® motor (Fig. 9a) and the connection to the housing is outside. Ideally when using the image sphere approach, connection to the inside of the housing (thus inside skin current) is preferred to the outside. Fig. 13 shows the emissions of the production X2Y® versus outside prototype.

Figure 12. X2Y® component prototyped on the outside of the washer-pump. (Note: the prototyped motor used a 1014 size X2Y® for easier attachment).

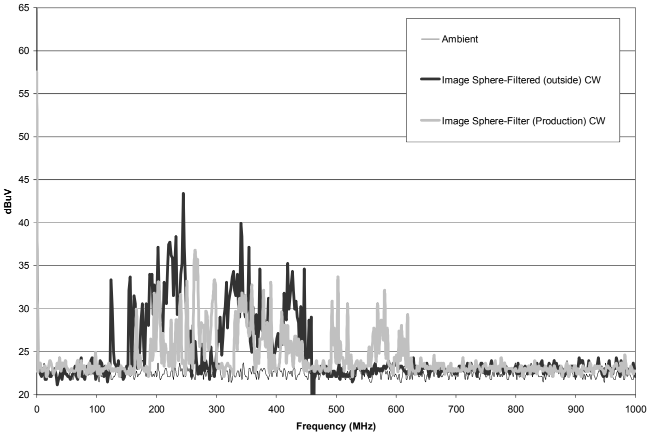

Figure 13. Radiated emissions comparing X2Y® inside vs. outside of the washer-pump.

VI. CONCLUSIONS

Image theory is one way of looking at how energy propagates through a DC motor. Utilizing this approach can significantly reduce radiated emissions from the cables. The keys to applying image theory are using a broadband low-impedance device to cancel the image charges/currents with conducted charges/currents and properly designing from an image sphere concept.

Traditionally motor design is engineered from a mechanical perspective with electromagnetic considerations limited to the armature function within the magnetic field of the stator, with little or no thought given to the unwanted EMI noise.

As filtering requirements become more stringent, addressing electromagnetic energy propagation early in the design phase can alleviate later problems. Making mechanical joints not just functionally strong, but also conductive (low-impedance across a broad frequency range), and the recognition that emissions are both radiated and conducted for a DC motor is important during design. High impedance in a mechanical metal joint of the motor may create a crude and unintentional antenna for the unwanted energy to propagate from the motor.

Currently several motor manufactures are using the concept of image spheres in production motors. Future work should investigate the use of image theory with other consumer applications such as integrated circuits, laptop computers, PDAs and heart monitors.

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REFERENCES

[1] W. Weeks. "Electromagnetic Theory for Engineering Applications," John Wiley & Sons, Inc., New York, 1964, pages 50-55.

[2] R. German, H. Ott, and C. Paul, "Effect of an Image Plane on Printed Circuit Board Radiation," IEEE EMC Symposia Records 1955 to 1995, vol. IEEE004, 1996.

[3] T. Hsu. "The Validity of Using Image Plane Theory to Predict Printed Circuit Board Radiation," IEEE EMC Symposia Records 1955 to 1995, vol. IEEE004, 1996.

[4] J. Fessler, K. Whites, and C. Paul, "Effect of Image Plane Dimensions on Radiated Emissions," IEEE EMC Symposia Records 1955 to 1995, vol. IEEE004, 1996.

[5] D. Halliday, R. Resnick, and J. Walker, "Fundamentals of Physics," 5th edition, John Wiley & Sons, Inc. 1997, pages 632 – 633.

[6] "DC Motor Design with X2Y," Application Note #1020, http://www.x2y.com/cube/x2y.nsf/(files)/MotorDesign080403.pdf/$FILE/MotorDesign080403.pdf

[7] D. Sanders, J. Muccioli, A. Anthony, and D. Anthony, "X2Y® Technology Used for Decoupling," Published by IEE at EMC issues in Design Techniques, Tools and Components Event Symposium, April 2004, © X2Y® Attenuators 2004.

[8] "X2Y Circuit 1 and Circuit 2 Configurations," Application Note #1006, http://www.x2y.com/cube/x2y.nsf/(files)/CircuitConfig112703.pdf/$FILE/CircuitConfig112703.pdf

[9] "DC Motor Design with X2Y Example A," Application Note #1020A, http://www.x2y.com/cube/x2y.nsf/(files)/082703MotorA.pdf/$FILE/082703MotorA.pdf

[10] "DC Motor Design with X2Y Example B," Application Note #1020B, http://www.x2y.com/cube/x2y.nsf/(files)/MotorB102903.pdf/$FILE/MotorB102903.pdf

[11] "DC Motor Design with X2Y Example C," Application Note #1020C, http://www.x2y.com/cube/x2y.nsf/(files)/MotorC111003.pdf/$FILE/MotorC111003.pdf.