VERIFYING WIRE-GRID MODEL INTEGRITY WITH PROGRAM "CHECK"

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Abstract

A wire-grid model of a complex surface such as an aircraft consists of hundreds of "vertex" points joined by hundreds of wires or "links". A wire antenna analysis program such as NEC is used to find the currents on the wires. The formulation within NEC imposes restrictions on the geometry of the wires, which limit the length of "segments" compared to the wavelength, the radius compared to the wavelength, the ratio of the segment length to the radius, and so forth. This paper collects these limitations together into a set of "modeling guidelines". The "integrity" of a wire-grid is its ability to represent the electrical behaviour of the continuous surface that it models. An important aspect of integrity is conformance to the "modeling guidelines". Gross errors creep into complex grids: repeated wires, omitted wires, wires of zero length. More subtle errors which violate the "modeling guidelines" can lead to incorrect current distributions and misleading radiated or scattered fields from the wire-grid when solved with the NEC code.

This paper describes a program called CHECK which examines an input geometry file for the NEC program for conformance to the "modeling guidelines" by each individual wire, by wires forming junctions, and by pairs which do not join but are closely spaced. CHECK tabulates "notes", "warnings" and "errors" to aid the user in assessing the degree to which the model satisfies the guidelines. CHECK systematically finds all the guideline violations in a model. CHECK produces lists of wires for display with computer graphics to show the location of each type of problem that CHECK finds. The guideline violations found by CHECK inherently suggest improvements that can be made to the wire-grid.

1. Introduction

Wire-grid models are often used to represent aircraft, helicopters and ships to determine the performance of their antennas, or their radar cross-section, at frequencies where their dimensions are comparable to the wavelength. A moment-method code such as the "Numerical Electromagnetics Code"(NEC)[1] is used to calculate the current flow on the wires of the grid, and thence the radiated or scattered fields. Grids are usually quasi-orthogonal sets of wires dividing the surface into nearly-square cells of roughly uniform size. The task of constructing a wire-grid model starts with the design of the grid: a target segment length is chosen, and the wires are drawn onto three-view drawings, or often are drawn onto an actual scale model. Building the grid consists of deriving the coordinates of all the vertex points in the grid from drawings, and then defining the wires themselves as "links" joining the vertices. Finer subdivisions, that is, smaller cells, are often used in critical regions of the structure such as near antenna feed points. Radii are assigned to the wires in order to produce a model which is electromagnetically equivalent to the structure being modeled[2,3].

The wires of a grid must conform to certain specific rules which arise from the mathematical and numerical formulation of the NEC code. This paper groups these restrictions as "modeling guidelines". The term "integrity" has been used to describe the correctness of a wire-grid[4]. Here, "integrity" will be taken to have three aspects: that the grid is free from gross errors; that the grid conforms to the "modeling guidelines"; and that the grid is able to reproduce the electrical behaviour of the surface it represents. An error-free grid accurately expresses the model-builder's intention. Conformance to the modeling guidelines is essential, because NEC cannot be expected to compute physically reasonable currents for the wires of a grid that violates the guidelines. If a grid satisfies the guidelines, then it is expected that the currents computed by NEC would correspond to those on the wires of a real wire cage. Whether the cage has the same electrical behaviour as the continuous surface it represents can only be firmly established by comparison with valid measured data. This is the "model validation" problem discussed in reference [5].

Mistakes are easily made in preparing wire-grid models. Certain gross errors are found because NEC crashes or terminates with an error message. Others are not found by NEC in this way, and may exist in a model over many "runs" of NEC before being discovered. NEC will calculate currents and fields for structures which violate the guidelines: NEC itself does no checking. The model-builder often searches the model for errors using computer graphics to display the wire-grid, representing each wire by its centerline. It is not obvious from such graphics that a wire has too many or too few segments, that its radius is so large that the wire overlaps another wire, that a short wire lies inside the volume of another wire, and so forth. To avoid the wasted computational effort from "running" models containing such errors, program CHECK was written to verify model integrity systematically, wire by wire, and junction by junction, against the "modeling guidelines". CHECK finds all violations of the guidelines.

This paper summarizes the rules set out in the NEC User's Guide[6], and the authors' experience, into "modeling guidelines". CHECK's application of these guidelines in assessing model integrity is briefly described. An example of a wire-grid model of an aircraft is used to show the nature of the errors found by CHECK, and to illustrate how CHECK's errors suggest improvements to the model.

2. NEC's Moment Method Solution of the EFIE

A wire-grid is specified to NEC by giving the endpoint coordinates of each wire, and a radius for each. NEC finds the currents flowing on the wires by satisfying an "electric field integral equation"(EFIE) stating the boundary condition that at any point on any wire, the net tangential electric field must be zero[7,8,9]. The net electric field is made up of the source field plus the sum over all the wires of the field due to the current flow on each individual wire. NEC obtains an approximate solution to the EFIE with the "moment method". NEC's solution is described in detail in the "Program Description - Theory" manual[7]. The following reviews key steps and assumptions.

The wires of the grid are assumed to be "thin", that is, to carry current flow in the axial direction only, with no circumferential component. Further, the axial current is assumed to be uniformly distributed about the periphery of the wire[7,8].

NEC's solution proceeds by subdividing each wire into "segments". On each "segment" the current is assumed to vary with distance according to "basis functions" having a constant-plus-sine-plus-cosine form, with three unknown, complex-valued coefficients for each segment. Within a wire, at the boundaries between segments, KCL is enforced, and the charge density is made continuous. At junctions between wires, both KCL and a charge condition called the King-Wu junction constraint[7,10] are enforced. These conditions allow two of the unknowns for each segment to be eliminated, leaving one complex-valued unknown to be found per segment.

To find the values of these coefficients, NEC uses the "moment method" to enforce the EFIE at a "match point" at the center of each segment. This calls for the computation, at any match point, of the electric field due to the current flow on each segment in the wire-grid. The electric field is expressed as an integral over the cylindrical surface of the wire segment, of the current density **J** times a kernel function which is the free-space Green's function for a current-element[7]. The current density **J** is assumed to flow uniformly over the segment surface. It must be integrated around the segment circumference, and then over the length of the segment.

TABLE 1

Summary of the "modeling guidelines".
Δ = segment length
a = wire radius
λ = wavelength

INDIVIDUAL SEGMENTS	WARNING	ERROR
segment length	$\lambda/10 < \Delta < \lambda/5$	$\Delta > \lambda/5$
radius	$30 < \lambda/a < 100$	$\lambda/a < 30$
segment to radius ratio	$0.5 < \Delta/a < 2$	$\Delta/a < 0.5$
JUNCTIONS		
segment length ratio		$\Delta_{big}/\Delta_{small} > 5$
radius ratio	$5 < a_{big}/a_{small} < 10$	$a_{big}/a_{small} > 10$
segment to radius ratio	$2 < \Delta/a < 6$	$\Delta/a < 2$
match point	segment center within half a wire radius of another wire's surface.	segment center lies within the volume of another wire.
WIRE SPACING		
crossed wires		wire axes cross
overlaps		wire axes pass closer than the sum of the wire radii
near misses	wire axes pass closer than 1.5 times the sum of the wire radii	
proximity	wire endpoints closer than 1.5 times the sum of the wire radii	wire endpoints closer than the sum of the wire radii

Two levels of approximation are used in evaluating this surface integral. In the "normal thin-wire kernel" or "thin wire kernel" approximation, the circumferential integration is approximated by a single point. This amounts to assuming that the current flows along the axis of the wire, and collapsing the surface integration to an integral along that axis.

A better approximation is the "extended thin-wire kernel" or "extended kernel"[7]. The circumferential integration is expressed as a series solution in powers of the wire radius. The lowest term is the "thin wire" kernel approximation. Retaining the second term of the series obtains the "extended kernel" approximation and better accounts for phase differences due to the current being spread over the wire surface rather than concentrated on its axis. The "extended kernel" approximation is only used for segments that are co-linear and of the same radius. It is not used at bends in wires or for segments of different radius.

NEC forms a matrix equation in which each row of the matrix expresses the EFIE at the match point at the center of one of the segments of the wire-grid. The matrix is solved for the coefficients of the current expansion. NEC has been extensively tested on simple interconnections of wires. The User's Guide makes some specific recommendations on the lengths of segments, wire radii, and so forth which have been found to lead to physically reasonable solutions. These recommendations, and others, will be called "modeling guidelines" and are discussed in the following.

3. Modeling Guidelines

The advice tendered in the NEC User's Guide and the authors' own experience are assembled in this section into the "modeling guidelines" of Table 1. If a wire-grid which violates NEC's basic assumptions is input to the NEC program, no warning is given of unreasonable input geometry. NEC computes currents and fields which may be physically meaningless and quite misleading. The "modeling guidelines" help to identify those structures which NEC can solve correctly, and conversely point out structures for which NEC is not likely to obtain a correct solution. The "modeling guidelines" can be regarded as "necessary conditions" for NEC to correctly solve for the currents on a wire-grid structure. But they are not "sufficient conditions" for if a wire-grid model satisfies the modeling guidelines, the wire-grid is not necessarily a good electrical representation of the surface.

The CHECK program compares an input geometry to the "modeling guidelines" and identifies violations. Table 1 is organized into conditions which must be satisfied by individual wires, conditions which must be satisfied by wires which are part of a wire junction, and conditions that must be satisfied by pairs which do not join but are closely spaced. The specific modeling guidelines are presented in the following.

3.1 Individual Wire Guidelines

Segment Length

NEC requires that each wire be subdivided into "segments" of length nominally comparable to $\lambda/10$. There is significant loss of accuracy if segments are allowed to be as long as $\lambda/5$. Ref. [11] remarks that segments as long as 0.14λ "may be acceptable on long straight wires or non-critical parts of a structure". Segments as short as $\lambda/20$ may be required "in modeling critical regions of an antenna"[11]. The "modeling guidelines" in Table 1 accept segments shorter than $\lambda/10$ without comment, issue "warnings" for segments between $\lambda/10$ and $\lambda/5$, and consider segments longer than $\lambda/5$ to be in "error". Thus the "modeling guidelines" of Table 1 may not be sufficiently conservative. Perhaps an "error" should be issued for segments longer than 0.14λ.

Wires must not be so finely subdivided that the segment length is less than 1/1000 of a wavelength, but this is rarely a problem.

Equal-Area Wire Radius

For an orthogonal grid of wires representing a solid surface, the segment length determines the "cell size" of the wire-grid. The highest frequency of interest usually determines the segment length: it is set at 0.10λ or perhaps 0.14λ at that frequency. The radius is then chosen according to the "equal surface-area rule"[2,3], stating that the total surface area of the wires in one direction is made equal to the area of the surface. For a square grid cell of side length Δ, the "equal-area rule" radius is $\Delta/2\pi$.

Thin Wires

For analysis by NEC, the wires of the scatterer must be "thin" because the current is assumed to flow axially on the wire with no circumferential component. The NEC User's Guide[6] specifies that $2\pi a/\lambda \ll 1$ or $a \ll 0.159\lambda$, where a is the wire radius. In Table 1, wires are considered to fully satisfy the guideline if they are thinner than $\lambda/100 = 0.01\lambda$. As "rule-of-thumb", wires fatter than $\lambda/30 = 0.0333\lambda$ are too fat to be considered "thin". Thus in Table 1 a wire thicker than $\lambda/30$ is considered an error. This is 20 percent of the User's Guide's figure of 0.159λ.

In the literature[2] "thin wires" are usually defined in terms of the length to radius ratio. Thus let

$$\Omega = 2\ln(L/a)$$

where L is the wire length and a is the wire radius. If $\Omega > 10$ the wire is considered "thin" in the sense that the current is primarily axial with negligible circumferential current flow. Thus a "thin wire" has

$$L > a\,e^{5}$$

or $L > 148a$. Segments for analysis by NEC rarely have such a large segment length to radius ratio, hence are often not "thin" in the sense of Ref. [2].

Segment Length to Radius Ratio

NEC requires that the segments be kept sufficiently long compared to their radius. The NEC User's Guide[6] recommends that, with the "thin wire kernel", the ratio of segment length to wire radius should be maintained greater than 8, but states that "reasonable current solutions" are obtained with the segment to radius ratio as small as 2. Fig. 1(a) shows a wire drawn as a cylinder. The length of the wire is 8 times its radius. Fig. 1(b) shows the same wire subdivided into four segments, so that the length of each segment is twice its radius. With the "extended thin wire kernel"[6], Δ/a should be maintained greater than 2, with "reasonable current solutions" down to 0.5. Fig. 1(c) shows segments of length equal to half the wire radius. The authors' experience is that with the "extended kernel" the restriction $\Delta/a > 2$ should be strictly observed. The "extended kernel" is recommended for analysing all wire-grid models. Table 1 thus assumes that the "EK" card has been included in the input geometry file.

By drawing the wires of a wire-grid including the wire radius, as in Fig. 1 and the figures which follow, the user develops a sense of a "wire" as an entity with volume rather than as a mere centerline. Recalling the ratios depicted in Fig. 1 allows the user to pinpoint segments in a drawing which are in violation of the segment-to-radius ratio guidelines. But in viewing a drawing of a complex wire-grid such errors are easily missed.

NEC uses the full "extended kernel" formulation only for segments embedded in a wire, or for segments on co-linear wires of the same radius. At bends in wires, the NEC User's Guide[6] comments that the normal "thin wire kernel" is used. The Appendix of the NEC Theory manual[7] discusses the "end terms" associated with segments at bends, and points out that the "end terms" associated with the "thin wire kernel" are always used at bends, rather than the "end terms" of the "extended thin wire kernel". In fact, the "thin wire" end terms are used for any segment which forms a junction with another segment which is not co-linear or which has a different radius.

In a wire-grid model of a solid surface, almost all of the wires have only one segment and form junctions with other segments at both ends. Thus NEC does not use the full "extended kernel" for most of the interactions in a wire-grid. The "thin wire kernel" rules must be used to assess the segment length to radius ratio. In CHECK, the segment-to-radius ratio is verified for each individual segment according to whether the EK card has or has not been invoked. Then, for segments that are part of wire junctions, the segment-to-radius ratio is verified against the no-EK rules, as described below.

3.2 Wire Junction Guidelines

Segment Length and Radius at Junctions

Any pair of wires in the input geometry that have a common endpoint form a junction. NEC allows charge to accumulate on wires immediately adjacent to wire junctions, which is distributed among the wires according the King-Wu relationship[7,10]. This relation has poor accuracy if the ratio of the largest to the smallest wire radius is too large. As a "rule-of-thumb", Table 1 recommends that the ratio of the largest to the smallest radius not exceed 5, and considers a radius ratio greater than 10 to be an "error". Also in Table 1, it is recommended that large differences in segment length be avoided for pairs of wires which are part of a wire junction. Thus for any pair of wires the larger segment length divided by the smaller segment length must be less than five. The purpose of these restrictions is to ensure that segments forming a junction will not be too dissimilar in segment length or radius.

Fig. 2 depicts two wires forming a junction with the segment length on one wire five times that on the other. Geometrically, this is a very large difference in segment length. Fig. 3(a) illustrates that a radius ratio of five is quite a large step in radius. In Fig. 3(b), a ratio of ten is an enormous change. Including the wire radius in a drawing of a wire-grid makes large radius steps quite visible.

Match Point Errors

Wires are cylinders of a specified radius, hence occupy a volume of space. When two segments have a common endpoint and so form a junction, the "match point" at the center of either segment is required to lie outside the volume of the other segment[6]. Non-physical currents may be computed if this guideline is violated. The guideline restricts the segment length and the wire radius of wires forming junctions according to the angle at which the wires join. This is illustrated in the following examples.

Fig. 4 illustrates a "match point error" for wires forming a junction at a shallow angle. The center of the segment adjacent to the junction on wire #1, marked with a cross in Fig. 4, lies inside the volume of wire #2. In preparing a wire-grid representation of a complex surface, match point errors are often created inadvertently, and must be identified and removed, before meaningful computations can be done.

When the angle between wires is wider, as in Fig. 5, then the match point on the first segment of wire #2 lies outside the volume of wire #1. To alert the user that a match point is very close to the surface of another wire, a "warning" condition exists if a match point lies closer to the surface of another wire than one-half of the radius of that wire.

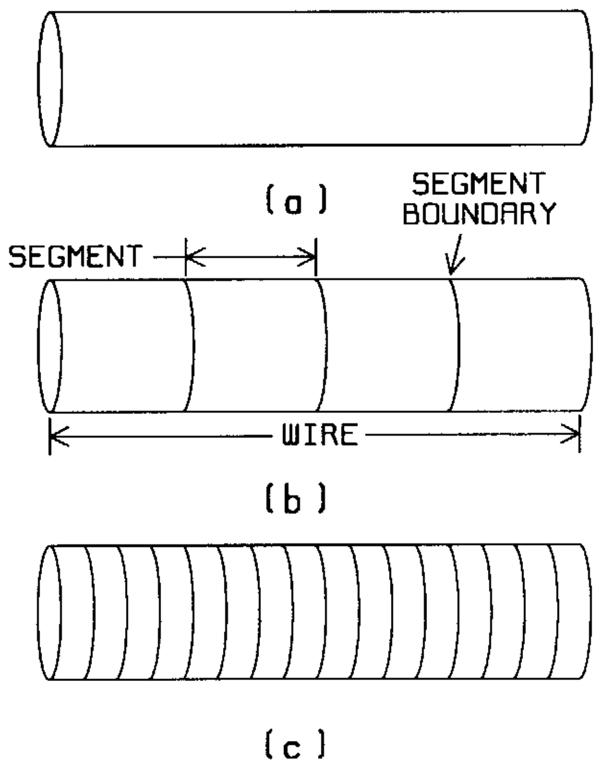
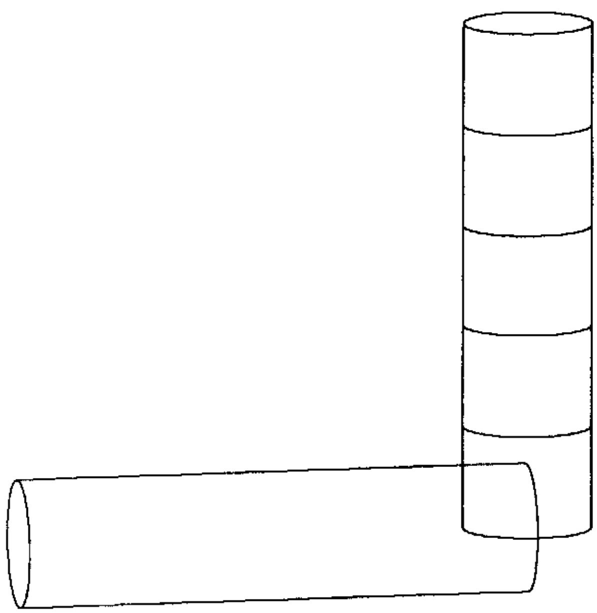


Figure 1 Wires with various segment length to radius ratios.
(a) Segment-to-length ratio equal to 8.
(b) Segment-to-length ratio equal to 2, an "error" without the EK option.
(c) Segment-to-length ratio equal to 1/2, an "error" even with the EK option.



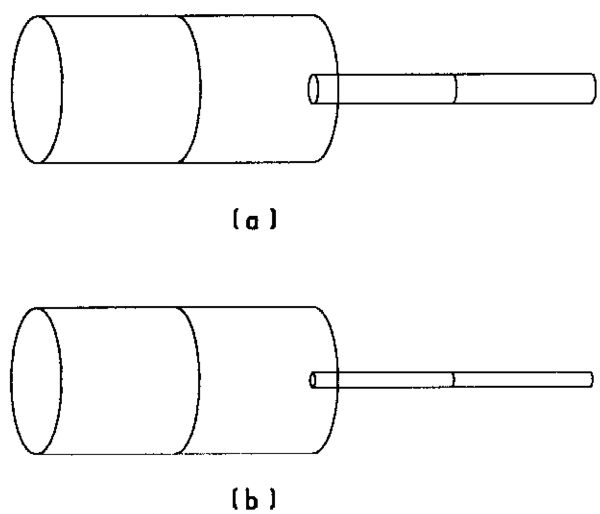


Fig. 2 Wires forming a junction with a segment-length to segment-length ratio of five.

Fig. 3 Wires forming junctions with various radius ratios. (a) Radius ratio equal to 5, a "warning" condition. (b) Radius 10, an "error" condition.

Fig. 6 shows that match point errors can occur even if the angle between wires is nearly 90 degrees. Thus when the segment length on one wire is less than twice the radius of the other, the match point can lie inside the volume of the other wire. If the angle between the wires in Fig. 6 were exactly 90 degrees, then the match point would lie on the surface of the endcap of wire #2. This is considered to be a "match point error". Fig. 7 shows the case where the angle is greater than 90 degrees. The match point lies outside the volume of wire #2, but very close to the surface of the endcap. This is a poor construction. When the match point lies within half the radius of wire #2 of the endcap, then a "warning" condition exists in the "modeling guidelines" of Table 1.

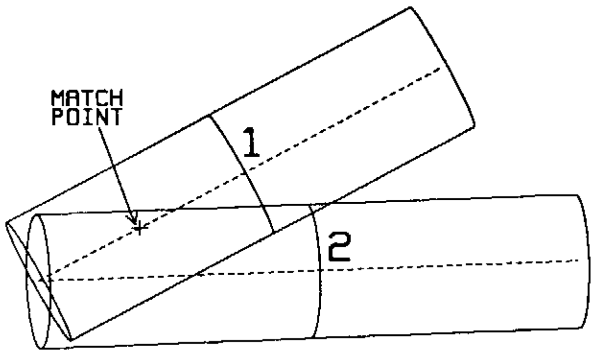


Fig. 4 Wires #1 and #2 form a junction at a shallow angle. The match point at the center of the first segment of wire #1 lies inside the volume of wire #2, a "match point error".

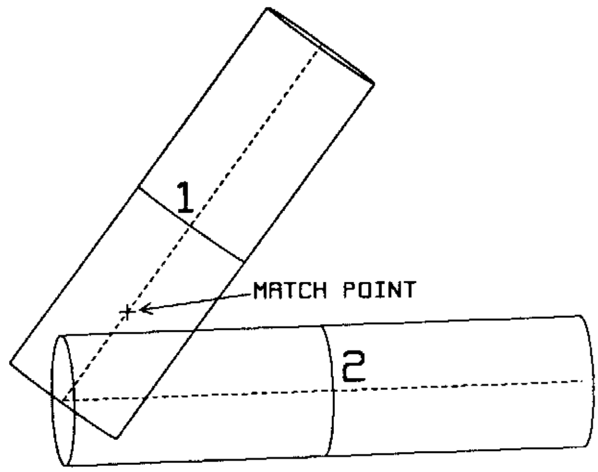


Fig. 5 Wires #1 and #2 form a junction at a wider angle than in Figure 4. The match point on the first segment of wire #1 now lies just outside the volume of wire #2, but within half a radius of the surface, giving rise to a "match point warning".

Segment to Radius Ratio at Junctions

Because the "extended kernel" is not applied to segments at wire junctions in a wire-grid, the criteria for the "thin wire kernel" must be applied for segments which are part of junctions. The segment length to radius ratio should be maintained greater than 8, to fully satisfy the NEC manual's recommendations. But for the wires of a wire-grid where the radius has been found by the "equal-area rule", the segment length to radius ratio is 2π or about 6.28. This falls in NEC's "grey area": not sufficiently large to be fully acceptable, yet much larger than the minimum value of 2. For assessing segment to radius ratios at junctions, values greater than 6 have been considered acceptable in the CHECK program. Thus grids using the "equal-area radius" do not generate warnings by the criteria of Table 1. Values less than 2 are considered "errors" in Table 1.

3.3 Wire Spacing Guidelines

In constructing wire-grids, a common mistake is to regard the "thin" wires as infinitely thin, hence mere line segments. In this erroneous view, wire centerlines can pass one another as closely as desired. Parallel wires can be as closely spaced as desired as long as the centerlines are distinct. This viewpoint tends to be reinforced by the common practice of drawing the wire-grid by depicting each wire with its centerline. It is much more useful to visualize wires as cylinders of a specified radius. Then wires must be spaced by a distance at least as great as the sum

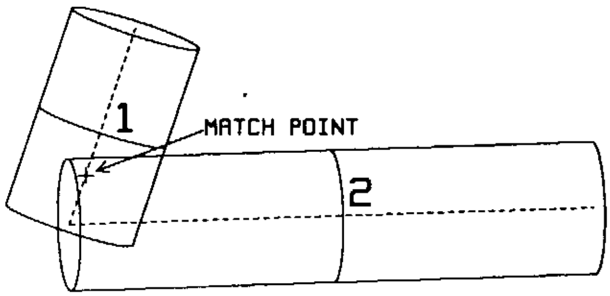


Fig. 6 Wires #1 and #2 form a junction at an angle slightly less than 90 degrees. The match point at the center of the first segment of wire #1 lies just inside the volume of wire #2, a "match point error".

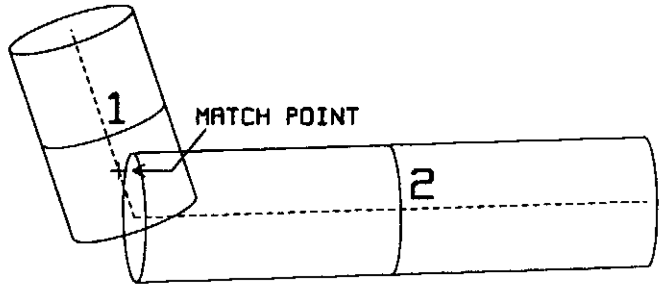


Fig. 7 Wires #1 and #2 form a junction at an angle slightly greater than 90 degrees. The match point at the center of the first segment of wire #1 lies just outside wire #2, but within half a radius of the surface, giving a "match point warning".

of their radii, otherwise they would overlap and be physically connected. This limits how closely parallel wire centerlines can be placed. It also limits how closely perpendicular wires may pass one another in space, without forming a wire junction.

It is difficult to obtain guidance from the literature on how far apart wires should be spaced in order that the "thin wire" assumption be valid. The NEC User's Guide[6] recommends that wires be "several radii apart". Ref. [3] suggests that parallel wires must be at least several diameters separated in order to satisfy the "thin wire" assumption. Perpendicular wires which pass one another extremely closely will not satisfy the "thin wire" assumption of current which flows axially only with no circumferential variation. Nor would the "thin wire" assumption be valid for a wire which passes very close to an open-circuited endpoint of another wire.

Crossed Wires

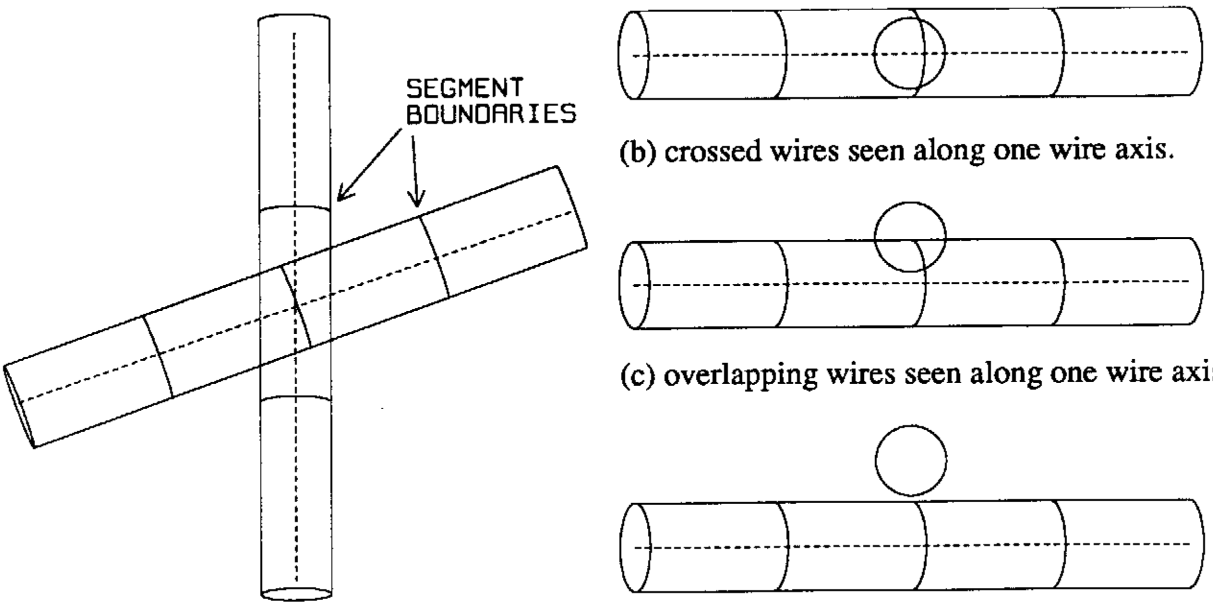
Fig. 8(a) shows a pair of wires whose axes intersect, seen from above. Fig. 8(b) shows the same wires seen along the axis of the thinner wire. The wires intersect. Physically the wires form a junction. But the common point is not a segment boundary on one of the wires, hence NEC will not form a junction between the wires. The configuration is a "crossed wires error". It makes little physical sense to form a junction between nearly-parallel wires, of the kind shown in Fig. 9(a). The configuration puts match points on each wire inside the volume of the other wire. This geometry is a "crossed-wires" error.

Overlapping Wires

Fig. 8(c) shows a pair of wires, whose centerlines do not have a common point, hence do not "cross". But the distance of closest approach of the two wire centerlines is smaller than the sum of their radii, hence physically the wires must "overlap", that is, form a junction. NEC does not form junctions between such wires. The geometry illustrates an "overlap" error. Fig. 9(b) shows nearly-parallel wires which are so closely spaced that they overlap. Overlap errors are common in preparing wire-grid models of complex surfaces, and must be cleared before meaningful computations can be done.

Near Misses

Parallel or nearly-parallel wires must be sufficiently far apart that the assumption that the current is uniformly spread about the periphery of the wire remain valid. Wires which nearly cross must be spaced sufficiently far apart that the "thin wire" assumption of current flowing axially, with uniform distribution about the wire periphery, remains valid. If a spacing requirement of several wire diameters were used, then these assumptions could be reasonably guaranteed. But in a typical wire-grid model, a great many of the wires are closer than several



(a) crossed wires seen from above.

(b) crossed wires seen along one wire axis.

(c) overlapping wires seen along one wire axis.

(d) a "near miss" seen along one wire axis.

Figure 8 A pair of wires which pass one another at a wide angle.

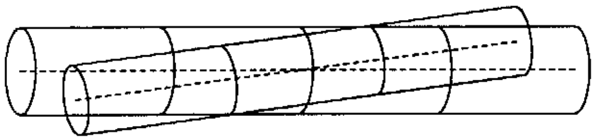
diameters. The modeling guidelines to be enforced in the CHECK program must be chosen to avoid a great many error messages of little importance. Thus CHECK uses limits chosen to alert the model-builder to very closely spaced wires, rather than to guarantee that the "thin-wire" approximation is fully satisfied.

Fig. 8(d) shows wires that are barely far enough apart to avoid an overlap. If the shortest distance between the wire centerlines is less than 1.5 times the sum of the wire radii, then the geometry results in a "near miss" warning. Fig. 9(c) shows nearly-parallel wires which are very closely spaced. The shortest distance between the wires occurs between one end of the smaller wire and the centerline of the larger. The geometry is also a "near miss warning". "Near misses" have not been accorded the status of "error". For a complex wire-grid model, "near miss" warnings and notes are usually evidence of dubious constructions.

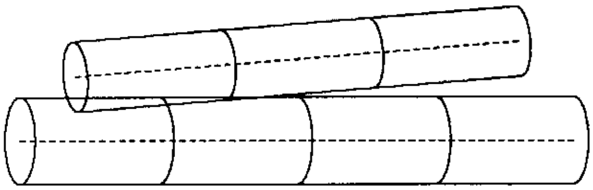
Proximity Errors

Fig. 10 shows a pairs of wires with endpoints very close to one another, without sharing a common point and hence forming a junction. Such constructions sometime occurs in modeling physically-distinct wires with an insulating gap between them. The user should be wary of relying on the NEC code to correctly compute the coupling between such wires.

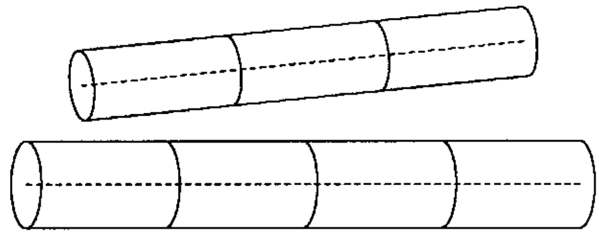
The construction of Fig. 10 often occurs implicitly in complex wire-grids when the two wire ends are joined by a third wire which is very short, and often quite fat compared to its length. The geometry might model a step change in the surface represented by the wires. The length of the joining wire, d, is thus comparable to its radius. This might be acceptable for co-linear wires, where the "extended kernel" is used, and the radius of all three wires are the same, for then the segment length to radius ratio can be as small as two for acceptable accuracy. But if the wires are not co-linear, as is usually the case in wire-grids, or if the radius changes from one wire to the next, then the "extended kernel" is not fully used, and a segment to radius ratio of 2 is too small. The resulting interconnection may not be the best practice in wire-grid modeling and might be better avoided.



(a) crossed wires.



(b) overlapping wires.



(c) a "near miss".

Figure 9 A pair of wires which pass one another at a shallow angle, hence are almost parallel.

The "modeling guidelines" of Table 1 draw attention to such interconnections when the spacing of the wire ends is comparable to the wire radius. Thus if the gap "d" between any two wire ends is less than the 1.5 times the sum of the radii of the two wires, then Table 1 specifies a "proximity warning". If the gap between the ends is less than the sum of the wire radii, then the construction leads to a "proximity error". These warnings or errors do not depend on whether a third wire "fills" the gap. If the gap is indeed closed by a wire, then a "proximity warning" is of little importance, but a "proximity error" means that the joining wire is likely too short compared to its radius. If no wire fills the gap, then a "proximity warning" is more serious and should be remedied by changing the geometry. The purpose of "proximity warnings" and "errors" is to draw attention to such constructions, to encourage the model-builder to rearrange the geometry to eliminate such poor practice.

4. Functions Performed by CHECK

CHECK searches the geometry file for wires, junctions, and pairs of wires, which violate the NEC "modeling guidelines", and hence have "CHECK errors". CHECK prepares a tabulation of the tag number of individual wires and of pairs of wires that are in violation of the guidelines, in file "CHECK.OUT". Three levels of "CHECK errors" are used. A "note" serves to alert the user to a condition which comes close to violating the guidelines. A "warning" is generated when a wire has less than the most desirable value of a parameter. Warnings serve to alert the model-builder to a construction which may not be the best practice in wire-grid modeling. A "warning" condition can often be tolerated in the sense that NEC's computed currents may be

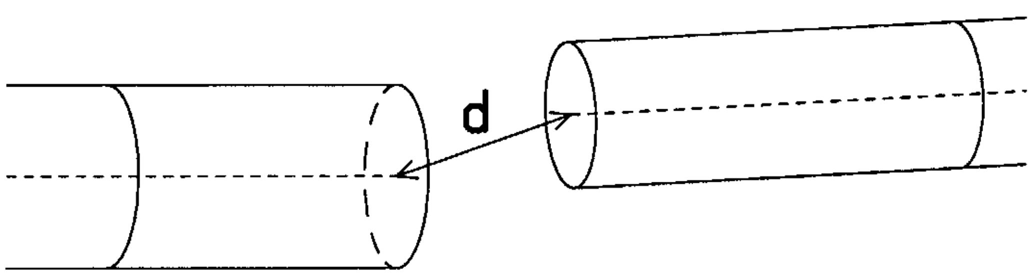


Figure 10 Wire ends in close proximity.

physically reasonable. However, models which violate the "modeling guidelines" at CHECK's "error" level may generate nonsense results when solved with the NEC program. A violation of the guidelines at the "error" level requires a modification to the input geometry to eliminate the "error", before a correct solution can be expected from NEC.

CHECK's search through the wire-grid is organized into three "passes". On the first "pass" the individual-wire guidelines listed in Table 1 are verified for each wire of the model, and a table of "individual errors" is written to file CHECK.OUT . On the second "pass" the junction conditions are verified, and a table of "junction errors" is prepared. On the third "pass", pairs of wires that do not form junctions are examined to ensure that they are spaced sufficiently far apart. These searches are described in detail in the following.

4.1 Individual Wire CHECK Errors

CHECK begins by reading and storing the tag number, the number of segments, wire end-point coordinates, and radius for each wire, and computing the segment length. The control cards are searched for the highest frequency, and for the "EK" card. On the first pass through the geometry file, CHECK compares each wire with the NEC modeling guidelines of Table 1 for individual wires. Four parameters are verified, as follows.

Zero Length Wires

The first class of "individual wire" errors found by CHECK is "zero length wires". Errors in constructing a complex wire-grid by joining "vertices" with "links" sometimes lead to two vertices having the same coordinates. Then a "link" joining the two vertices constitutes a zero-length wire. Or, a "link" can be defined joining a vertex to itself, also leading to a wire of zero length. CHECK identifies such wires with "zero length error".

Segment Length to Radius Ratio

The suitability of the Δ/a ratio for each individual wire is assessed according to whether or not the "extended kernel" option has been invoked. With no EK card, Δ/a must be maintained greater than the value of 8 shown in Fig. 1(a). If Δ/a lies between 8 and 2, then CHECK issues a "warning", and if Δ/a is less than 2, and "error" is generated. If the "EK" option has been invoked, then NEC permits Δ/a to be as small as the value of 2 of Fig. 1(b). A "warning" is issued if the ratio falls between 0.5, shown in Fig. 1(c), and 2. An "error" is generated if Δ/a is less than 0.5.

Segment Length to Wavelength Ratio

The remaining two "individual wire" tests depend on the highest frequency specified in the "control card" section of the input file. CHECK computes the segment length Δ to wavelength ratio, Δ/λ. Notes, warnings and errors are issued according to the rules of Table 1.

Wavelength to Radius Ratio

CHECK evaluates the ratio of the wavelength to the wire radius and issues warnings and errors according to Table 1.

4.2 Junction CHECK Errors

The second "pass" of the CHECK program searches for pairs of wires which have a common endpoint hence form a junction.

Coincidence Errors

Sometimes, in error, a wire is included twice in a geometry file, often with two different tag numbers. Sometimes the direction of the wire is reversed when it is duplicated. CHECK examines all wire endpoints to see if any wire has the same endpoints as any other. If so a "coincidence error" is reported for that pair of wires.

Segment Length Ratio Errors

CHECK examines the ratio of the segment lengths on any two wires which join, and issues an "error" if the ratio of the segment lengths of the two wires is greater than five.

Radius Ratio Errors

CHECK computes the ratio of the radii of any pair of wires which join, and issues "warnings" and "errors" according to the NEC modeling guidelines of Table 1.

Junction Segment Length to Radius Ratio Errors

For any wire which is part of a junction, CHECK verifies the segment length to radius ratio. If the ratio is less than two, an "error" is generated. If the ratio is less than six, but greater than two, a "warning" is issued. Thus with EK active, a wire may "pass" the segment length to radius ratio test as an "individual wire", but may "fail" the test if it is part of a junction.

Match Point Errors

For pairs of segments that form a junction, CHECK verifies the "match point" rules of Table 1. If the included angle is less than 90 degrees, as in Figs. 4, 5 and 6, then CHECK computes the distance from the match point on wire #1 to the centerline of wire #2 in the figures. If this distance is less than the radius wire #2, a "match point error" is issued. If the distance is less than 1.5 times the radius, then a "match point warning" is given. For wires at an angle greater than 90 degrees as in Fig. 7, CHECK computes the perpendicular distance from the match point on wire #1 to the plane of the endcap of wire #2, and also computes the distance from the match point to the center of the endcap. If the perpendicular distance is less than half the radius of the wire #2 and also the distance from the match point to the center of the endcap is less than radius of wire #2, then a "match point warning" is issued.

4.3 Wire Spacing CHECK Errors

CHECK examines each pair of wires in the geometry file, and for pairs that do not form a junction, CHECK verifies that the wire spacing rules of Table 1 are followed.

Crossed Wires

CHECK computes the shortest distance between the wire centerlines. If that distance is zero, then a "crossed-wires" error is issued. The present version of CHECK does not permit intersecting wires to be joined at a segment boundary.

Overlaps

CHECK verifies that wires pass one another further apart than the sum of their radii. For geometries such as Fig. 8(c) or Fig. 9(b), CHECK issues "overlap errors".

Near Misses

For closely-spaced wires, such as those of Fig. 8(d) or Fig. 9(c), the distance limits chosen for the CHECK program serve to alert the model-builder to very closely spaced wires, rather than to guarantee the validity of the "thin-wire" assumption. If the shortest distance between the wire centerlines is less than 1.5 times the sum of the wire radii, then CHECK generates a "near miss" warning. If the shortest distance is greater 1.5 times the sum of the radii, but less than twice the sum, then CHECK generates a "near miss" note. Thus "near misses" have not been accorded the status of "error" in CHECK.

Proximity

CHECK draws attention to wires with closely spaced endpoints, such as those of Fig. 10, when the spacing of the wire ends is comparable to the wire radius. Thus if the gap "d" between any two wire ends is less than the 1.5 times the sum of the radii of the two wires, then CHECK generates a "proximity warning". If the gap between the ends is less than the sum of the wire radii, CHECK generates a "proximity error". These "CHECK errors" are generated whether or not a third wire "fills" the gap. CHECK's warnings and errors draw attention to such constructions to encourage the modeler to rearrange the geometry.

The rules for "near misses" of wires, and "proximity" of wire endpoints, have been designed to be meaningful with typical wire-grid models - that is, to avoid generating a great many "CHECK errors". Thus those warnings and errors that CHECK does generate are the extreme cases, and should be investigated to determine whether geometry changes should be made to clear the errors. Thus the user is advised to eliminate "crossed wire errors" and "overlap errors". "Near miss warnings" are sometimes tolerated. Proximity errors should usually be eliminated. "Proximity warnings" are often tolerated if a third wire joins the closely-spaced wire ends which lead to the warning.

5. Frequency Limitations

The "bandwidth" of a wire-grid is the range of frequencies over which the grid, as analysed by the NEC program, is electrically equivalent to the continuous surface that the grid represents. The "modeling guidelines" of Table 1 lead to specific limits to the frequency range over which a wire-grid model is expected to generate reasonable results. If the longest segment in a model has length Δ_{max}, then the highest frequency at which this segment is shorter than 0.14λ is given by

$$f_1 = \frac{(0.14)(300)}{\Delta_{max}} = \frac{42}{\Delta_{max}}$$

in MHz. The model should not be used if the frequency is greater than that which makes the longest segment 0.2λ, given by

$$f_2 = \frac{(0.20)(300)}{\Delta_{max}} = \frac{60}{\Delta_{max}}$$

These limits based on the longest segment in a model are often too restrictive. CHECK finds the "mean" or average segment length in the model, and provides an alternate estimate of the frequency limitation. If Δ_{av} is the mean segment length, then for a mean segment shorter than 0.14λ, the frequency must be less than

$$f_1^{av} = \frac{(0.14)(300)}{\Delta_{av}} = \frac{42}{\Delta_{av}}$$

and for the mean segment shorter than 0.20λ,

$$f_2^{av} = \frac{(0.20)(300)}{\Delta_{av}} = \frac{60}{\Delta_{av}}$$

These more liberal frequency limits may be misleading if the long segments in the model fall in critical regions of current flow.

If the largest wire radius in the grid is a_{max}, then the ratio of the wavelength to this largest wire radius is greater than 30 at frequencies less than

$$f_{thin} = \frac{300}{30a_{max}} = \frac{10}{a_{max}}$$

in MHz. For a uniform rectangular mesh with square cells, the equal-area radius formula chooses $a = \Delta/2\pi$ which makes the thin-wire frequency limit equal to

$$f_{thin} = \frac{10}{\Delta/2\pi} = \frac{62.8}{\Delta}$$

which is approximately the same as the "segment length" frequency limit f_2.

A less obvious upper bound on the frequency at which a given wire-grid can be used concerns the path length around the meshes the grid. If L_{max} is the longest mesh path in the grid, then the model should not be run above the frequency which makes that mesh path one wavelength. The limiting frequency is

$$f_{loop} = \frac{300}{L_{max}}$$

in MHz. Above f_{loop}, the long mesh may carry a large, resonant current flow. For a uniform grid of square meshes of side length Δ, f_{loop} is $75/\Delta$, which is greater than f_2. However a poorly designed grid can have some long individual mesh paths, making f_{loop} significantly smaller than f_2, and thus it can be the longest mesh path that limits the frequency range of the model.

The minimum frequency at which a wire-grid model can be analysed with NEC is the frequency at which NEC itself fails. To represent current flow on each segment, NEC uses basis functions consisting of a constant plus a sine plus a cosine. When the segments are extremely short, there is little difference between the constant term and the cosine term, leading to an ill-conditioned matrix. As a consequence, when the distance around a mesh in a wire-grid is small compared to the wavelength, NEC sometimes yields a large circulating current around the mesh. Burke[11] cautions that the mesh paths in the model must be longer than 0.07 wavelengths, leading to a lower bound on the bandwidth of

$$f_1^{min} = \frac{(0.07)(300)}{L_{min}} = \frac{21}{L_{min}}$$

Running NEC in 64-bit precision, the authors use a less strict lower bound, making the shortest mesh path $\lambda/25$, given by

$$f_2^{min} = \frac{(0.04)(300)}{L_{min}} = \frac{12}{L_{min}}$$

When analysing a wire-grid model at frequencies approaching the lower bound, it is advisable to inspect the current flow on the wires at each frequency, to look for suspiciously large currents flowing around any individual meshes.

6. Aircraft Wire-Grid Example

Fig. 11 illustrates a mid-sized aircraft modeled as a wire-grid. The grid was designed to have six axial wires along the fuselage. The fuselage circumference then fixes the segment length in the model at a "nominal" value of about 1.5 m. The grid was then constructed to have nearly-square cells 1.5 m on a side. The aircraft carries an HF wire antenna which is insulated from the dorsal fin and fed coaxially from inside the fuselage. The wire-grid is intended to study the performance of the wire antenna from 2 to 30 MHz.

The wire-grid uses triangular cells to provide an "elegant transition" whenever the number of axial wires must be increased or decreased[13]. For example, on the wing a triangular cell is used in the transition from three to four wires across the wing. There are several occurrences of such transitions in the fuselage.

For an orthogonal grid representing a cube or square, the "equal-area rule" calls for a wire radius that makes the surface area of the wires in one direction equal to the area of the surface. The aircraft is for the most part a quasi-orthogonal grid of nearly-square cells, but has many exceptional cells with 3 sides, 5 sides, 6 sides, and so forth. The "equal-area rule" has been generalized[12] such that the radius of a given wire is chosen in proportion to the areas of the two grid cells that the wire subtends, independent of the shape of those cells. For a regular grid of square cells or of triangular cells, the total surface area of all the wires is then equal to twice the area of the surface that the wires represent.

The "modeling guidelines" of Table 1 impose restrictions on the details of the geometry of the grid that are highly local in nature, affecting individual wires, pairs of joined wires or pairs of very closely spaced wires. The generalized "equal-area" rule is somewhat less local: the radius of a given wire is determined by the six other wires making up the wire-grid cells on either side of the wire. Yet it can be remarkably difficult to satisfy the seemingly simple "modeling guidelines" if the "equal-area" radius rule is strictly adhered to. The derivation of wire-grid meshes which satisfy these restrictions is an "engineering art" involving compromise. The aircraft wire-grid described in the following illustrates the difficulties that may be encountered, and suggests how they may be resolved.

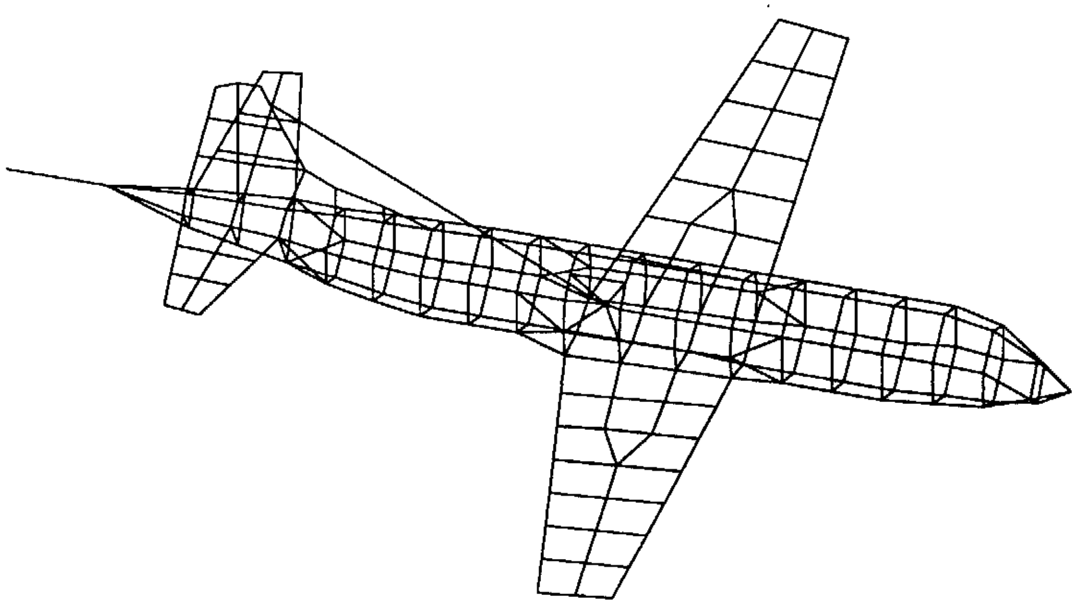


Figure 11 A wire-grid model of an aircraft.

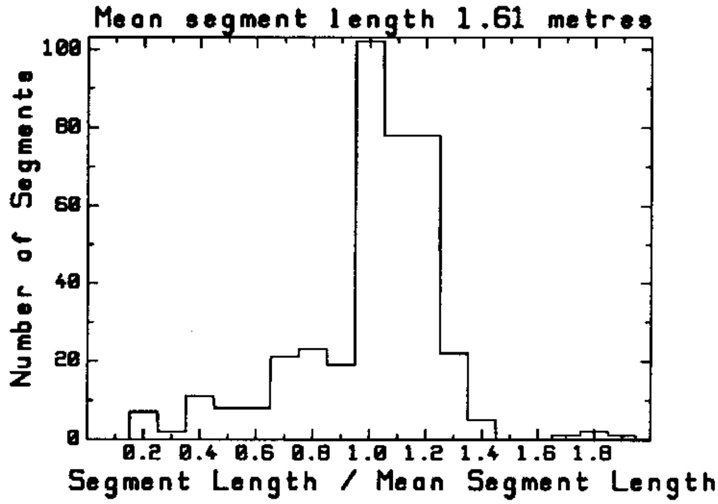


Figure 12 The distribution of the segment lengths in the wire-grid model of the aircraft.

Segment Length Distribution

CHECK was run at 15 MHz, approximately the center of the 2 to 30 MHz HF band. The wire-grid model contains a variety of segment lengths. CHECK prepares a data file giving the bar graph distribution of the segment lengths shown in Fig. 12. CHECK determines the mean or average segment length to be 1.61 m, somewhat longer than intended, with a standard deviation of 0.4 m, so that most segments lie in the range from 0.6 to 1.4 times the mean.

CHECK lists the following frequency limits for this model. The model has mean segment length shorter than 0.10λ up to 18.8 MHz. The mean segment is shorter than 0.14λ up to 26.3 MHz, and is shorter than 0.20λ up to 37.6 MHz. Thus good results would be expected to about 19 MHz, poorer results to 26 MHz, and perhaps useful data could be obtained to higher frequencies, but not beyond 38 MHz.

The spread of segment lengths in Fig. 12 arises as follows. It is not possible to maintain "square" cells of uniform size in tapering structures such as the tail section or wing. As a structure gets narrower, the cell size is permitted to become considerably smaller than the nominal 1.5 m side length. Then the number of axial wires is decreased at a point which brings the cell size up to a value larger than the nominal size. Also, at the transition, a triangular cell is used which has wires of length comparable to the diagonal of a square cell, 1.4 times the nominal segment length. The feed region contains a substantial number of segments much shorter than the mean.

The very short segments seen in Fig. 12 are associated with "critical regions" of the structure such as the feed of the wire antenna, shown including wire radius in Fig. 13. The feed region is designed to attach the wire antenna to the fuselage at the physical connection point on the actual aircraft, which does not coincide with a vertex of the wire-grid. The wire antenna has a 30 cm "standoff" oriented perpendicular to the aircraft skin, which is excited with a 1 volt generator. Around the base of the standoff, wires have been arranged to support radial current flow. The segment length is deliberately kept small adjacent to the standoff to improve the computed input impedance for the wire antenna. The arrangement of Fig. 13 is designed to confine the feed region to one grid cell. But the feed arrangement causes many "CHECK errors", as described below.

Individual Wire Pass

The "individual wire" pass of the CHECK program at 15 MHz shows "warnings" for some segments: they are longer than 0.10λ. CHECK writes a file listing these segments. With graphics program "MODEL"[12] the listed segments can be displayed in the format shown in Fig. 14. Some of these segments are the especially long segments in the bar graph of Fig. 12. Others are associated with tapering wings and fuselage. The location of these segments may determine

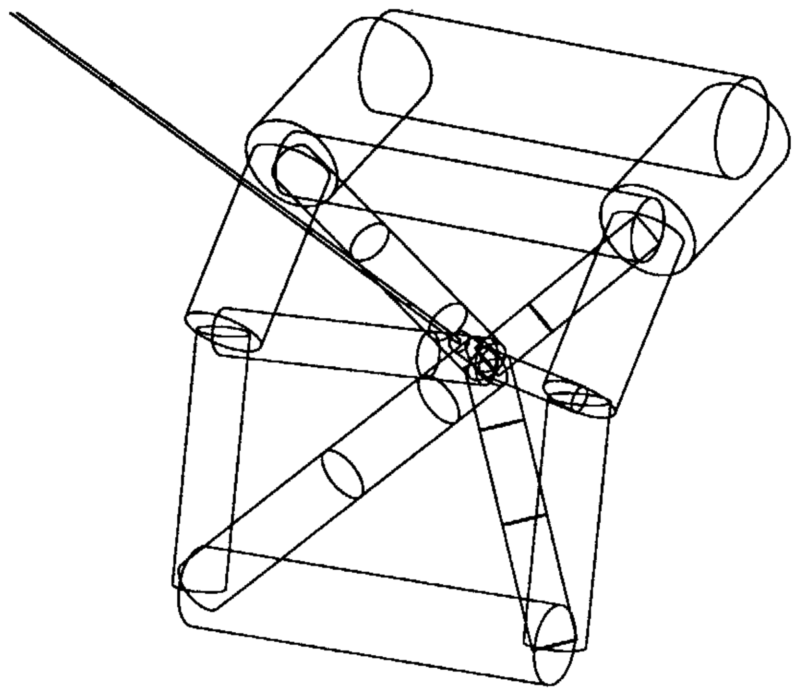


Figure 13 The feed region of the wire antenna, depicting the radii of the wires.

whether the user wishes to tolerate their excessive length, or whether they can simply be subdivided. Subdividing long segments increases the values of the frequency limits f_1 and f_2 discussed above. But fundamentally, subdivision does not extend the frequency range of a model very much, for as the frequency increases cells must be subdivided into a finer grid. In some cases the user may wish to modify the grid to have a finer cell size at the location of some of the "long" segments. The wires with "long" segments are readily identified from CHECK's output file SEGMENTS.GW, giving the wires in descending order of segment length.

The "individual wire" pass finds a great many wavelength-to-radius ratio warnings. They arise from the "equal-area" rule choice for the wire radius. With segment length 1.6 m, the "equal-area" wire radius is 0.255 m, and at 15 MHz, with a wavelength of 20 m, the wavelength-to-radius ratio is about 79. This is less than the most-desired value of 100, hence "warnings" are obtained from CHECK. As the frequency increases the ratio decreases and the "warnings" become more significant. At 39.2 MHz, the wavelength-to-radius ratio with the nominal radius of 0.255 m becomes 30, and the "warnings" become "errors". At that frequency, the mean segment length of 1.6 m is 0.21λ, too long to expect reasonable results. Thus the figure of 30 has been chosen so that the "equal-area" radius wires become "too fat" at about the same frequency that the mean segment becomes "too long", that is, longer than 0.20λ. As previously mentioned, segments longer than 0.14λ may be "too long" for some purposes.

Junction Pass

The "junction" pass of CHECK reveals a number of difficulties with the aircraft model. Fig. 15 shows wires at junctions which have a segment length to radius ratio less than six, a "warning" condition. The "equal-area" rule makes the segment length to radius ratio $2\pi = 6.28$ for square cells, greater than the value of 6 used in CHECK as the limit for segments at junctions. But for cells that are not square, the generalized version of the "equal-area" rule leads to some wires which are fatter than segment-to-radius equal to 6, and so CHECK generates warnings. If the ratio remains close to 6, then no remedial action need be taken, and the "warnings" are tolerated. The user must inspect the graphics display, or else scan the tabulations in

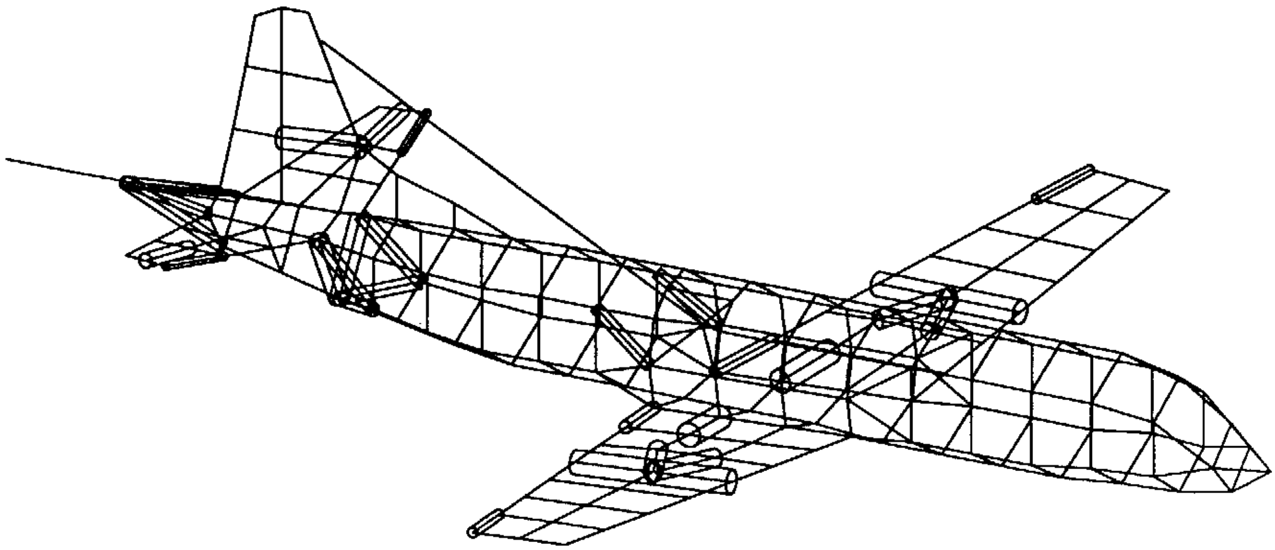


Figure 14 The set of segments identified by CHECK as longer than 0.10λ at 15 MHz.

CHECK.OUT, for ratios close to 2, which should not be tolerated. In Fig. 15, only the wires in the feed region are problems. Fig. 13 shows that the very short segments at the antenna base are all too fat compared to their length. This requires modifications of the geometry input.

The feed region leads to other "CHECK errors". Fig. 16(a) shows wires giving rise to "match point warnings" where the center of a segment lies too close to the surface of another segment at a junction. Fig. 16(b) shows segments having "match point errors" where the segment center is inside the volume of another wire. These problems arise because the segments in the feed region are in general too short compared to their radius, that is, compared to the areas of the cells which they subtend. There are two remedies: either increase the length of the segments in Fig. 13, or if the short segments are really necessary, add segments to subdivide the cells into smaller areas, leading to smaller wire radii.

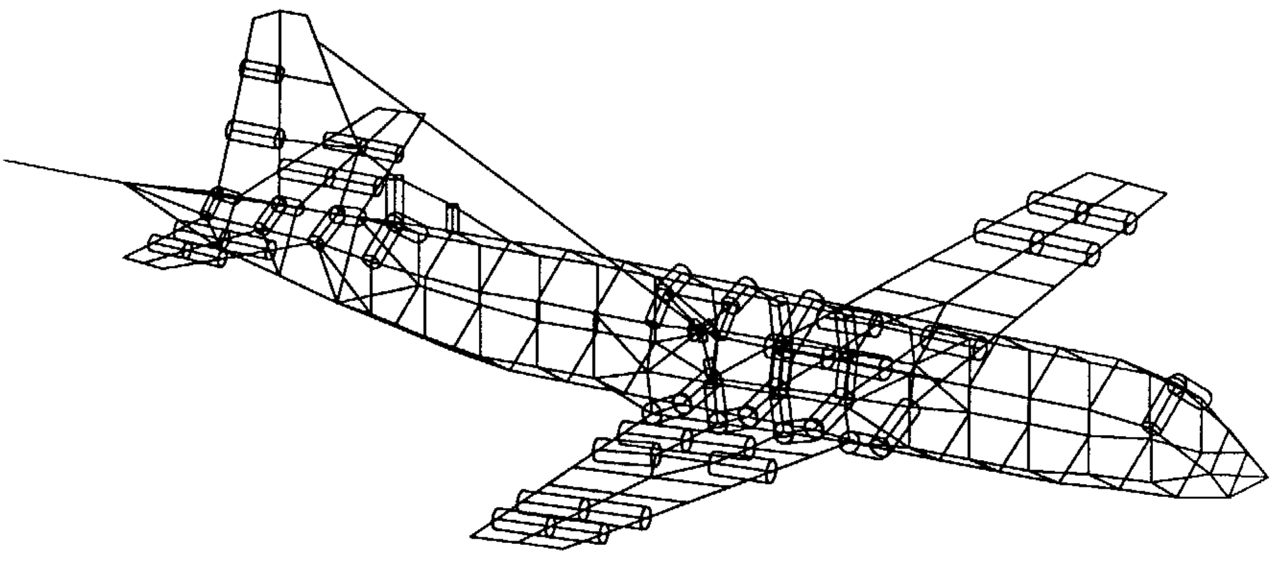
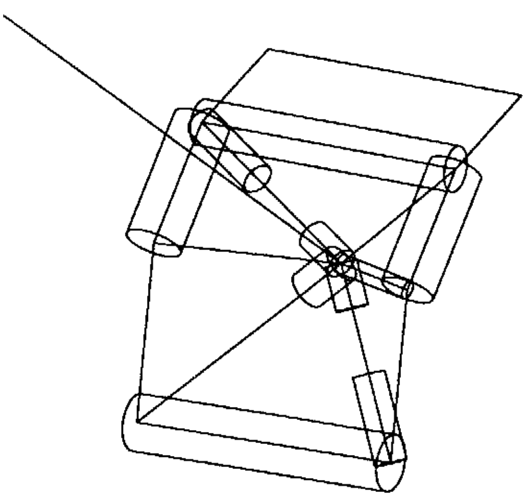


Figure 15 The set of segments identified by CHECK as having a segment-length to radius ratio less than six. Only those in the feed region are a serious problem.



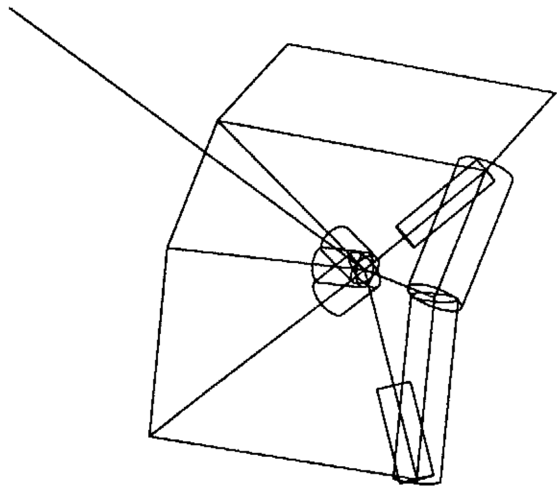


Fig. 16(a) Wires in the feed region giving rise to "match point warnings" in CHECK.

Fig. 16(b) Wires in the feed region giving rise to "match point errors" in CHECK.

CHECK finds another problem with the aircraft grid of Fig. 11. Fig. 17 shows the forward end of the dorsal fin where the fin joins the fuselage. There, an edge wire of the dorsal, having a thin radius, joins a much fatter wire of the fuselage, at a very shallow angle. A "match point warning" is generated because the center of the thin wire, that is the "match point" on the thin wire, lies very near the surface of the fat wire. Also, the ratio of the "fat" radius to the "thin" radius greater than five, so a "radius ratio warning" is obtained. These must be cleared by modifying the geometry.

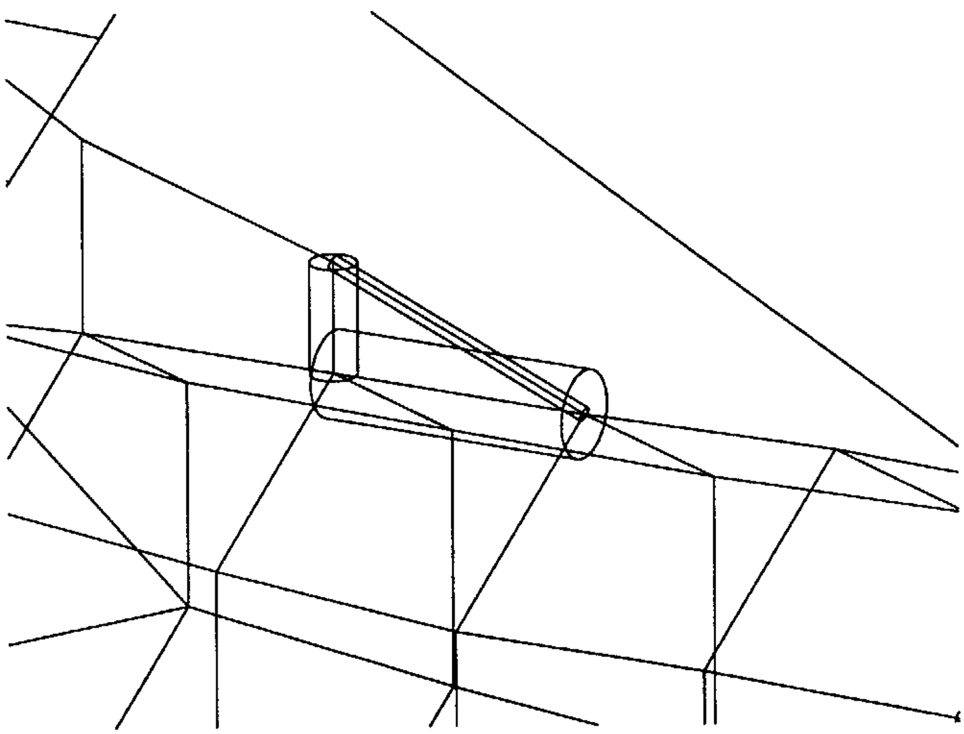


Figure 17 These wires at the forward end of the dorsal fin lead to "match point warnings" and to a "radius ratio warning" in CHECK.

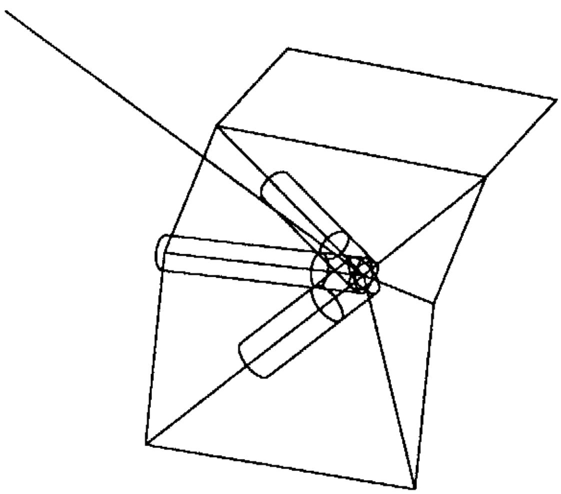


Fig. 18(a) Pairs of these wires in the feed region lead to "proximity errors" in CHECK.

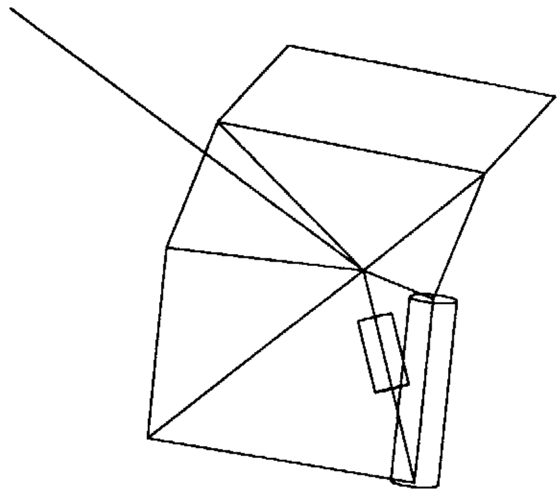


Fig. 18(b) These two wires overlap and give a "spacing overlap error" in CHECK.

Spacing Pass

The third pass of CHECK examines pairs of wires that are not actually connected, to determine if they are far enough apart. The feed region of the wire antenna again gives problems. "Proximity errors" are found for the radial wires at the antenna base and the wires adjacent to them. Fig. 18(a) shows the set of all wires having "proximity errors". They arise because one end of a short, fat wire at the antenna base is too close to a long wire on an adjacent radial. CHECK is trying to indicate that the construction is poor in the sense that the wires are too closely spaced compared to their radii.

Fig. 18(b) shows a pair of wires having an "overlap error". Thus the short wire would physically be joined to the longer wire halfway along the long wire. Clearly this is not intended. This problem again arises through the subdivision of the boundaries of the triangular cells into three segments, too many compared to the cell area. This problem must be "cleared" before meaningful computations can be done.

A further problem is illustrated in Fig. 19, which shows the top of the dorsal fin and the end of the HF wire. The radius of the segment modeling the forward edge of the dorsal fin is determined by the area of the adjacent quadrilateral cell. The wire antenna endpoint is very close to the edge wire, closer than twice the radius of the dorsal edge wire from the centerline of the dorsal edge wire. CHECK generates a "near miss note" for this geometry. Such a "near miss" may be a serious error. There will be capacitive coupling between the end of the wire antenna and the dorsal fin. There may be a local accumulation of charge on the dorsal edge at the point closest to the wire antenna, hence in the wire-grid, on the dorsal edge wire at the point closest to the wire antenna end. Modeling the dorsal edge with one long segment in this region thus may not be the best construction. In the following the aircraft model is somewhat modified to "clear" some of these problems identified by CHECK.

Clearing the CHECK Errors

The feed region for the wire antenna was redesigned as shown in Fig. 20. A new vertex has been introduced in the adjacent grid cell, and has been used to make the radials more symmetric about the base of the antenna. Wires joining at shallow angles have been eliminated. The areas of the grid cells have been kept small around the antenna base.

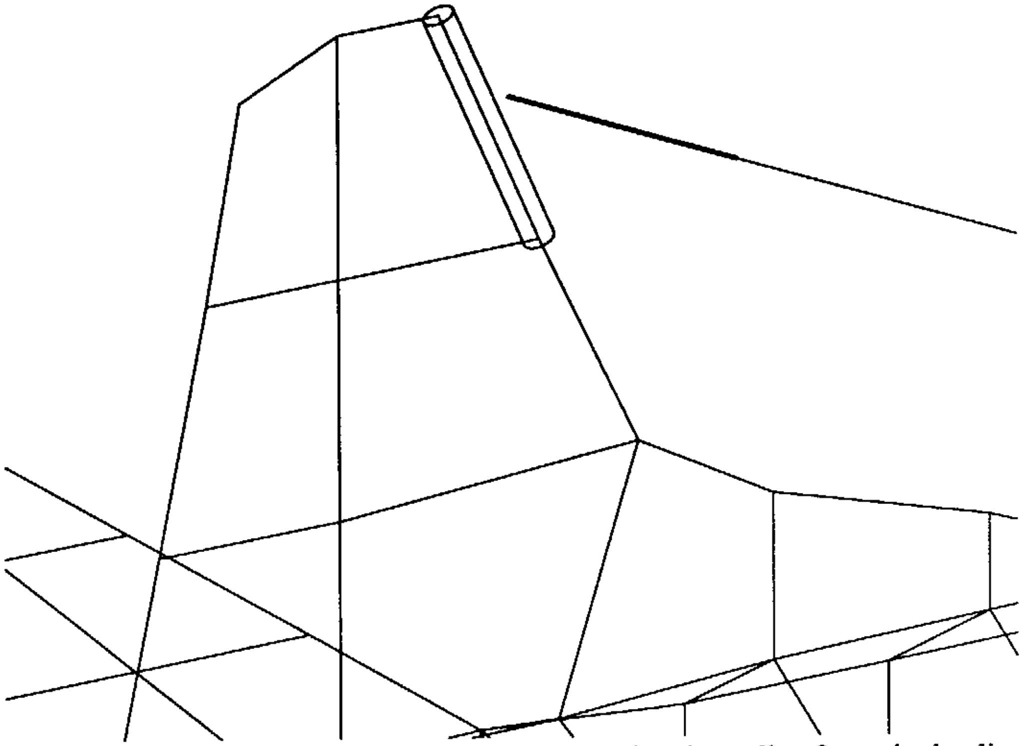


Figure 19 The open end of the wire antenna is less than twice the radius from the leading edge of the dorsal fin, and gives a "spacing near-miss note" in CHECK.

In Fig. 13 a set of six very short "feed radials" at the connection point of the wire antenna feed to the fuselage are connected to the grid vertices by six "joining wires". Four of these "joining wires" have been subdivided into two segments. In the new arrangement of Fig. 20, only one segment is used for each of these "joining wires". A more subtle change is that the length of the "feed radials" in Fig. 20 has been increased by about twenty percent. Also, in Fig. 20 the feed radials use a thinner radius than the joining wires, providing a gradual taper of radius from the fat wires of the fuselage grid to the very thin HF antenna wire.

When CHECK is run on the redesigned feed region, the problems encountered above are all "cleared". The proximity errors of Fig. 18(a) are reduced to proximity warnings. Such warnings can be tolerated between wires which are joined by short segments, as in the feed arrangement, but would be serious if the wires were not joined and NEC were expected to compute accurate capacitive coupling.

The problem with "match warnings" and "radius-ratio warnings" associated with the forward end of the dorsal, shown in Fig. 17, has been remedied by introducing new wires which subdivide the adjacent fuselage cells into smaller cells, as in Fig. 21. Subdivision reduces the radius of the fuselage wire to about half its former value, making the "match point" on the wire on the leading edge of the dorsal fin far enough away from the fuselage wire to satisfy CHECK's requirements. The problem with radius ratio is also solved.

The "proximity note" associated with the end of the wire antenna has been cleared by subdividing the adjacent cell on the dorsal fin into four small cells, as shown in Fig. 22. The new wire junction on the leading edge of the dorsal is located as close as possible to the end of the wire antenna. Subdivision reduces the radius of the wire on the leading edge of the dorsal to one-quarter of its former value for the cells are one-quarter the size, and now CHECK's criteria for wire spacing are satisfied. An even better arrangement might be to use a segment to join the end of the wire antenna to the dorsal fin, and to load that segment with a series capacitance representative of the extra capacitance of the insulator used in the actual aircraft wire arrangement.

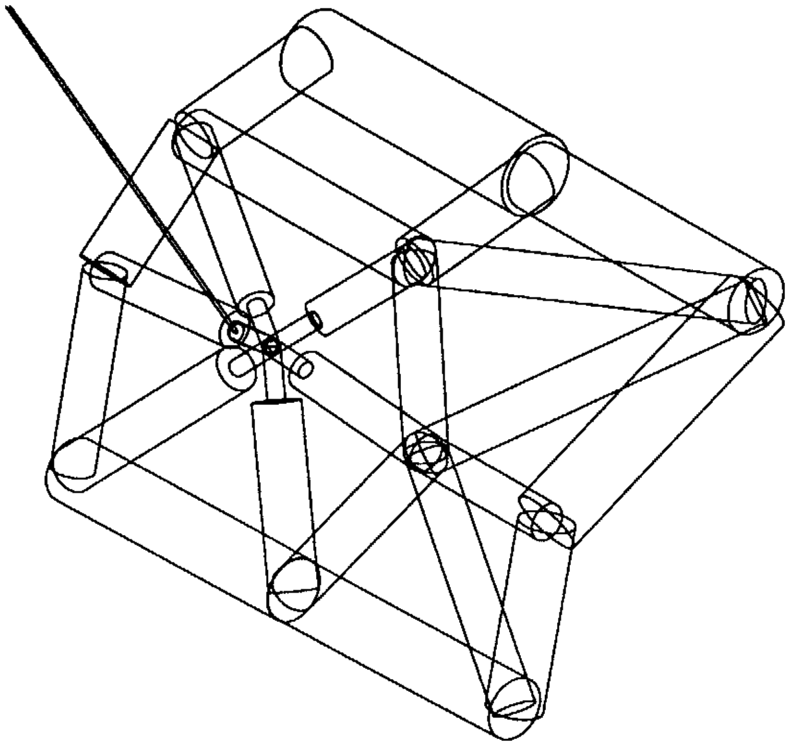


Figure 20 A redesigned feed region eliminates most of the "CHECK errors".

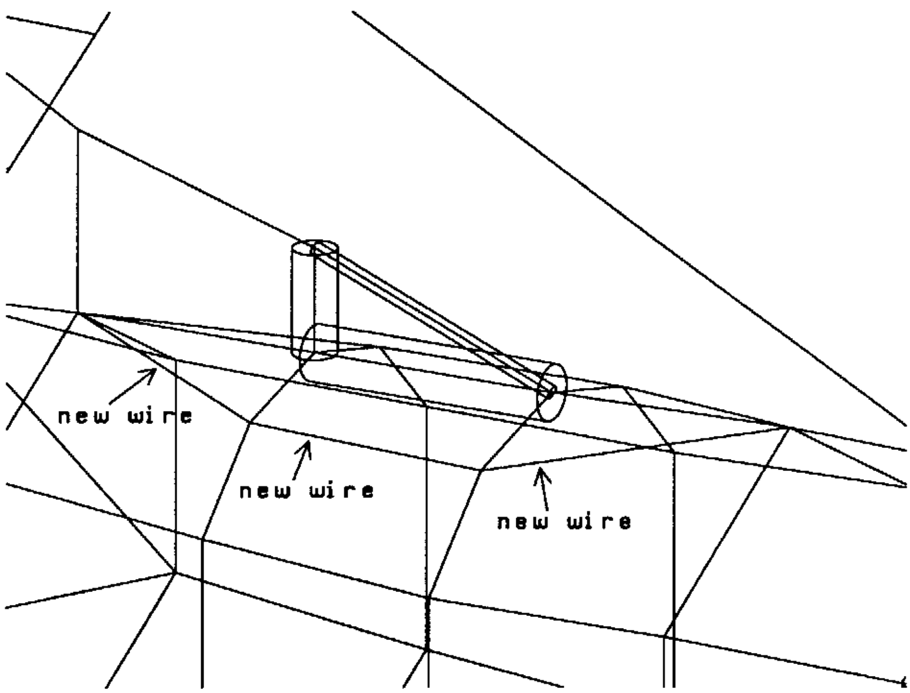


Figure 21 The fuselage near the leading edge of the dorsal is subdivided into smaller cells to reduce the radius of the fuselage wires, and "clear" the "match warning" and "radius ratio warning" illustrated in Figure 17.

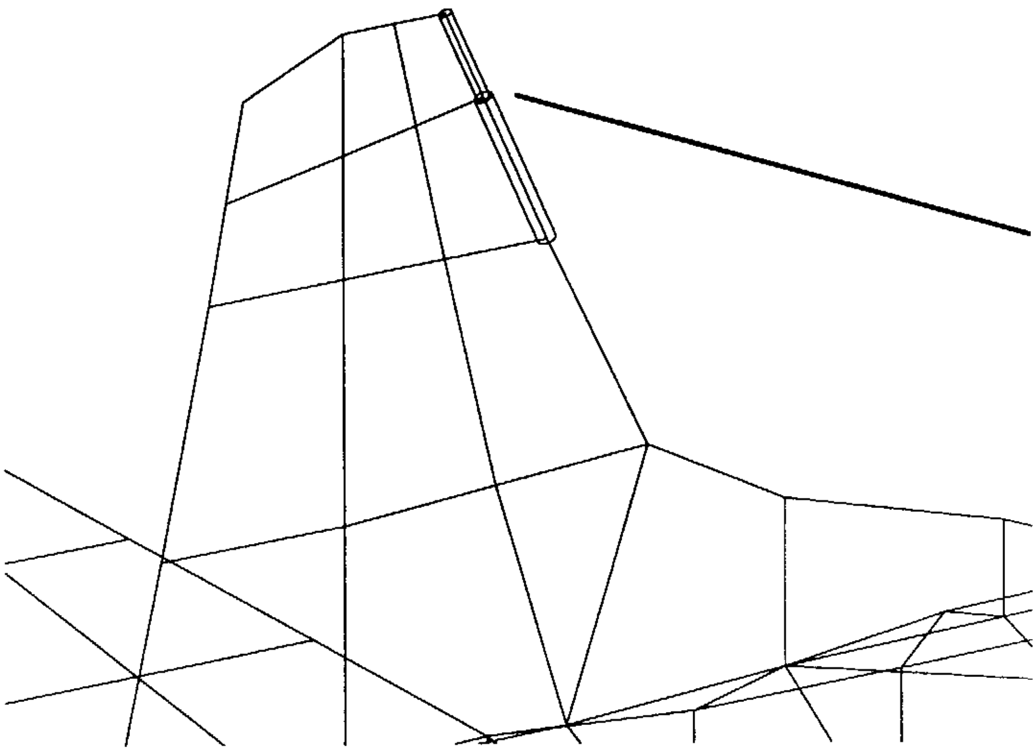


Figure 22 The top of the dorsal fin is subdivided into smaller cells, with a wire junction close to the open end of the wire antenna.

7. Restrictions in Program CHECK

The present version of CHECK has some limitations. Wires that cross are not permitted to form junctions if the crossing point is at a segment boundary on both wires. In CHECK, junctions occur between wire endpoints only. No geometry scaling, shifting or mirror symmetry is supported. For nearly parallel wires, CHECK does not verify that segment boundaries are aligned, which is required by the NEC program. CHECK uses a somewhat approximate algorithm to decide whether cylinders(wires) overlap or are far enough apart. The astute user can devise (unusual) geometries for which CHECK will claim an overlap where there is no physical overlap. Such geometries are poor wire-grid practice and CHECK's approximate condition serves the purpose: to alert the user to a dubious wire-grid construction.

8. Conclusion

The "integrity" of a wire-grid is often assessed by asking whether the grid conforms to the basic assumptions of the wire-grid program to be used to find the currents on the grid. The model-builder endeavors to ensure that the grid is free of gross errors, that the segments are all sufficiently short, that the radii are not too "fat" compared to the segment length, and so forth. An aid to such integrity assessment is often a computer graphics drawing of the wire-grid representing each wire by its centerline. But for a complex model such as the aircraft grid of Fig. 11, it is very easy to miss even gross errors. Zero-length wires do not appear. A duplicated wire cannot be seen. The drawing does not depict radius nor segment length and is little help in ensuring conformance to the guidelines for these quantities.

A considerable improvement is realized by including the wire radius in the graphics, for then the "eye" can be trained to spot the inadequate segment-to-radius ratios of Fig. 1, too-large segment-to-segment ratios at junctions as in Fig. 2, unacceptable radius ratios such as those of Fig. 3, and match point problems as in Figs. 4 to 8. But a graphics display of a complex model including radius is quite confusing. Errors are easily missed.

Program CHECK was written to systematically verify the "integrity" of a wire-grid model. Every wire and every pair are evaluated against the quantitative "modeling guidelines" of Table 1. CHECK finds all violations of these "modeling guidelines". CHECK finds surprisingly large numbers of errors in models that were carefully prepared and diligently searched manually.

Running on a 25 MHz 80386 computer under MS-DOS, CHECK takes about 37 seconds for a model with 248 segments, 147 seconds for 445 segments and 288 seconds or about 5 minutes for 649 segments.

The specific values delimiting "notes", "warnings" and "errors" are something of a "moot point". The values chosen are a "rule-of-thumb" compromise and perhaps could be refined to generate more meaningful messages from CHECK. Thus the boundary between "warning" and "error" for segment length might be changed so that segments longer than 0.14λ are "errors" rather than the present value of 0.20λ. The minimum acceptable wavelength-to-radius ratio might be changed from 100 to 75, so that radii chosen according to the "equal-area rule" do not generate "warnings" at a frequency where most segments are 0.10λ.

CHECK is designed to work in conjunction with the graphics program "MODEL"[14]. MODEL is built around depicting wire-grids including the radius as seen in many of the above figures. MODEL is oriented toward highlighting specific subsets of wires in the manner seen for example in Fig. 14. CHECK is designed to take advantage of MODEL's capabilities.

CHECK has proven a useful tool for refining the details of wire-grids, as was done above for the aircraft. Many of CHECK's warnings and errors, especially those associated with match points, overlaps, spacing and proximity, inherently suggest improvements. With a modest increase in the number of segments, a model then generates more reliable results.

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