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Lawrence Livermore Laboratory

A LITERATURE REVIEW OF EMP EFFECTS ON APERTURES

James N. Brittingham

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A LITERATURE REVIEW OF EMP EFFECTS ON APERTURES*

INTRODUCTION

This report is a review of the literature on the electromagnetics coupling through apertures. The particular problem of interest is the various methods used to find the effect of EMP coupling through apertures. Once the present literature has been cited a description of the areas needed for future studies will be outlined.

Coupling electromagnetic energy into a structure from EMP radiation can be partitioned into three distinct classes:

- Direct penetrations
- Apertures
- Diffusion.

Direct penetrators are those devices that carry the electromagnetic energy into a structure via conductors and pipes that penetrate the walls of the structure. Examples of direct penetrators include: power lines, deliberate antennas, ground loops, and plumbing. Apertures are openings in the structure that allow electromagnetic energy to couple into the structure. Examples of apertures include: doors, windows, and bomb bays. Diffusion refers to energy that diffuses through the walls of the structure. The particular electromagnetic energy coupling mechanism depends greatly on the type of structure being considered.

A high-reliance answer to the electromagnetic coupling through an aperture in a complicated three-dimensional body would require a resource expenditure (money, time, and facilities) possibly far in excess of that available. To understand the coupling through some aperture the problem is always reduced to an idealized representation called a canonical representation of the problem. It is in the solution of these canonical representations of the actual problem where the literature plays an important role. Because of the limitations of the literature

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one may use canonical representation which is so simple that it may not adequately represent the original problem.

The electrical quantities needed to study EMP coupling through an aperture are:

- Total energy transmitted through the aperture for an incident pulse
- Electric and magnetic fields behind the aperture
- Transient response and transfer function of the current in the load and the voltage across the load when loaded wires are placed behind the aperture
- Energy dissipated in the load, for wires behind the aperture.

These quantities, for the right set of canonical problems, can be used to give the bounds on how much coupling is expected for most practical EMP problems.

The current canonical literature applicable to practical aperture problems can be divided into four classes:

- Apertures in a perfectly conducting plane of infinite extent
- Apertures in two-dimensional perfectly conducting bodies
- Apertures in three-dimensional perfectly conducting bodies
- Apertures with wires behind the opening.

It is these specific canonical problems which will be discussed in the review of the literature.

Apertures in Planes

The problem of apertures in a perfectly conducting plane has received the greatest attention in the literature. These solutions can be separated into two types:

- Low-frequency approximation-limited to electrically small apertures.
- Moment-method solutions of integral equation - good (in principle) for all aperture sizes.

The first method of solving apertures in planes is not a method, but a means to obtain the solution from an equivalent problem. The method is called Babinet's equivalence principle. It allows an aperture in a perfectly conducting plane to be represented (in a dual problem) by a perfectly conducting disk of the same shape as the aperture. The equivalent sources in the disk problem are expressed in terms of the sources to the original. A good discussion for Babinet's equivalence principle is presented by Collin (1960). On the back side of the aperture the sum of the fields for the disk problem and for the aperture problem are equal to the incident fields. This procedure allows the problem of the scattering from a conducting disk to express the scattering through an aperture in a screen.

Low-frequency approximation was originally developed by Lord Rayleigh (1897) when he solved the problem of a circular aperture by expanding the solution in terms of the power series in ka , where k is the wave number of free space and a is the radius of the aperture. He obtained the first term to this series. Bethe (1944) was the first to write the solution for the fields behind the plane in terms of an equivalent magnetic and electric dipole currents in place of the aperture. Bouwkamp (1954, 1970) was able to obtain higher-order terms to Rayleigh's series approach to the problem. Bouwkamp shows that Bethe had an error in his development (1944). Low-frequency approximations are given in analytic form and, therefore, are easy to use. This is why these approximations are used so much; however, they are only accurate for small apertures.

A different formulation of the low-frequency approximation was obtained by Umashankar and Butler (1974), who developed an integral equation solution in terms of the equivalent magnetic currents in the apertures. The electromagnetic quantities are expanded in a Rayleigh series to obtain a formulation for the coefficients of the Rayleigh series for the magnetic current in the aperture. These coefficients are written as integral equations. The first three terms of the expansion are formulated numerically in terms of a moment method. The case of a circular aperture is computed numerically in a paper by Wilton, Butler, and Umashankar

(1974). A different integral-equation solution for the Rayleigh series of a circular aperture was formulated by Rahmat-Samii and Mittra (1975). They formulated the solution by writing an integral equation in terms of the tangential electric fields in the aperture. The electric fields are then expanded in a Rayleigh series to obtain a set of integral equations for the coefficients of the Rayleigh series expansion for the tangential components of the electric field in the aperture. The first three terms of this series are solved analytically for the case of a circular aperture. While these two methods are used to calculate the first three terms of the Rayleigh series for a circular aperture, they can be used to find any aperture shape. These solutions are still limited to electrically small holes.

Thus far, the discussion of apertures in planes has been limited to electrically small apertures. The following plane-problem solutions are good for all aperture sizes.

The problem of an infinite slit in a perfectly conducting plane where the incident plane wave is assumed to have an electric field polarized along the center axis of the slot was studied by Libelo and Bombardt (1970, 1972). Their solution for the electric field is formulated in terms of the series expansion for the wave equation in cylindrical coordinates. The incident electric field is written in the cylindrical wave functions. The problem is divided into three different regions of space. One is a cylindrical region which contains the aperture on both sides of the plane. The second region is all of the volume on the incident side of the aperture except the cylindrical volume covering the aperture. The third region is all of the volume on the backside of the aperture except the cylindrical volume covering aperture. The electric fields in these three regions are written in terms of cylindrical wave functions. By using the boundary conditions that tangential component of the electric field on the surface of the conductor and the condition that the electric field is continuous across the boundaries of region one the unknown coefficients are found. Also presented are the low frequency approximations to the expansion obtained for this problem.

The solution is studied by numerical computation. This procedure is a frequency domain solution to the problem of infinite slit in a conducting plane but is good for all apertures of sizes.

A solution for a circular aperture was developed by Taylor, Crow, and Chen (1973, 1974). They formulated the solution in terms of the current on a Babinet's equivalent disk with the current on the disk being written in terms of an electric-field integral equation. The disk's current and the incident fields were then expanded in terms of transverse-electric and transverse-magnetic cylindrical modes at the surface of the disk. This gives a new set of integral equations for the transverse-electric and transverse-magnetic current modes on the disk. These integral equations are solved numerically by a moment method. Numerical results for the current on the disk and the fields behind the aperture are given.

A formulation of an aperture in a plane which is not limited to only circular apertures was presented by Wilton and Dunaway (1974). The solution is formulated in terms of an equivalent magnetic current in the aperture. Once the fields on both sides of the aperture are written in terms of the electric vector potential, an integral equation is obtained by forcing the electric field to be continuous through the aperture. This integral equation is written in terms of the unknown magnetic current and the incident electric field in the aperture. The moment method approach is used to develop a procedure to handle numerical calculations. A solution to the same problem was obtained by Mautz and Harrington (1975) by using a different moment method solution.

A different approach for aperture of any size in a plane is presented by Rahmat-Samii and Mittra (1975). They formulated the solution in terms of the unknown tangential component of the electric field in the aperture. In this development they obtained an inhomogeneous integral - differential equation for the unknown electric field in the aperture. This formulation was a two dimension wave equation operating on an integral which contained the unknown electric field. The two-dimensional wave equation the

integral was written in terms of an unknown function which are evaluated by making sure that the fields are well behaved on the edges of the aperture. This integral has an integration consisting of the product of the free space Green's function multiplied by the unknown electric fields in the aperture. The integral equation is solved by a moment method. The authors present numerical solutions for several rectangular and circular apertures.

The studies presented above for apertures in planes are frequency-domain solutions. A time-response solution to this problem can be obtained by using Babinet's equivalence principle to represent the aperture problem as an equivalent plate in free space. The time-domain problem of a plate in free space has been solved by Menger, Bennett, Peterson and Maloy (1975). They formulated the problem in terms of the unknown current on the plate. The electric field was written as an integral-differential equation in terms of the unknown current. The expression for the current was obtained by using the boundary condition at the surface of the plate. These integral-differentials representations of the current were then solved by numerical methods.

Before this review of the literature leaves apertures in planes let us discuss some results obtained from experimental measurements. A measurement of a finite plate with an aperture in it was presented by Stark (1972) who used an EMP-type signal. He measured the time response of the field.

He compared his results with numerical formulations from earlier authors. Also presented are some plots showing that the maximum field occurs along a line perpendicular to the plane and passing through the center of the aperture.

This completes a general review of the literature for apertures in perfectly conducting planes of infinite extent. The next section will present the literature for apertures in two dimensional bodies.

Apertures in Two Dimensional Bodies

The problem of a plane wave incident on a slotted, perfectly conducting cylindrical shell has been presented by Bombardt and Libelo (1972, 1972, 1975). In their solution the incident electric field is polarized parallel to the center axis of the cylinder. They write the incident field in terms of cylindrical wave functions. The fields inside the cylinder are written in terms of the cylindrical wave function with unknown coefficients. The scattered fields outside the shell are written as the sum of the fields as if the aperture was not present plus the component of field due to the presence of the aperture. The fields due to the aperture are written in terms of cylindrical wave functions with unknown coefficients. Using the boundary condition that the tangential electric field is continuous across the aperture the unknown coefficient are shown to be identical. By assuming that the electric field is known in the aperture the coefficients are then written in terms of an integral containing known fields in the aperture. An integral equation relating the electric field in the aperture to current that would be present if the aperture was replaced by a conducting surface was then written by requiring that the tangential component magnetic field to be continuous across the aperture. A similar integral was obtained expressing the current on the conducting surface in terms of the incident electric field. These integral equations were solved by moment methods to obtain numerical results. Numerical results for the current on the conductor surface, electric and magnetic fields are presented in this study. This procedure is a frequency-domain solution good for all size apertures.

The problem of a normally slotted, infinite cylinder has been presented by Kligman and Libelo (1974). In this approach the integral equation is obtained for the unknown tangential electric field in the aperture. This is also a frequency-domain solution. No numerical results are presented in this paper.

The problem of an incident plane wave on a slotted cylinder with incident electric field polarized parallel to the center axis of the cylinder was also studied by Senior (1975). An integral equation for the unknown

current on the surface of the cylinder was formulated. These unknown currents were solved by a moment method program and once the current on the surface was found the fields were known. He presented plots of the magnetic and electric fields at various points inside and outside the cylinder. This is a frequency domain solution to the problem which is good for all size apertures.

This completes the review of aperture in two dimensional bodies. Attention will next turn to apertures in three dimensional bodies.

Apertures in Three Dimensional Bodies

The literature review for the effects of apertures in three dimensional bodies begins by discussing the experimental studies being carried on by Libelo, Heckl, Andrews, and Morgolis (1976) on finite-length cylinders, these cylinders were both open-ended and capped. The cylinders used in this study have slotted aperture parallel to the center axis of the cylinders. Some of the slots are short; others run the full length of the finite-length cylinder. The incident electric field is polarized parallel and perpendicular to the center axis of the cylinder. Measurements are made for both CW and EMP pulse sources. The electric field along the center axis of the cylinder and out through the aperture are measured. The magnetic fields are measured at various points along the surface of the conducting cylinder. Some of the results from these measurements appear in their paper (1976) while additional results from these experiments will be published in several reports (private communication with Libelo).

A frequency-domain study of a circular aperture in spherical shells will be discussed next. The approach of least squares was used to obtain an analytic formulation in the paper by Chang and Senior (1969). They began by writing the fields inside and outside the sphere in terms of an infinite series of wave function. These series representations contain unknown coefficients yet to be determined. Using the boundary conditions that the tangential electric field is zero on the conducting portion of the sphere and magnetic fields and electric fields are continuous across

the apertures, a set of equations is obtained in terms of the spherical wave function and the unknown coefficients. This is an infinite series equation that must be satisfied over the whole surface of the sphere. An error function equation is written for a finite number of the terms in these infinite series equations by integrating the absolute value square of the different of both sides of the new equation over the surface. The error function is minimized with respect to the unknown coefficients to obtain a first set of equations for these coefficients. These equations can be solved to obtain the coefficients that fit the problem in the least square sense. The authors compare their analytic results with some backscattering cross sections measured for a spherical shell with a circular aperture. They also present electric field plots for their analytic results.

To improve the amount of time needed to compute the previous results for circular holes in spherical shells Senior and Desjardines (1973) developed a method to assume the fields in the aperture. Once the fields in the aperture are known the field at other points in the problem can be calculated. The results developed by this method was compared to the results from the previous work by Chang and Senior (1969). Yet another formulation of this problem was presented by Senior (1975). In this latest work Senior developed an electric field integral equation in terms of the unknown current on the surface of the conductor. There are no numerical results given in this paper. This completes the discussion of circular apertures in spherical shells.

The case of an annularly slotted sphere was presented by Heckl, Libelo and Bombardt (1973). The authors developed an analytic formulation for the field from an annularly slotted spherical shell. They expressed the problem in terms of two Debye potentials, one for no aperture on the spherical shell and the other due to the presence of the aperture. They then used the boundary conditions across the aperture to develop a set of coupled integral equations. This set of coupled integral equations is formulated in terms of the unknown tangential electric field in the

opening of the aperture. Also developed in this report is an integral equation formulation in terms of the current on the conducting surface of the shell. There are no numerical results presented in this report. This completes the review of aperture in spherical shells.

One of the most important practical problems for apertures in three dimensional bodies is the case of an aperture in a box. Most of this is handled by dividing the problem into internal and external regions. A typical example of this approach is presented in a paper by Chen (1970). In this paper the author used the Bethe hole approximation to account for the external to internal coupling. The external problem is treated as a plane wave incident in a small hole in a plane of infinite extent. The equivalent magnetic source from the Bethe hole approximations is used to excite the interval made of a closed rectangular cavity. This Bethe hole approach neglects the coupling from the cavity back to the aperture. This condition requires the aperture to be small.

Recently Cheng and Chen (1975) reported an analytic method to account for the interaction between the aperture and cavity. They formulated the problem of a rectangular cavity behind an aperture in a plane. The problem is formulated in terms of the Laplace transform of the electric potential. The second order wave equation is converted to a set of first order equations and expressed as a normalized set of state equations. This set of equations is expanded in a set of expansion functions which satisfy the boundary condition on the conducting surface. The electric fields on the plane side of the aperture are first written in terms of a set of plane waves. This plane wave expansion is then written in terms of the expansion function at the surface of the aperture. The tangential electric field across the apertures are set equal to each other. Then a moment method is used to formulate a set of equations for the coefficients of the expansion functions. There are no numerical results given for this work. Before leaving apertures with cavities behind the aperture there is another problem which has been formulated and solved.

The case of an aperture in an infinite plane with a second plane behind the first has been studied by Taylor (1971). He formulated the problem by assuming that the aperture is small. This allowed him to use Bethe hole equivalent sources to express the source of fields behind the aperture. These Bethe hole sources are in the form of equivalent magnetic dipoles. Image theory then is used to account for the effect of the dipole source in the presence of the two conducting planes. The electric field is plotted for the region between the two planes. This is a frequency domain solution to the problem which is limited to small apertures. Also in this formulation of the problem there is no interaction between the interior and exterior regions.

Another formulation of the same problem which takes into effect the coupling between the interior and exterior regions was given by Rahmat-Samii and Mittra (1975). Using the same type formulation that was used to formulate just the aperture in the plane, they developed a set of integral equations in terms of tangential electric fields in the aperture. In this formulation they write the kernel in the integral as the sum of the free space Greens function plus the images in the second conducting surfaces. A moment method is used to find numerical results from this problem. This procedure is good for all size apertures and it includes the coupling between the external and internal problems.

Apertures with Wires Behind

The problem of a wire behind an aperture has a very important part in the understanding of how energy couples through apertures into electrical systems. The papers in the literature which develop a solution to the problem of a wire behind an aperture will now be presented. The first approach discussed is the one developed by Lin, Curtis, and Vincent (1974). They formulated the problem of a wire behind an aperture in a perfectly conducting plane by first finding fields behind the aperture from the use of a Babinet's equivalent. This Babinet's equivalent neglected the existence of the wire behind the aperture. Their equivalent Babinet's disk was solved numerically by a wire mesh equivalent of the

disks. Once the fields behind the disk are found Babinet's principle is used to find the fields behind the aperture in the plane. The voltage at the terminals of the wire is written in terms of an integral of the current on the wire dotted into the electric field behind the aperture. The current on the wire is assumed to be as if it had a transmission line variation down the wire. By doing the integral numerically the voltage at the end of the wire is found. In these papers they show some comparison of the computation with experimental results. This problem neglects the coupling between the aperture and the wire.

A different formulation for the current on a wire behind an aperture in a conducting screen when a plane wave incidences on the screen was presented by Kajfez (1974). He formulated the current on a wire by assuming that the aperture could be represented as a Bethe hole equivalent current source and that the energy on the wire would propagate as a TEM. The magnetic current sources are then used to excite the TEM made on the wire and its image through the conducting plane. He used this formulation to obtain the transmission line equation for the two wires. Then he studies transient problems on the wire. Even though this method does give a simple procedure to study the time domain solution the formulation lacks the coupling between the aperture and wire.

The interaction between the wire and the aperture is taken into account in the development of this problem presented by Butler and Umashankar (1976). In their formulation of the problem they expressed the solution in terms of a magnetic current on the aperture and an electric current on the wire. They reduced the problem to a set of coupled integral equations in terms of the different currents on the different surfaces. This general integral formulation is too large to be placed on a computer by a moment method. Therefore, they reduced the aperture to a slot. This reduced integral equation is then put on a computer by a moment method. The current on the wire is presented in this paper. This development is in the frequency domain and requires a thin aperture.

The most prevalent solved case for aperture with wires behind them is the aperture in the screen but there is another configuration of wire and aperture which is the problem of an aperture in a cylinder with a wire along the center axis of the cylinder. This was solved by the use of Bethe hole approximation by Taylor and Harrison (1972). They assumed that the aperture can be replaced by a Bethe hole equivalent current along the inside surface of the cavity. This equivalent current was then used to excite the TEM mode in the coaxial structure. This solution leads to a transmission line equivalent for the current in the center wire of the coaxial line. The method used by these authors does not allow interaction between the interior and exterior portions of the problem.

A different formulation of an aperture in a finite cylinder with a wire along the center axis of the cylinder was presented by Schuman and Strait (1975). In their formulation the wire need not run the full length of the cylinder. They began their solution by using Schekunoff's equivalent theorem to formulate the problem in terms of a known current in the aperture. The solution for the equivalent problem with the known current source in the aperture was found by using a numerical code for bodies of revolution developed by Mautz and Harrington (1969). The authors presented the current along the wire. This approach is good for all size apertures, but it is limited to wires along the center axis of the cylinder.

This concludes the review of the present state of the literature. Not every paper in the literature has been presented here, but a cross section of the presently known methods and data has been given.

DISCUSSION

Although the literature on apertures is very extensive, it is still difficult when trying to study the EMP coupling into a complicated structure through an aperture. These difficulties can be partitioned into three classes:

- The known approximations have not been validated.
- The use of canonical representation for an actual configuration has not been established.
- The knowledge and data on many canonical problems is either sparse or non-existent.

A large amount of work has also been published on low frequency approximations in planes. These low frequency approximations are used in the study of apertures in planes, but there are no studies of the accuracy of these approximations in the representation of an aperture in planes. The aperture in a plane should be studied to determine the accuracy of the low frequency approximation. This study should determine the relative size of the aperture when this approximation starts to become incorrect. This validation study should include the effect of the approximations on calculation of the near-fields, and far-field, and the total energy transmitted through the aperture. Some of the low frequency approximations have had higher order terms developed in the literature. Another aspect of the study of apertures in planes should be the validation of the use of these higher order terms in calculating various electrical quantities behind the aperture. The low frequency approximations are used to account for coupling into three dimensional bodies, but this approximation has not been proven by numerical or experimental studies. The accuracy in using this approximation developed for planes but used on three dimensional bodies needs to be understood both for the frequency domain and the transient response.

The easy use of equivalent representation to predict the EMP coupling through apertures into complex three dimensional bodies requires a large collection of data on many aperture problems. Without a systematic

collection of these results on apertures, a person needing a number to make a design decision may have to first solve some aperture problem. This may not be practical due to his limited resources. The classes of apertures are listed below:

1. Apertures in planes,
2. Apertures in planes with wire behind,
3. Apertures in planes with cavities behind,
4. Apertures in planes with loaded wires in cavities behind the apertures,
5. Apertures in three dimensional bodies,
6. Apertures in three dimensional bodies with loaded wires inside the body,
7. Apertures in three dimensional bodies with different size and shape cavities inside the body,
8. Apertures in three dimensional bodies with different size and shape cavities inside the body when these cavities contain loaded wires.

The electrical quantities needed for these aperture problems are:

- Total energy coupling through the aperture,
- Electric and magnetic fields map behind aperture,
- Current on the wires,
- Voltage across the loaded wires,
- Total energy dissipate in the loads.

These electrical quantities will cover a large range of practical applications.

COMMENTS

A table is presented showing the present extent of applicable literature on apertures. It is quite obvious from this table that there are vast gaps in the area of apertures. To fill in the knowledge on apertures

will require a significant amount of analytic and experimental investigation. Unless this work is undertaken the understanding of aperture coupling from EMP will remain a worrisome problem.

FD = Frequency domain
 TD = Time domain
 SA = Electrically small apertures
 AA = All apertures

	Theoretical formulation				Closed-form results				Numerical implementation				Validation of approximations		Experimental data		Data on canonical problems	
	FD		TD		FD		TD		FD		TD		FD	TD	FD	TD	FD	TD
	SA	AA	SA	AA	SA	AA	SA	AA	SA	AA	SA	AA						
Aperture in plane	5	5	5	5	5	0	0	0	5	5	5	5	3	0	3	3	3	3
Aperture in plane with loaded wire behind	3	0	3	0	0	0	0	0	3	0	3	0	1	0	2	0	3	0
Aperture in plane with cavity behind	3	0	3	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0
Aperture in plane with loaded wire contained in a cavity behind the aperture	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Aperture in three-dimensional bodies	3	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0
Aperture in three-dimensional bodies with loaded wire inside the body	3	3	0	0	0	0	0	0	3	3	0	0	0	0	0	0	2	0
Aperture in three-dimensional bodies with different shaped cavity inside the body	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Apertures in three-dimensional bodies with cavity inside the body where the cavities contain loaded wires	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

- 0 Nothing in literature.
 1 Denotes very little formulation, information or results.
 2 Denotes some formulation, information or results do exist, but it is limited to unimportant cases.
 3 Denotes a limited amount of formulation, information or results do exist for a small number of important cases.
 4 Denotes a good amount of formulation, information or results do exist on most cases, but needs a little work to be complete.
 5 Denotes a fairly complete formulation, information or results on all important cases.

Table 1. Present status of the literature for electromagnetic coupling through apertures.

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