Calculating the Effects of Non-Uniform Ice Accumulation on Radome Performance by Ray Trace Analysis

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Abstract—The general effects of variable-thickness ice accumulation on radome performance have been studied by ray-tracing analysis. Results are presented for both clear ice and rime ice, which accumulate differently on a radome.

Keywords—radome; radome analysis; ray tracing; radome ice

I. INTRODUCTION

Radomes on aircraft are all subject to ice accumulation, and this ice is generally not uniformly distributed over the surface. In addition to the detuning caused by added dielectric thickness, there is antenna pattern distortion. These things need to be quantified early in the design process, before the design is fixed and parts are made. The method described in this paper allows these calculations to be made.

The analysis method employed is ray tracing. Until recently computers were too limited in speed and memory capacity to be useful for such an intense effort. Few prior attempts at ray tracing have been found in the literature, all for very limited cases. Tricoles [1] studied a very limited configuration in 1966 at a time when computers were cumbersome to use and execution times were long. Huddleston [2] made a much more comprehensive study in 1982, but again for limited applications. Computer resources at those times did not allow rapid and interactive computations of the kind now expected of analysis tools. The author knows of no prior art respecting ice.

The computer program used for this study was independently contrived without use of any prior art, beginning in 1990 and continuously updated as computational resources have improved. The most recent version can trace first and second order reflected rays. Other experts may have similar capabilities, but none have ever been brought to this author's attention.

These procedures only apply to radome structures at a sufficient distance from the source antenna that the ray-tracing method can be considered to be a valid approach, and to radomes that are reasonably uniform in design, thus precluding any of a long list of problems.

II. DESCRIPTION OF THE COMPUTATIONAL METHOD

This section describes the computational method used for this analysis. This is a generalized program, not one written

specifically for this problem. The method is provided here so that the reader may be better able to understand the results and potential error sources.

A. Radome surface model

The radome is modeled as a surface mesh of triangular facets, conforming to either the inside or the outside surface of the radome. The selection of the inside surface is required when one is calculating reflected rays because selection of the more readily available outside surface would introduce phase errors along these rays with respect to the direct rays. If only direct rays are to be calculated, such as with the subject of this paper, then the outside surface is a suitable reference.

The surface mesh must completely surround the coordinate origin, so that no ray can escape the radome without passing through some facet. No ray can re-enter the radome once it exits. No other conditions are imposed. Each facet is assigned a table of transmission and reflection coefficients, which may be different from those of adjacent facets. This is the feature that allows modeling of non-uniform panel structures and variable ice accumulations across the outer surface, albeit in a step-wise manner.

B. Panel structure model

The transmission and reflection properties of the panel are related to the panel internal structure and materials properties. These are calculated by a separate program and supplied to this program as a set of lookup tables. Ice accumulation is treated as part of the total radome panel by adding an additional layer of material to the panel structure.

C. Antenna model

This method analyzes the *effect* of a radome on an enclosed antenna, not the antenna itself. Thus, it is sufficient to represent only the aperture field of the source antenna, and this is easily done by defining an array of point sources, arranged and excited such that the aperture field is reasonably the same as that of the actual antenna to be used with the radome. For an array antenna, this is a trivial problem since the elements are already treated as point sources. For a continuous aperture, Huygens' principle is employed to represent a continuous aperture as an equivalent array of point sources.

One embellishment to the antenna model allowed by this program is that the user can define several aperture excitations for the array at the same time, with minimal impact on the execution time. Allowance is made for three excitations, accommodating a 2-axis monopulse antenna configuration

D. Antenna pattern generation

Calculated far-field antenna patterns are calculated as sequences of points. For any one point it is only necessary to trace rays from each antenna element to that point. The only ray characteristics of significance are radome-induced polarization, insertion loss and insertion phase delay. The complex summation of all rays from all antenna elements gives the relative field voltage for that point. In this program a separate summation is made for direct rays, first-order reflected rays, and second-order reflected rays, and these may be combined as desired.

It is necessary to strictly account for polarization, magnitude, and phase. These change at every transmission and reflection interface. At the end, it is necessary to calculate the phase delay of each ray based on the extra travel distance required to get to the distant observation point. This is why it is necessary to model the inside surface of the radome instead of the more readily available outside surface.

At each beam position, the gains of all patterns are normalized to the gain of the co-polarized no-radome sum beam at that beam position. No attempt is made to compare different beam positions within the program, or to calculate absolute gains.

E. Radome with ice simulation model

The transmission and reflection coefficients of a radome panel depend on frequency, incidence angle, and polarization. These properties are readily calculated for any number of panel layers, resulting in a number of interpolated lookup tables. There are many programs available to make these calculations.

For the purposes of the ice study, a simple A-sandwich (3-layer) radome was modeled at one frequency, with the usual surface coatings but without ice. Additional models were calculated with different amounts of ice added to various parts of the outside surface.

The radome itself was wholly notional in shape and design, as was the ice configuration. The radome had a simple circular arc representing a relatively blunt aircraft nose radome. It was not necessary to use a large number of facets for such a simple problem, so the surface normal differences from one facet to the next were set at approximately 5 degrees.

Ice accumulation depends on a large number of flight and weather variables. Both clear ice and rime ice are possible on a radome, but since rime ice may have a variable density and is unpredictable, it is more difficult to model. The dielectric constant and loss tangent of clear ice are approximately 3.17 and 0.007 respectively, which resembles the properties of other common dielectric materials. Clear ice accumulation is greater near the aerodynamic stagnation point, and tapers to a lesser thickness along the sides of the radome. Rime ice builds up more locally and tapers off more quickly.

III. CALCULATIONS AND RESULTS

A. Baseline simulation - Antenna only pattern

The end purpose of any radome analysis is to determine the effect of the radome system performance, which is the same as how the radome affects the source antenna far-field pattern. The source antenna was a simulated square array of horizontal half-wave slots in a ground plane. This configuration gives rise to vertical polarization. While it does not simulate any practical antenna, it does simulate an aperture field that could arise from an array of patches. A typical low-sidelobe distribution was applied to the elements, both a sum distribution and an azimuth difference distribution. In keeping with more modern systems that can adjust distributions upon receive in the system computer, these were modeled as independent distributions, not by simulating a four-port hybrid combining network. Fig. 1 shows this baseline antenna pattern. The peak of the main beam is normalized to itself, 0 dB, and serves as a reference for all other patterns.

B. Performance with no ice

Since the purpose of this study is to characterize the effects of added ice on a radome, initial calculations were made with no ice. Fig. 2 shows the antenna and radome performance for the simulated gimbal at the nominal boresight position. This appears to be identical with the no-radome pattern, but in fact there is a small amount of insertion loss and a very small amount of pattern distortion. There is also some cross-polarized energy generated by the panel curvature, but in this case that level is over 330 dB below the peak of the sum beam (up from a noise floor of -1000 dB), and is not significant. It is not always that low. This is the information that is normally given to the systems engineer, along with some phase information, to construct an angle-of-arrival table. Since the gimbal rotates the antenna about the center of curvature, all patterns of the radome without ice are identical for this study. This is not true in general.

Figure 1. No-radome antenna pattern.

Figure 2. Pattern with radome only, 0 degrees scan angle, no ice.

C. Clear ice simulation

Clear ice thickness was modeled as a cosine-squared distribution with respect to the aspect angle to the aircraft flight vector. In actual practice the ice profile is usually not predictable with an equation, and indeed may not even be monotonic, but this profile serves the present purposes. This is illustrated in Fig. 3. Note that the thickness at 45 degrees is less than it is at 0 degrees, and there is a definite variation in thickness across the antenna field of view that should lead to boresight shift.

Fig. 4 shows the pattern for the nominal boresight case. There is increased insertion loss, as expected, and some minor beam broadening, but not large amounts. The ice is actually more than a quarter-wave thick at the center, yet the insertion loss is still less than 1 dB. The most pronounced effect is on the sidelobes, which are more affected by the ice profile.

Fig. 5 shows the effect of clear ice at a 45 degree scan angle. Now the effects of the ice layer are becoming prominent. The insertion loss is less than at 0 degrees, but that is because the average thickness is less. The taper on the thickness causes the monopulse null to shift toward the aircraft nose by a noticeable amount, and the same is true of the sum beam. This shift would be cause for concern for some radar systems. There is also an increase in the cross-polarized energy from -330 dB to -110 dB, but it is below the scale of these plots and of no practical significance. If this had been a circularly polarized antenna with a differently shaped radome, the levels could easily have been very significant, perhaps to the -20 dB level. While in some systems -20 dB is low enough, in many others it is not acceptable.

Note that the null depth appears to be diminished, but this may be an artifact of the simulation. The actual pattern points calculated may have skipped over the exact bottom of the null.

Figure 3. Notional clear ice configuration.

Figure 4. Radome and clear ice at 0 degrees scan.

Figure 5. Radome and clear ice at 45 degrees scan.

D. Rime ice simulation

Rime ice is a bit different from clear ice in that it is lumpy, not smooth, and it may have a variable density that is not easily characterized. What is known about rime ice is that it stacks up on the front of the radome. A notional configuration is shown in Fig. 6. For this configuration the dielectric constant is assumed to be the same as for clear ice, since it serves to illustrate the concept.

This amount of rime ice happens to be about as wide in extent as the antenna aperture itself. Thus there should not be a large effect at nominal boresight, as Fig. 7 shows. The only clear difference is in the area of the sum pattern first sidelobes. If one looks closely, there is also some added insertion loss.

As the beam moves off boresight the effect of this patch of ice becomes pronounced. Fig. 8 is for a scan angle of 20 degrees. The sum pattern is actually breaking up, having lost one sidelobe completely. The difference pattern is beginning to show the two peaks at different heights, which also means that the shape of the null is beginning to show some skew.

Fig. 9 is at 40 degrees of scan and the boresight error is less than it was at 30 degrees, but not much less. Both the sum and difference beams remain distorted.

At the mechanical scan angle of 60 degrees, Fig. 10, the pattern has fully recovered except for one sum beam sidelobe which apparently is still being slightly occluded by the ice.

This progression of plots shows what could be expected of radome performance in the presence of rime ice. The maximum error of over two degrees would be fatal to a fire-control radar system, but would be acceptable for other systems.

Figure 6. Notional rime ice profile.

Figure 7. Pattern with rime ice at 0 degrees scan.

Figure 8. Pattern with rime ice at 20 degrees scan.

Figure 9. Pattern with rime ice at 40 degrees scan.

Figure 10. Pattern with rime ice at 60 degrees scan.

This simulation was for a relatively simple radome structure with only one degree of curvature, and with the antenna array relatively close to the radome inner surface. If the antenna had been closer to the center of the radome the results would have been different. Had there been two degrees of curvature, there would have been substantially more complexity to the results. If the ice had accumulated differently, the results would have been different. The author's point is that every situation is different and it is difficult to generate many standard rules for rapid evaluation.

IV. SUMMARY CONCLUSIONS

Ice on a radome, indeed anywhere on an aircraft, is a serious issue. This computer program was originally written for another purpose, hence the reflected ray capabilities, but the method has proved to be very useful to the study of almost any radome problem, the effects of ice accumulation being the most far-reaching yet studied. It can also be used to look at radome damage effects and the impacts of repairs. To the author's knowledge, no other program presently can do this.

Most of the effects shown herein could have been estimated by other means. However, analysis of step discontinuities, wedges, and blockages of other types all involve artificial situations that can only estimate the magnitude of the errors, not quantify them in a practical way. This method can closely calculate actual boresight error and pattern distortion data for situations that cannot be easily modeled by these other means.

This method is admittedly a brute-force method, fraught with a plethora of poorly supported assumptions, questionable approximations, uncontrolled error sources, and potentially very long execution times. There is no practical way to calibrate the results other than to compare with final system testing. However, this still is an effective means to screen designs at a time when design changes can be made. In the case of ice accumulation, the question is perhaps whether or not anti-icing or de-icing measures need to be taken. This method provides the information required to make that decision.

REFERENCES

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