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2-DAL SIMULATION OF EM FIELDS RADIATED BY ROTATING CYLINDER CARRYING SURFACE CURRENTS USING PASSING CENTER SWING BACK GRIDS TECHNIQUE

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Abstract—The passing center swing back grids (PCSBG) technique, in conjunction with the method of characteristics (MOC), was proposed to model electromagnetic problems featured with rotating objects. The drive of this proposal lays mainly on the fact that MOC defines all field components in the center of grid cell. Its practicability was validated by exhibiting the radiated EM fields from a rotating cylinder which carries surface currents with Gaussian profile and flowing in the axial direction. To clearly demonstrate that the cylinder is rotating and radiating EM fields simultaneously, the following arrangements were made. The cylinder may be equally sliced into an even number of segments that are with and without currents alternatively since a rotating circular cylinder yields no relativistic effects. The computational results showed that the radiated electromagnetic fields bear vortex structures as the cause of rotating cylinder, which serves as the evidences that PCSBG works properly.

1. INTRODUCTION

The scattered electromagnetic fields from moving objects have been attracting researchers' attentions dated back to the early 1970s. Many studies providing theoretical solutions and computational results for problems involved with moving or oscillating objects [1–13] or rotating objects [14, 15] can be easily found. Harfoush et al. adapted the finite-difference time-domain (FDTD) technique for simulating electromagnetic wave scattering from moving surfaces. At the point adjacent to the moving surface both Faraday's and Ampere's laws are

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employed to approximate the magnetic- and electric-fields whenever the moving boundary travels away from the grid point [9]. For the same objective, under the excitation of a Gaussian electromagnetic pulse or continuous wave train, the method of characteristics (MOC) combined with the relativistic electromagnetic field boundary conditions and successfully predicted the reflected electromagnetic fields from perfect planes moving at a constant velocity and/or vibrating at a fixed frequency. The computational results revealed not only the Doppler frequency shift but also the changes in phase and amplitude [1–3]. Though so, attempts to numerically simulate the electromagnetic scattering problem from rotating objects are postponed for the reason that grid cells suffer from being stretched and distorted due to the rotational motion of the object under examination, which brings the numerical efforts a major difficulty.

The feasibility of the application of MOC to the solution of electromagnetic scattering by rotating objects primarily depends on the nature of the numerical procedure. All field components are defined at the centroid of the grid cell. The evaluation of the field quantities by MOC for each cell requires all metric terms or the geometric shape of the grid cell. In the case involved with moving boundary or rotating object, so long as the metric terms of each changing size and/or form grid cell are accurately updated, all field magnitudes are computable merely with little efforts in modifying the existing program code. References [1–3, 16] and [17] give several examples of MOC application to problems where grid cell(s) may be gradually eliminated from the grid system, or extra cell(s) may be portion by portion introduced into the grid system caused by the moving boundary or dielectric half-space.

The analysis of the scattered electromagnetic fields from a rotating body is usually complicated, especially those with complex structures or lack symmetry of revolution. The return signal from rotating objects reveals additional modulation effects with the possibility of exposing physical information of the target under investigation. It is therefore important to develop efficient and accurate numerical methods to overcome the cell distortion difficulty when one tries to solve the electromagnetic scattering by rotating objects. It is then the main purpose of this paper to elaborate the proposed technique in MOC for the solutions of the radiation problem and then to demonstrate the radiated electromagnetic fields from a rotating cylinder carrying Gaussian-form currents. The latter serves as the evidence that the proposed approach combines with MOC works properly.

2. PASSING CENTER SWING BACK GRIDS (PCSBG) TECHNIQUE

The idea of the PCSBG technique in association with MOC is based on the need of resolving cell distortion due to the rotational motion of objects under study. This is mainly because every field component is positioned in the center of grid cell by MOC. All field quantities are calculable when the grid cell is stretched to a certain extent such that all changes in the cell measurement can be accurately computed and before irreversible damages were done to the grid cell. Consider a two-dimensional numerical model, an O-type concentric grid system, a circular cylinder is located at the center, and grid cells are trapezoidal in shape. Supposed that there is one layer of cells adjacent to the cylinder which will be stretched when the cylinder rotates. For each cell immediately next to the cylinder, one side of it will rotate concentrically with the rotating cylinder while the opposite side is fixed. As a result, the other two sides are tilted in the same direction. The area of each cell is found to be unaffected during the process

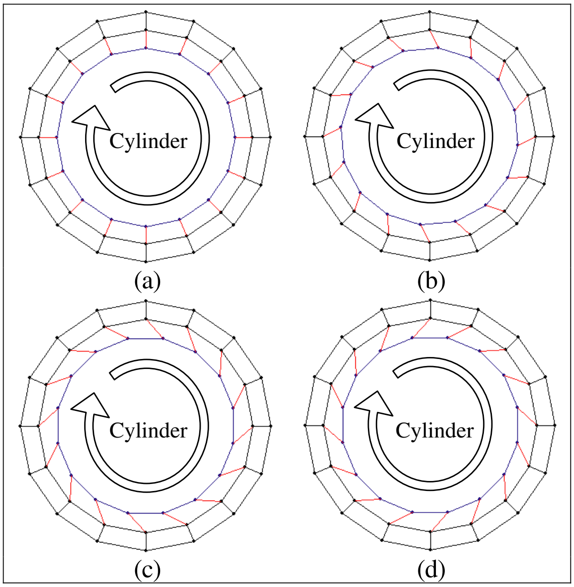

Figure 1. The passing center swing back grids (PCSBG) technique: (a) Cylinder is about to rotate, (b) cells next to the cylinder are stretched, (c) the grid points are about to pass the centroid, (d) grid lines swung back and swing back grids are ready for the next move.

despite the fact that cell has been skewed.

A sequence of diagrams illustrates how PCSBG functions are given in Figure 1. For clear demonstration a quite coarse body-conforming grid system is employed. It includes a solid cylinder in the center and only two layers of cells. The cylinder rotates clockwise as indicated. The outer layer of cells is fixed and represents the space. Cells in the layer immediately next to the cylinder are designated as swing back grids and will be stretched by the rotating cylinder. Figure 1(a) depicts that the cylinder is about to rotate from its initial position. A moment later, the swing back grids are skewed due to the rotation of cylinder as in Figure 1(b). At one particular instance of time, when each grid point on the cylinder side coincides with or about to pass the centroid of the grid cell as in Figure 1(c), the grid lines swing back as in Figure 1(d). Note that the area of each swing back grid cell stays constant when it is deformed and that all field magnitudes within each swing back grid seem impervious to the cell reformation when grid lines are swinging back. The latter is because MOC places all field components in the centroid of the grid cell.

3. MODIFIED O-TYPE GRID AND PCSBG/MOC

It is mentioned earlier that a body-conforming grid system is used in the numerical model for the presence of a rotating cylinder. Simulating the electromagnetic problems, unlike that in fluid dynamics related problems, requires a certain grid density domain-wide, i.e., there must be a sufficient number of grids for the component with the shortest wavelength to assure the scheme accuracy. The modified O-type grid showed in Figure 2 is adapted from the regular O-type grid which is devised to satisfy the requirement. As can be obviously observed, the number of grid is doubled as radius increases to a certain quantity such that the grid measurement along the circumferential direction is controlled within a specific range. It is also noticed that as indicated in Figure 2 the air gap is designated as an analogy to an electric motor in which there exists a thin layer of air between the stator and rotor. The gap is composed of a single layer of cells which are previously defined as swing back grids.

During the process, though some grid lines become dynamic, MOC has an accurate bookkeeping on every change in each swing back cell. MOC traces and updates the followings for every numerical time step: the normal vector, orientation and cell index of each grid on the surface of the rotating cylinder, and metric terms accounting for the geometric deformation of each swing back grid. Since the PCSBG approach has no effect on the cross-sectional dimension of the swing back grids, there

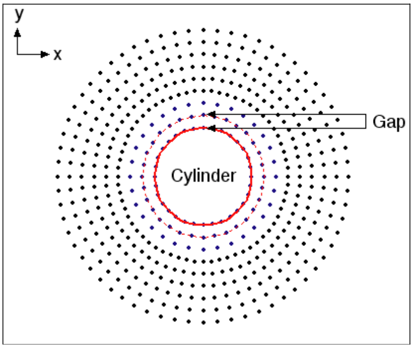

Figure 2. Diagram of the modified O-grid. The grid number is doubled from zone to zone.

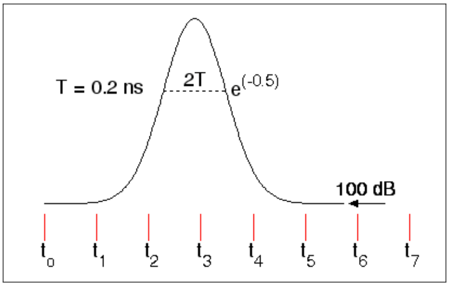

Figure 3. Diagram the Gaussian-form current with eight sampling instances.

is no need to make any adjustment in the numerical time step for these cells. Based upon the above reasoning, it is therefore suggested that PCSBG in conjunction with MOC can resolve the grid deformation difficulty caused by rotating objects.

4. THE CASE AND THE SETUP

With the aim of illustrating that the cylinder is rotating and radiating EM fields simultaneously providing the evidence of PCSBG together with MOC functioning properly, the following setups are arranged for clear demonstration. In the two-dimensional numerical model, the rotating cylinder is made of perfectly electric conducting material, 10 cm in radius, and carrying a surface current flowing in the axial direction but not along the curved surface. The current source has a Gaussian profile in the time domain with a pulse width of 0.2 ns measured from the peak (normalized to unity) to the value of $e^{(-0.5)}$ and is cut off at 100 dB level as shown in Figure 3. In addition, there are eight time instances differed by one third of one nanosecond at which a 2D plot of the electric field intensity over the whole computational domain is recorded. From the location of each sampling time one can tell the advancement of the current source on the rotating cylinder.

The Gaussian profile of the current source is measured about 1.92 ns from end to end. Accordingly, the highest frequency content is about 3.82 GHz corresponding to a wavelength of 79 millimeters or so. Providing that there are at least 10 grids for every wavelength the required grid density is 128 points per meter. The computational domain is set one meter in radius in addition to the cylinder. If the grid size in the radial and circumferential directions is set to be at least 160 points per meter, there are more than 160,000 grids in total. It is composed of five grid zones respectively with 144, 288, 576, 1152, and 2304 grids each layer. Moreover, to picture the evidence that PCSBG/MOC works properly, the cylinder is equally divided into an even number of segments such that segments carry currents (thick arcs), and those do not (thin arcs) are placed alternatively as shown in Figure 4.

If we set the time needed for the cylinder to rotate one complete cycle equal to the temporal duration of the Gaussian form (1.92 ns), then every point on the cylinder surface has an instantaneous angular velocity in the order of the light speed. For a cylinder having circular cross-section, at any point on its surface the instantaneous velocity is always perpendicular to the normal vector. Therefore, the relativistic effects have no role in this case. The application of boundary conditions to the cylinder surface carrying currents is driven from the following:

$$\hat{n} \times \vec{H} = 2\vec{J} \tag{1}$$

$$\hat{n} \cdot \vec{B} = 0 \tag{2}$$

$$\hat{n} \times \vec{E} = 0 \tag{3}$$

where $\hat{n}$ is the normal vector of the grid on the cylinder surface; $\vec{J}$ is the current flowing on the cylinder; $\vec{E}$ is the electric field intensity; $\vec{H}$ and $\vec{B}$ are the magnetic field intensity and flux density. Note that (2) guarantees that there are no electromagnetic fields with the magnetic field perpendicular to the surface radiated from the cylinder and that the electric field intensity polarized along the axial direction is assumed to be zero in magnitude on the cylinder surface as given in (3) since the cylinder is made of perfect conductor. The radiated electromagnetic fields are then of the transverse electromagnetic type.

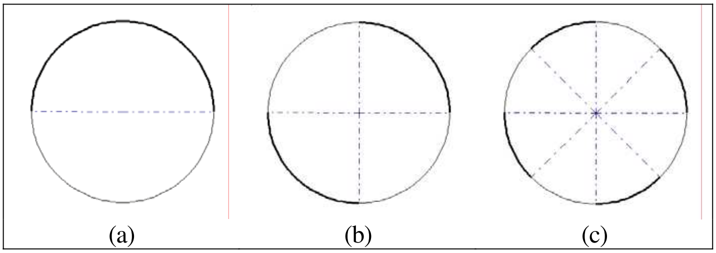

Figure 4. Currents around the cylinder: Thick arcs with currents, thin arcs without currents.

5. COMPUTATIONAL RESULTS

To indicate the orientation of the rotating cylinder in the plot, a line inside the cylinder is used to represent the angle-zero position as shown in Figure 5 where the cylinder is at rest and divided into eight segments. Four plots display four different electric field distributions at four different time instances. Note that the line coinciding with the x-axis indicates the orientation of the cylinder since it does not rotate. From this point on, when the cylinder rotates, it does it counter-clockwise. The next four plots in Figure 6 demonstrate the evidence that the cylinder is rotating and radiating electromagnetic fields at the same time where the cylinder is divided into four slices. With the cylinder rotates one complete turn within the pulse duration, referring to Figure 3, the first plot was taken at time t_4 which is just past the peak, and the line locates at an angle of more than 180 degrees. It is obvious that the electric fields form a symmetric whirlpool shape and propagate outward as a verification that the cylinder is rotating and radiating simultaneously.

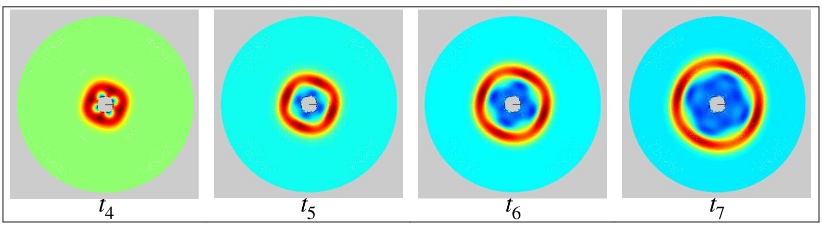

Figure 5. Electric field distributions: Cylinder is at rest and has eight segments. (Background: zero, bright: positive values, dark: negative values).

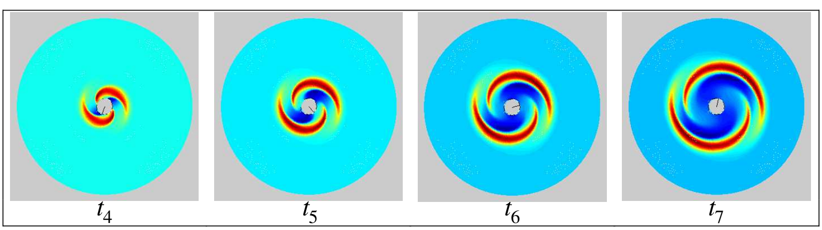

Figure 6. Electric field distributions: Four segments rotate counterclockwise one cycle. (Background: zero, bright: positive values, dark: negative values).

Another two efforts with different arrangements are carried out, and their results are given in Figures 7 and 8. In Figure 7, the cylinder is composed of two halves and rotates two rounds during the span of Gaussian pulse. At time t_3 it had already made more than one round and at time t_6 more than two rounds. A sequence of four plots showing the radiation electromagnetic fields from a rotating cylinder with eight segments are displayed in Figure 8 where the cylinder rotates with a

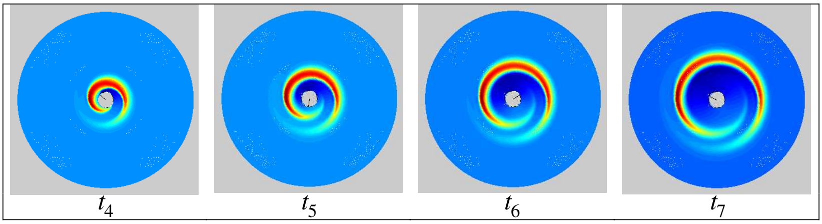

Figure 7. Electric field distributions: Two segments rotate counterclockwise two cycles. (Background: zero, bright: positive values, dark: negative values).

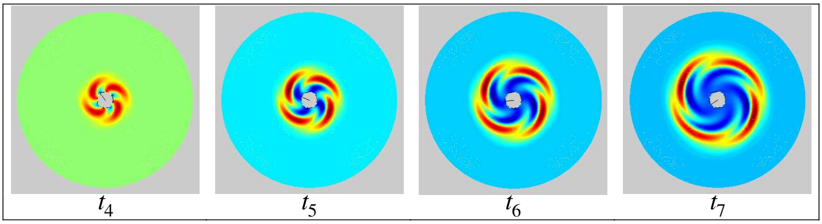

Figure 8. Electric field distributions: Eight segments rotate counterclockwise one half cycles. (Background: zero, bright: positive values, dark: negative values).

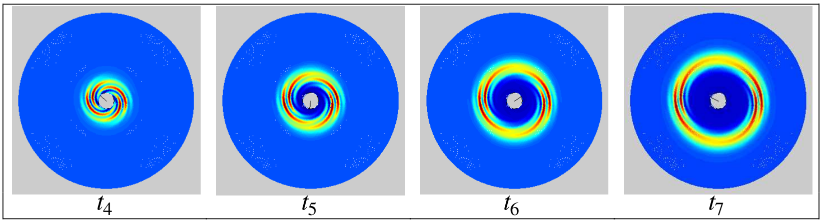

Figure 9. Electric field distributions: Eight segments rotate counterclockwise two cycles. (Background: zero, bright: positive values, dark: negative values).

slower angular velocity. A symmetric vortex structure was observed once again, another evidence of the success of the proposed approach. Finally, a set of four snap shots as in Figure 9 show the radiated electric fields from a eight-slice cylinder rotating one cycle for every 0.96 ns. The radiation pattern is structured by thinner band lines since the cylinder is finely divided and rotates faster.

6. CONCLUSION

The idea of passing center swing back grids (PCSBG) in association with the method of characteristics (MOC) has been proposed and validated to be a suitable approach in resolving the grid distortion problem due to the rotating objects. Radiated electromagnetic fields from a rotating, current-carrying cylinder are numerically simulated and illustrated. PCSBG/MOC is unique and planned to be directly applied to problems of the scattered electromagnetic fields by rotating objects under the excitation of Gaussian electromagnetic pulse in two- and three-dimensional models, especially, those with complicated shapes yet having symmetric structure where the relativistic effects have to be taken into consideration.

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