The Hamer Rotor Risk Model

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Our model for estimating avian rotor collision probabilities is an extension of the collision model introduced by Tucker (1996a) – an oft cited resource for estimating avian-turbine collision risk (Tucker, 1996b; Desholm and Kahlert, 2005; Chamberlain et al., 2006; Desholm et. al., 2006). Where the Tucker model addresses cases where the bird's air speed is either parallel or perpendicular to the wind direction, our model analyzes the more general case of oblique angles of approach. This is an important improvement, since birds often follow flight paths that are not dependent on the wind direction, but rather on established migratory routes or geologic features such as valleys or coastlines (Williams et al., 2001). A detailed description of this model follows. Additionally, an example application of the model is performed utilizing species specific flight speed and direction data from a raptor migration case study in Central Washington. This example shows that the angle of approach has a significant effect on collision probability and should be considered when estimating avian-turbine collision risk.

**2. Methods**

**2.1 Data Collection for Raptor Risk of Collision Case Study in Central Washington CCasC**

Our field surveys employed a combination of radar and outside observers to correctly identify and capture species specific raptor data during fall migration. The radar sampled in both the horizontal and vertical modes to gather passage rate and flight height data. In the horizontal mode, the modified marine radar (FR 1510, Mark III, Furuno Electric Co., Nishinomiya, Japan) tracked flight speeds, flight directions, and passage rates of birds (events) through the project area. In the vertical mode, the elevation above the radar unit was measured for each event. Radar sampling modes were alternated after 40 minutes of sampling.

The radar cannot reliably differentiate raptor species. As a result, the radar technician was in constant contact with visual observers to assign species to radar events via two-way radios. The radar technician conveyed event locations (height and distance) to the nearest visual observers in an attempt to get species confirmation. Confirmed individuals of two species (Sharp-shinned Hawk [*Accipiter striatus*] and Golden Eagle [*Aquila chrysaetos*]) were used in our analysis due to the notable differences in their body size, flight speed and pattern, as well as their abundance in the project area.

The horizontal radar scanning array was operated at 1.5 km radius at a short pulse length (0.07 µs). The radar detected raptors out to 1375 m on each side of the radar for a total diameter of 2750 m. The vertical radar scanning array was also operated at 1.5 km radius at a short pulse length. This range facilitated detection and recording of low altitude birds. The vertical radar was oriented to collect data along an east-west transect that was perpendicular to the main (north-south) direction of raptor migration. Slope distance and bearing above horizontal “ground level” were collected by the radar technician for each confirmed bird allowing for accurate calculation of horizontal distance and height.

**2.2 Model Assumptions/Simplifications**

To simplify the analysis of avian collision risk, a number of assumptions were made in the design of our model. While some of these simplifications limit the generality and accuracy of the model, they can be justified in that they make the derivation and implementation of the model more tractable while still modeling the salient features of the avian-turbine interactions. Most of the model assumptions were inherited directly from the Tucker model, but the most significant warrant further discussion.

One of the assumptions shared by both the Tucker and our proposed Hamer Model is that birds have a straight flight path which is parallel to the ground. Since birds engaged in other behaviors such as foraging and hunting often use erratic or circular flight patterns which vary in altitude (Thelander et al., 2003), the model would need further adaptations to incorporate the variations specific to those situations. However, the passage of a bird through the rotor plane of a wind turbine is typically a brief event. Therefore, even such complex flight patterns can be modeled using the simplified assumption of straight flight paths that are parallel to the ground while passing through the rotor plane.

Another simplification shared by both the Tucker and our Hamer Model is to model a flying bird as a two dimensional rectangle representing the wingspan and length of the bird. Clearly, a bird has girth as well, may be flapping its wings while traversing the plane of the turbine, and is often more of a ‘T’ shape than a rectangle when viewed from above. The decision to model a bird as a rectangle was made to simplify the mathematical analysis of the problem and to reduce the description of the bird's physical shape down to two parameters. These simplifications, as opposed to a more complete description of the physical dimensions of a bird in flight, can be shown to have only a small effect on the outcome of the model.

The third and most profound assumption in the current model is that there are no behavioral interactions between the birds and the turbine. Since bird species have been shown to avoid turbines and wind farms in existing installations (Kahlert et al., 2003; Chamberlain, 2006), this simplification will clearly bias the model towards over-estimating the collision probabilities. The Tucker model makes an attempt to address this interaction by defining a tangential rotor speed,, below which a bird can avoid the moving rotor. While the motivation behind this addition to the model is rational, it is not clear how  should be estimated for different bird species. Furthermore, it is clearly not a complete or accurate description of the behavioral interaction in question, since there is evidence that birds hit non-moving structures, such as communication towers (Shire, 2000). The model proposed in this paper does not include behavioral interactions. Instead, our Hamer Model provides an upper bound on the collision probabilities when a straight flight path and no behavioral interaction are assumed.

The last significant assumption concerns the collision probabilities that are calculated when a three-dimensional (3-D) rotor blade is considered (one that has a chord length and twist angle along its length). Similar to the Tucker model, the chord length and pitch is assumed to be constant in the region where the bird passes through the rotor plane. The chord and pitch are calculated from the rotor position where the nose of the bird passes through rotor plane, even though the bird may drift to the right or left depending on the angle of flight relative to this point of entry. This simplification can be shown to have an insignificant affect on the outcome and results in a more straight forward collision analysis when a 3-D rotor is considered.

**2.3 Model Inputs**

Each application of our model will correspond to a specific turbine design and the bird species under consideration. In addition, field survey results will provide critical site dependent information about the distribution of wind conditions and local flight paths. A number of model parameters are specified by the user based on site characteristics (Table 1). The axial induction,, accounts for the fact that air flowing through the turbine has a velocity less than the wind speed (Wilson, 1994). The angle of orientation describes the bird's rotational orientation with respect to the direction downwind (). A flight path rotated to the left relative to downwind results in negative angles of orientation, and rotation to the right results in positive angles of orientation. This is not generally equal to the angle that the bird's flight path will intersect the rotor plane (the angle of approach) because flight direction is dependent on both the bird and wind velocity.

|  |  |
| --- | --- |
| **Table 1. Definitions of Model Variables** | |
| **Parameter** | **Description** |
|  | Wing span (m) |
|  | Length of bird (m) |
|  | Bird’s groundspeed (m/s) |
|  | Bird’s groundspeed, after accounting for the axial induction factor (m/s) |
|  | Bird’s Air Speed (m/s) |
|  | Angle of approach (radians) |
|  | Angle of orientation (radians) |
|  | Number of rotors in turbine |
|  | Radius of Turbine (m) |
|  | Radius of hub (m) |
|  | Angular velocity (radians/s) |
|  | Wind velocity (m/s) |
|  | Axial induction factor |

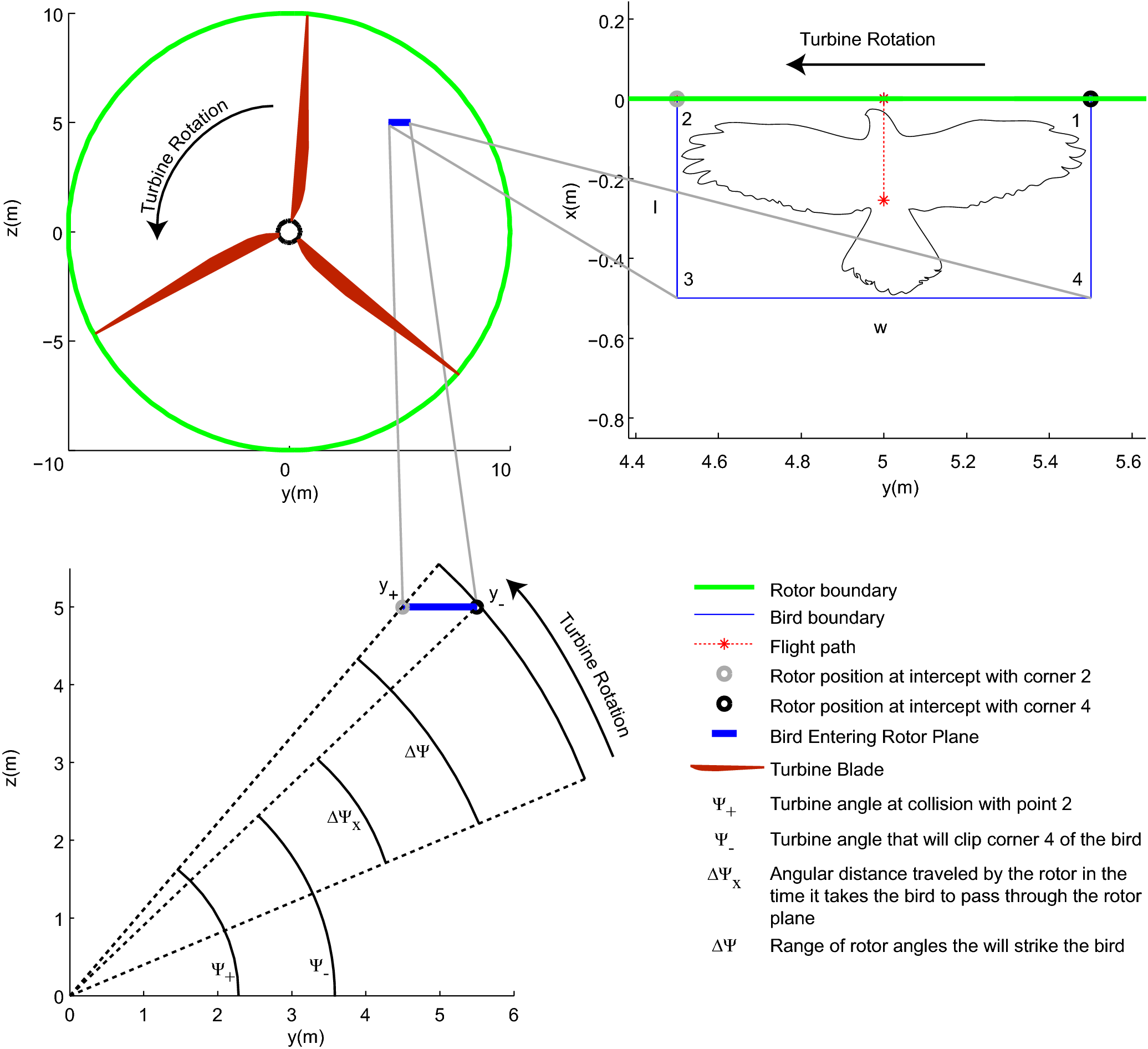


Figure 1. Overview of the model variables. Top Left Panel: A top-down view of a bird at the instant it enters the rotor plane for an approach angle of 0° (downwind). The small gray circle indicates the location of, the most advanced position of the rotor on the y-axis that can produce a collision with the bird. The earliest collision at this point takes place as soon as the bird enters the rotor plane and corner 2 of the bird clips the rotor as it is rotating away to the left. The small black circle indicates the location of , the least advanced position of the rotor on the y-axis that can produce a collision with the bird. The last possible collision at this point takes place as soon as the bird exits the rotor plane as the rotor clips corner 4 of the bird. Bottom Left Panel: A view of the area swept by the turbine rotors, looking downwind as the bird enters the rotor plane. The horizontal bar in the upper right quadrant depicts the position of the bird as it enters the rotor plane. Top Right Panel: A view of the top right quadrant of the area swept by the turbine rotors.  is the rotational angle associated with ,  is the rotational angle associated with ,  is the amount the rotor rotates in the time it takes the bird to pass through the rotor plane, and  is the range of initial rotor angles that will result in a collision with the bird.

**2.4 High-Level Algorithm for Calculating Rotor Collision Probabilities**

Given a linear flight path and a point of entry through the rotor plane, we used the following algorithm to calculate the probability of a collision with the rotor blades:

1. Determine the angular range of rotor positions that would result in a collision with the bird at some point during its passage through the rotor plane.
2. Divide this range by 2π radians to calculate the probability of a collision with a single rotor.
3. Multiply this by the number of rotors to calculate the probability of a collision with any of the rotors.

**2.5 Analysis of Downwind and Upwind Flight Path with One-Dimensional (1-D) Rotor**

We used a basic downwind flight path scenario to analyze and provide an introduction into the collision probability calculations described in this paper. Consider a wind turbine as it appears looking downwind (Fig. 1, upper left panel). The plane of the rotor blades is perpendicular to the wind direction, as is the case in normal operation. The origin of a left-handed 3-D (xyz) coordinate space is located at the center of the turbine hub. The *z*-component increases in the upward direction, the *y*-component increases to the right, and the *x*-component increases downwind and is negative from the figure viewpoint. The turbine blades rotate counter clockwise when looking downwind. Since the flight path is parallel to the wind direction in this case, there is no  component to the bird’s wind velocity  or ground velocity . Assuming that the bird’s ground velocity is the quantity measured in a field survey, we can calculate the bird’s ground velocity at the point of entry into the rotor plane:



where *a* is the axial induction factor and  is the wind velocity.

*Calculating Collision Points* — In the case of downwind flight (flight path perpendicular to the rotor plane), we must calculate the location of, the most advanced position of the rotor on the y-axis that can produce a collision with the bird, and, the least advanced position of the rotor on the y-axis that can produce a collision with the bird (Fig. 1, upper right panel). These two points are given by:



and



where  is the y coordinate of the point where the nose of the bird crosses the rotor plane and *w* is the width of the bird.

*Rotor Angle Resulting in Collision* — The rotational angles associated with the collision points  and  are  and , respectively (Fig. 1, bottom left panel). These angles are given by:



and



The time the bird spends in the rotor plane is given by , where  is the length of the bird, and the rotor can rotate



radians in this period of time. The complete angular range, , that would result in a collision as the bird passes through the turbine plane is therefore given by:



These results agree with those described by Tucker (1996a), with the exception that no small angle approximation is used in the current analysis. These models are therefore equivalent in the case where the flight paths are either upwind or downwind.

### *Collision Probability Calculation* — After specifying the bird, turbine, and wind characteristics (Table 1), and a point where the nose of the bird intersects the rotor plane, we can calculate the probability of a collision with one of the 1-D blades of the turbine given a downwind flight path:

(1)

where  is the number of turbine blades.

*Upwind Flight Path Analysis* — The analysis of upwind flight is identical to the downwind flight path analysis except that the sign of the bird’s downwind ground velocity  is negative instead of positive.

*Stationary Rotors –* Equation (1) is also applicable to the case where the rotors are stationary (e.g., when the wind speed is below the cut in wind speed or above the cut out wind speed of the turbine). In this case, Ω is 0, and the duration that the bird spends in the rotor plane has no consequence on the estimated collision probability.

**2.6 Analysis of Oblique Flight Path with 1-D Rotor**

Our analysis includes all angles of approach that the bird may take towards the wind turbine – not just the cases where the bird’s air speed is parallel or perpendicular to the wind speed as is the case for the Tucker model. Oblique angles of approach require additional analysis in the calculation of the first and last possible collision points between the bird and the rotor. This paper will cover the 4 different collision scenarios based on different angles of approach. Since the bird is no longer traveling parallel to the wind (and perpendicular to the rotor plane), there are now *x* and *y* components of the bird’s ground velocity at the point of entry in the rotor plane:



and



where  is the angle of approach of the bird relative to downwind. The angle of orientation of the bird (the direction the bird is pointing) is given by:



The angle of approach and the angle of orientation are generally not equal, due to the effects of wind.

**2.7 Approach in Direction of Turbine Rotation**

In this case, the bird moves toward the rotor plane with an approach angle in the direction of the rotor rotation (e.g., if the bird is moving to the left as it enters the rotor plane, the rotor is also rotating to the left at the point of intersection). For downwind flight paths and assuming counter clockwise rotation of the rotor when looking downwind, this is true for negative angles of approach in the top half of the area swept by the rotors (,) and positive angles of approach in the bottom half (,). For upwind flight paths, this is true for positive angles of approach in the top half and negative angles in the bottom.

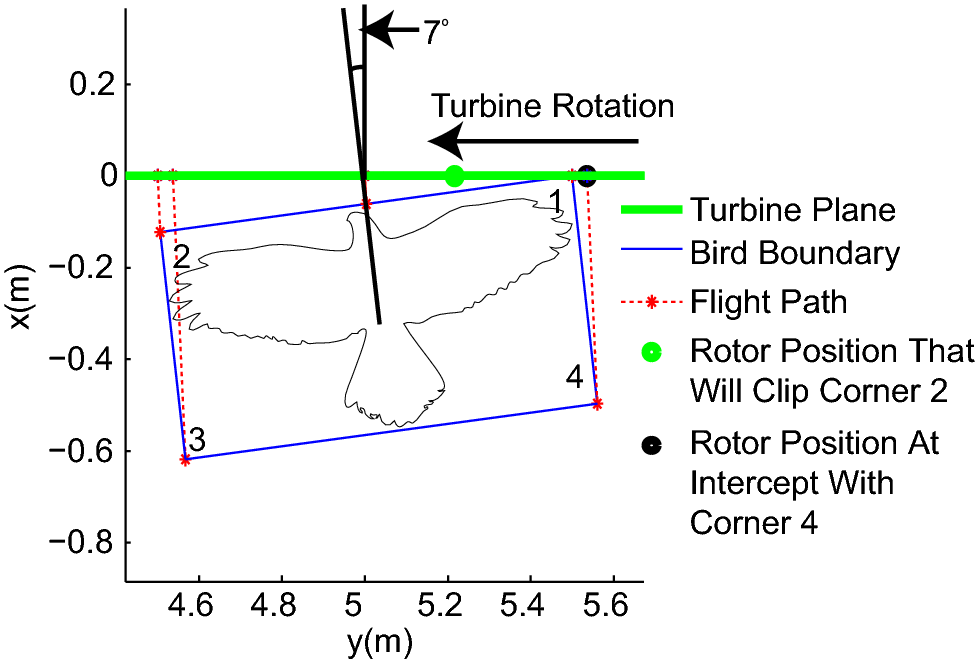


Figure 2. Leading Edge Collision. A bird at the instant it enters the rotor plane for an orientation angle of -7° (approach angle is -2.3°). The bird’s ground velocity  is 15 m/s and the wind velocity  is 10 m/s. The green circle indicates the position of the rotor at this instant that will clip corner 2 of the bird as the bird passes through the rotor plane. Any initial rotor position between this point and corner 1 of the bird will result in a leading edge collision. The black circle indicates the position of the rotor that will clip corner 4 of the bird as it passes through the rotor plane. This is the last point the bird can collide with the rotor since no trailing edge collision is possible in this case.

 (2)

and the y coordinates of these intercepts are given by:

 (3)

where  is specified by the flight path through the rotor plane.

Since the angular distance covered by the rotor in the time it takes corner 2 to cross the rotor plane is given by , the initial rotor position that will intersect with corner 2 as it passes through the rotor plane is given by:



Two cases must be considered to determine the types of collisions possible:  and . These two scenarios may result in leading edge (1-2) and trailing edge (3-4) collisions, respectively. Right edge (1-4) collisions are possible and left edge (2-3) collisions are impossible in both cases.

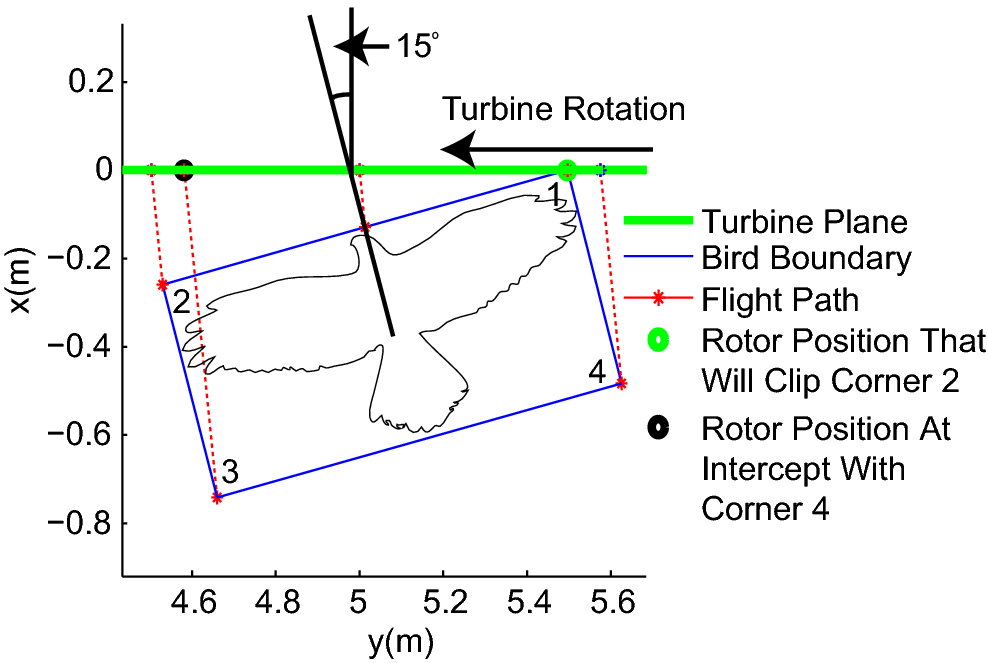


Figure 3. Trailing Edge Collision. A bird at the instant it enters the rotor plane for an orientation angle of -15° (approach angle is -5°). The bird’s ground velocity  is 15 m/s and the wind velocity  is 10 m/s. The green circle indicates the position of the rotor that will collide with corner 1 of the bird at the instant the bird passes through the rotor plane. No leading edge collision is possible in this case. The black circle indicates the position of the rotor that will clip corner 3 of the bird as it passes through the rotor plane. This is the last point the bird can collide with the rotor since a trailing edge collision is possible in this case.

*Leading Edge Collisions* — Even if the rotor is to the left of corner 1 as the bird enters the rotor plane, it is possible for the leading edge of the bird (1-2) to overtake the rotor if , resulting in a collision. In this case, the rotor is traveling to the left at a slower velocity than the point of intersection between the leading edge of the bird and the rotor plane. In this scenario, the bird essentially hits the rotor, rather than the other way around. An example of this situation occurs when =1 m, =0.5 m, =15 m/s, =10 m/s, =72 RPMs, =0.25,  (), and the point where the bird’s nose intersects the rotor plane is (Fig. 2). In this case,



Since the rotor is also traveling to the left at a slower velocity than the point of intersection between the trailing edge of the bird (3-4) and the rotor plane, it is impossible for the rotor to strike the trailing edge (3-4) of the bird. Therefore, the last possible collision with the bird occurs as corner 4 passes through the rotor plane (at the point of the black circle in Fig. 2). This point is given by  in (3). The rotation angle associated with  is  and is given by:



The probability of a collision as the bird passes through the rotor plane is therefore given by:



using  in (2).

The same analysis applies for ,  in downwind flight and ,  in upwind flight except the corner definitions must be swapped to account for the positive angle of approach where corner 2 is the first to intercept the rotor plane.

*Trailing Edge Collisions* — If the angle of approach in this example is changed to (), the increased angle of approach decreases the speed at which the leading edge of the bird (1-2) sweeps through the rotor plane, such that  (Fig. 3). This makes it impossible for a collision to occur between the rotor and the leading edge of the bird. Therefore, the most advanced position of the rotor as the bird enters the rotor plane that will result in a collision is equal to the point where corner 1 crosses the plane (at the point of the grey circle in Fig. 3). This point is given by  in (3). The rotational angle associated with  is  and is given by:



Since the trailing edge of the bird (3-4) also sweeps to the left through the rotor plane slower than the rotor, it is possible for the rotor to clip corner 3 of the bird. Therefore, the last possible collision with the bird occurs as corner 3 passes through the rotor plane (at the point of the black circle in Fig. 3). This point is given by  in (3). The rotation angle associated with  is  and is given by:



The probability of a collision as the bird passes through the rotor plane is therefore given by:



using  in (2).

Again, the same analysis applies for,  in downwind flight and ,  in upwind flight except the corner definitions must be swapped to account for the positive angle of approach where corner 2 is the first to intercept the rotor plane.

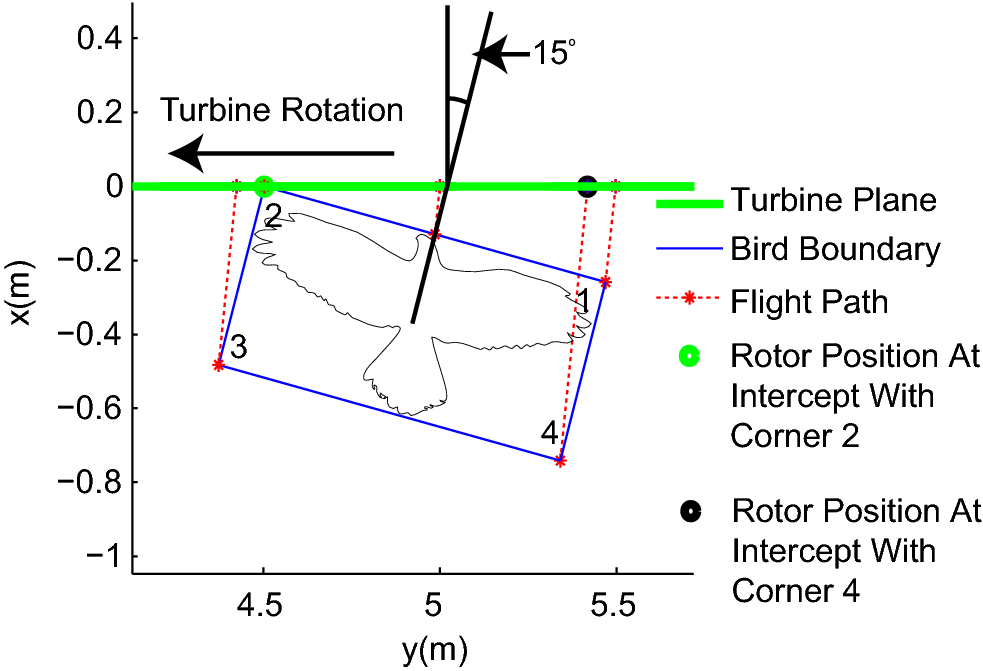


Figure 4. Right Edge Collision. A bird at the instant it enters the rotor plane for an orientation angle of 15° (approach angle is 5°). The bird’s ground velocity  is 15 m/s and the wind velocity  is 10 m/s. The green circle indicates the position of the rotor that will collide with corner 2 of the bird at the instant the bird passes through the rotor plane. No left edge collision is possible in this case. The black circle indicates the position of the rotor that will clip corner 4 of the bird as it passes through the rotor plane. This is the last point the bird can collide the rotor since a right edge collision is possible in this case.

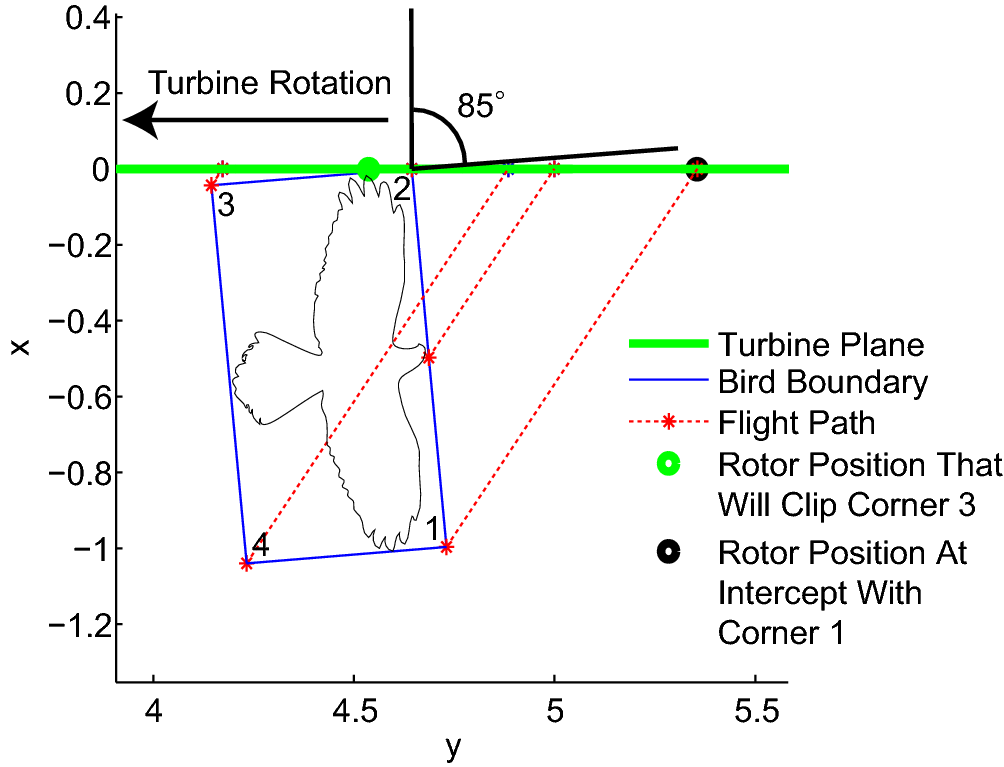


Figure 5. Left Edge Collision. A bird at the instant it enters the rotor plane for an orientation angle of 85° (approach angle is 43°). The bird’s ground velocity  is 15 m/s and the wind velocity  is 10 m/s. The green circle indicates the position of the rotor at this instant that will clip corner 3 of the bird as the bird passes through the rotor plane. Any rotor position between this point and corner 2 of the bird will result in a left edge collision. The black circle indicates the position of the rotor that will clip corner 1 of the bird as it passes through the rotor plane. This is the last point the bird can collide with the rotor since no right edge collision is possible in this case.

Consider the scenario where  and  (Figs. 4 and 5). In this case, corner 2 is the first point of contact of the bird with the rotor plane. If looking down from above, the turbine is rotating to the right. The time  at which corner 2 intercepts the plane is considered to be zero. The time at which the nose and the other corners intercept the rotor plane are given by:

 (4)

and the y coordinates of these intercepts are given by:

 (5)

Since the angular distance covered by the rotor in the time it takes corner 3 to cross the rotor plane is given by , the initial rotor position that will intersect with corner 3 as it passes through the rotor plane is given by:



Two cases must be considered to determine the types of collisions possible:  and . These two scenarios may lead to left edge (2-3) and right edge (1-4) collisions, respectively. Leading edge (1-2) collisions are possible and trailing edge (3-4) collisions are impossible in both cases.

*Right Edge Collisions* — Consider the case where=1 m, =0.5 m, =15 m/s, =10 m/s, =72 RPMs, =0.25, and the angle of approach is () (Fig. 4). In this example, , indicating that if the rotor is to the left of corner 2 as the bird enters the rotor plane, it is impossible for the left edge of the bird (2-3) to overtake the rotor, making a left edge collision impossible. The most advanced position of the rotor as the bird enters the rotor plane that will result in a collision occurs at the point where corner 2 of the bird enters the rotor plane (the grey circle in Fig. 4). The point is given by  in (5). The rotational angle associated with  is  and is given by:



Since the right edge of the bird (1-4) also sweeps through the rotor plane slower than the rotor sweeps to the left, it is possible for the rotor to clip corner 4 of the bird. Therefore, the last possible collision with the bird occurs as corner 4 passes through the rotor plane (the black circle in Fig. 4). This point is given by  in (5). The rotation angle associated with  is  (see bottom pane of Fig. 1) and is given by:



The probability of a collision as the bird passes through the rotor plane is therefore given by:



using  in (4).

The same analysis applies for,  in downwind flight and,  in upwind flight except the corner definitions must be swapped to account for the negative angle of approach where corner 1 is the first to intercept the rotor plane.

*Left Edge Collisions* — Consider the scenario where the angle of approach is increased to () (Fig. 5). In this case, the increased angle of approach increases the speed at which the left edge of the bird (2-3) sweeps through the rotor plane, such that . This makes it possible for a collision to occur between the rotor and the left edge of the bird. The initial position of the rotor (at ) that will clip corner 3 of the bird as the bird passes through the rotor plane (the grey circle in Fig. 5) is given by:



Since the right edge of the bird (1-4) also sweeps to the left through the rotor plane faster than the rotor, it is impossible for the rotor to clip corner 4 of the bird. Therefore, the last possible collision with the bird occurs as corner 1 passes through the rotor plane (the black circle in Fig. 5). This point is given by  in (5). The rotation angle associated with  is  and is given by:



The probability of a collision as the bird passes through the rotor plane is therefore given by:



using  in (4).

The same analysis applies for,  in downwind flight and ,  in upwind flight except the corner definitions must be swapped to account for the negative angle of approach where corner 1 is the first to intercept the rotor plane.

**2.9 Accounting for 3-D Rotor Blades**

We adapted existing methods to include the effects of 3-D rotor blades (Tucker 1996a). The chord length  and rotation  at each point along the length of the rotor  are defined as:

and

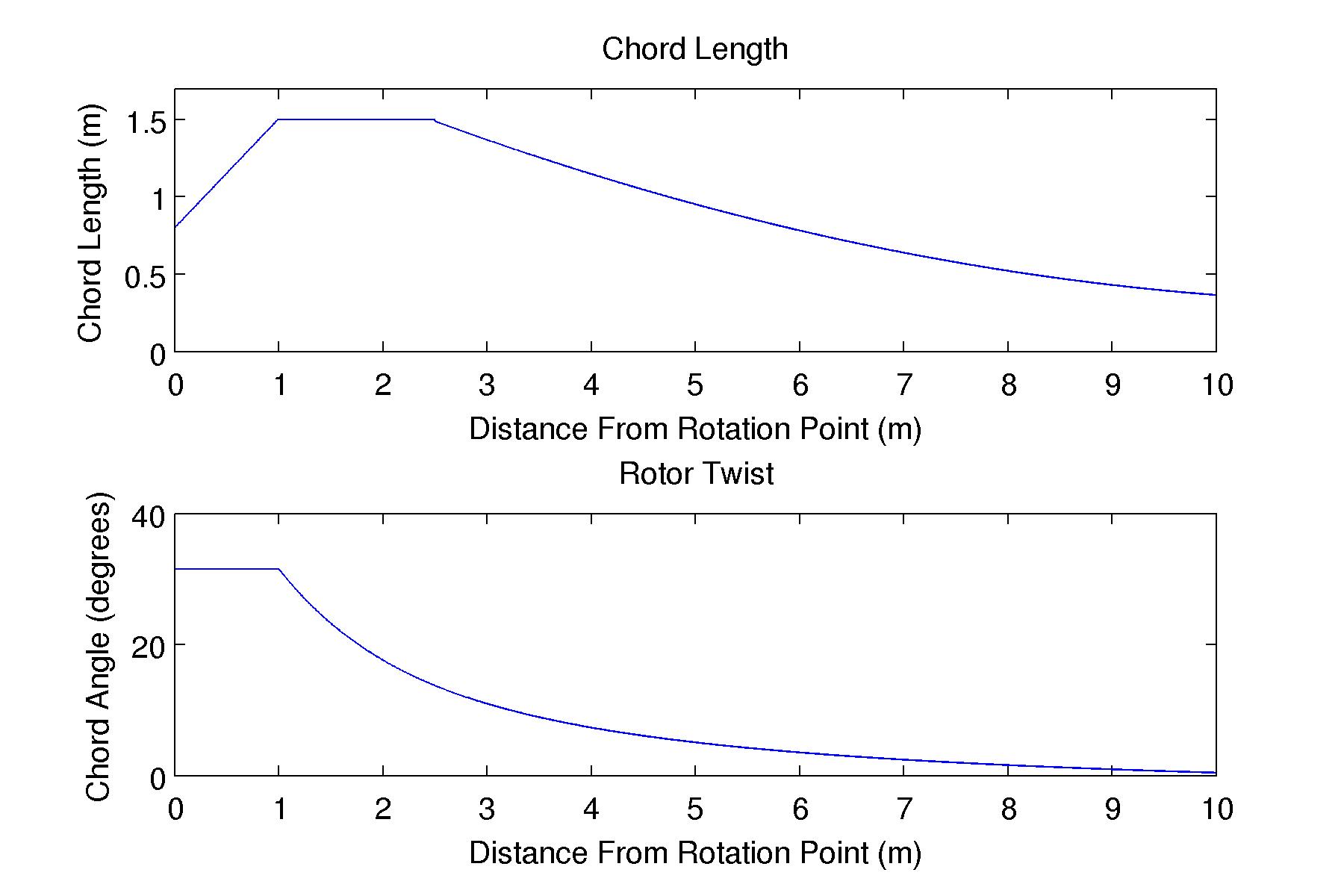


Figure 6. Three-dimensional rotor blade characteristics. Using only the maximum chord length  and the length of the rotor , the chord length  and chord angle  can be calculated. This figure shows the values of  and  for a rotor with  and .

chord length at the base of the rotor, , the ,,, Additionally, the rotors of modern turbines are often pitched in order to maximize the power transfer of the wind. The pitch value can be added to the chord rotation angle, *β*, to determine the composite chord rotation. A rotation of 0 degrees maximizes the wind profile of the chord, while a rotation of 90 degrees minimizes it.

The 3-D collision probability is calculated by adding a correction to the 1-D collision probability calculation described in the previous sections:



where  is the 3-D collision probability,  is the 1-D collision probability, and  is the additional probability of collision with the 3-D extension of the rotor extending behind the front rotor plane. This additional probability can be calculated using the formula:



where



is the angle subtended by the width of the rotor blade,



is the angular distance the blade progresses in the time it takes for the bird to pass from the front to the back of the rotor plane, and



is the angular drift of the bird in the y-axis in the time it takes for the bird to pass from the front to the back of the rotor plane. If the bird is flying upwind or downwind and , then  and  is identical to the formula proposed in Tucker (1996a), with the exception that no small angle approximation is used in the current analysis.

**3. Results**

Unless otherwise noted, we used the following input parameters for the following examples: =1 m, =0.5 m, =15 m/s, =10 m/s, =3 rotors, =10 m, =0 m, =72 RPMs, =0.25. We chose these parameters because they are identical to those used by Tucker (1996a), allowing direct comparison of model results. Our Hamer Model as an extension to the Tucker model, and the models produce identical results in the configurations where the bird’s wind speed is parallel or perpendicular to the wind direction. Our final result shows the importance of modeling oblique angles of approach, and we use realistic turbine parameters modeled after a common General Electric 1.5 MW (GE 1.5se) design.

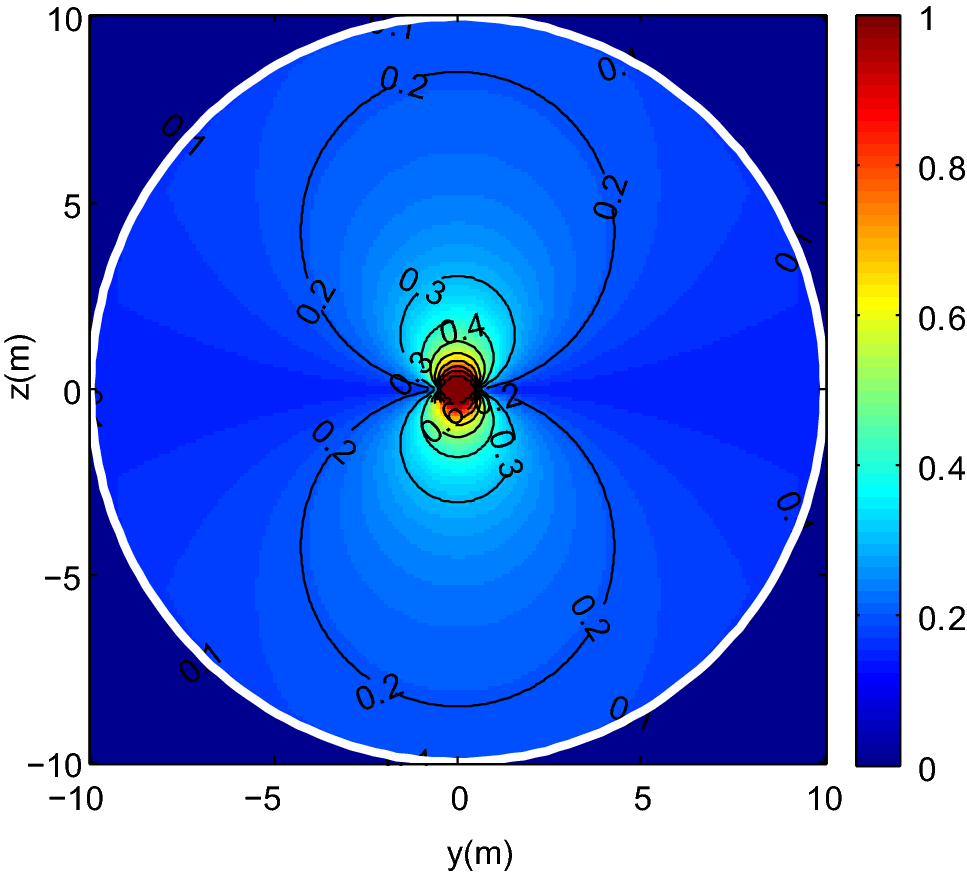


Figure 7. Probability contours for a downwind flight path where the bird’s ground velocity  is 15 m/s and the wind velocity  is 10 m/s.

**3.1 Collision Probability Contours for 1-D Rotors**

*Upwind and Downwind Turbine Collision Probabilities* — A plot of the collision probability contours was generated for downwind flight paths, predicting an increasing probability of collision above and below the center of the turbine (Fig. 7). We expect this result, because the wingspan of the bird subtends a larger angle swept out by the turbine as it enters the rotor plane closer to horizontal center. These results are identical to those published by Tucker (1996a) using the same model parameters.

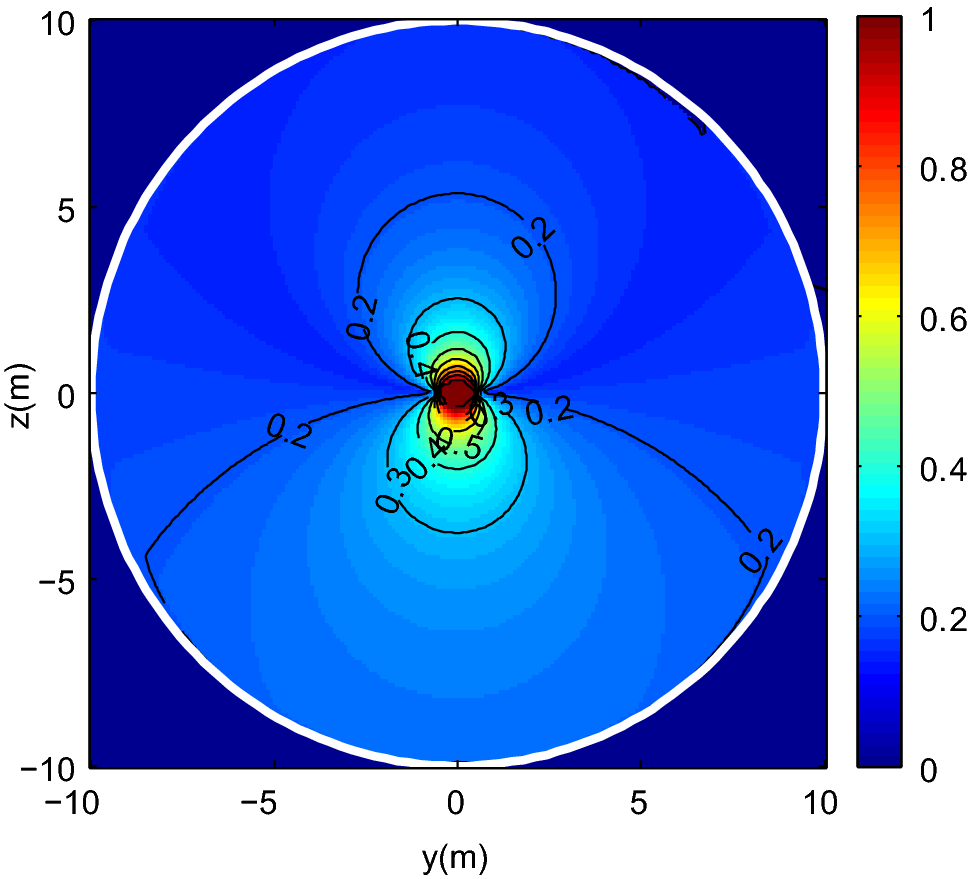
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Figure 8. Probability contours for a downwind flight path where the orientation angle is -7° (approach angle is -2.3°), the bird’s ground velocity  is 15 m/s, and the wind velocity  is 10 m/s.

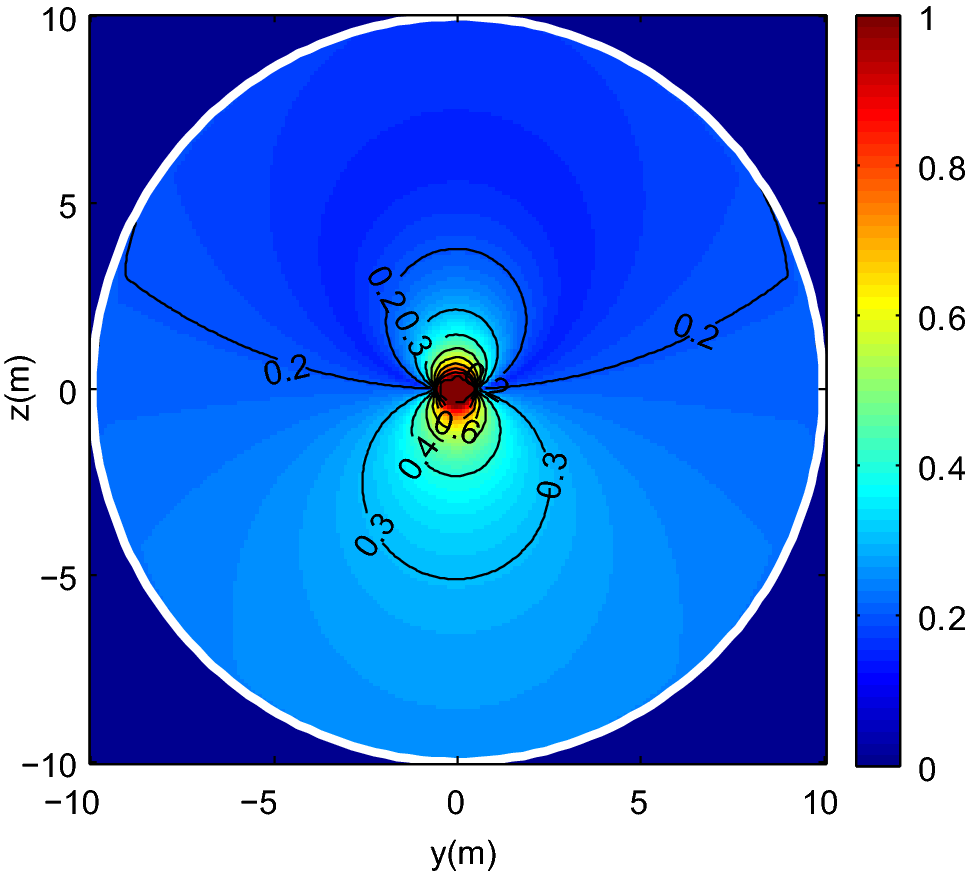
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Figure 9. Probability contours for a downwind flight path where the orientation angle is -15° (approach angle is -5°), the bird’s ground velocity  is 15 m/s, and the wind velocity  is 10 m/s.

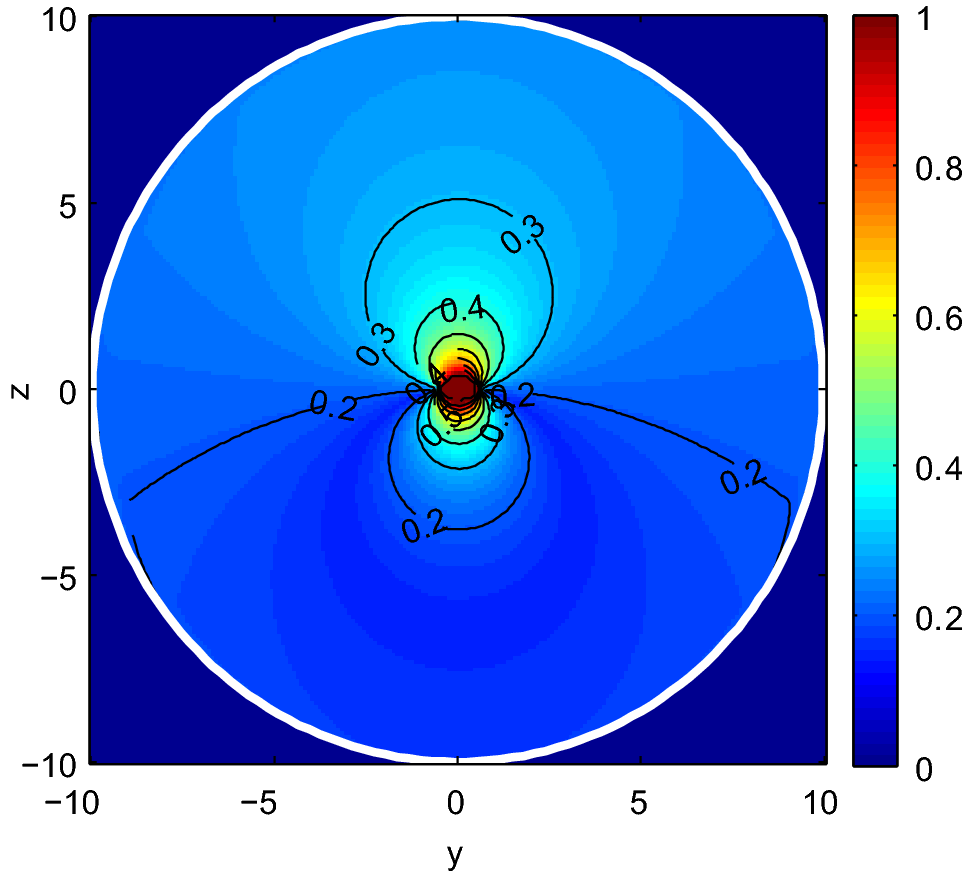


Figure 10. Probability contours for a downwind flight path where the orientation angle is 15° (approach angle is 5°), the bird’s ground velocity  is 15 m/s, and the wind velocity  is 10 m/s.

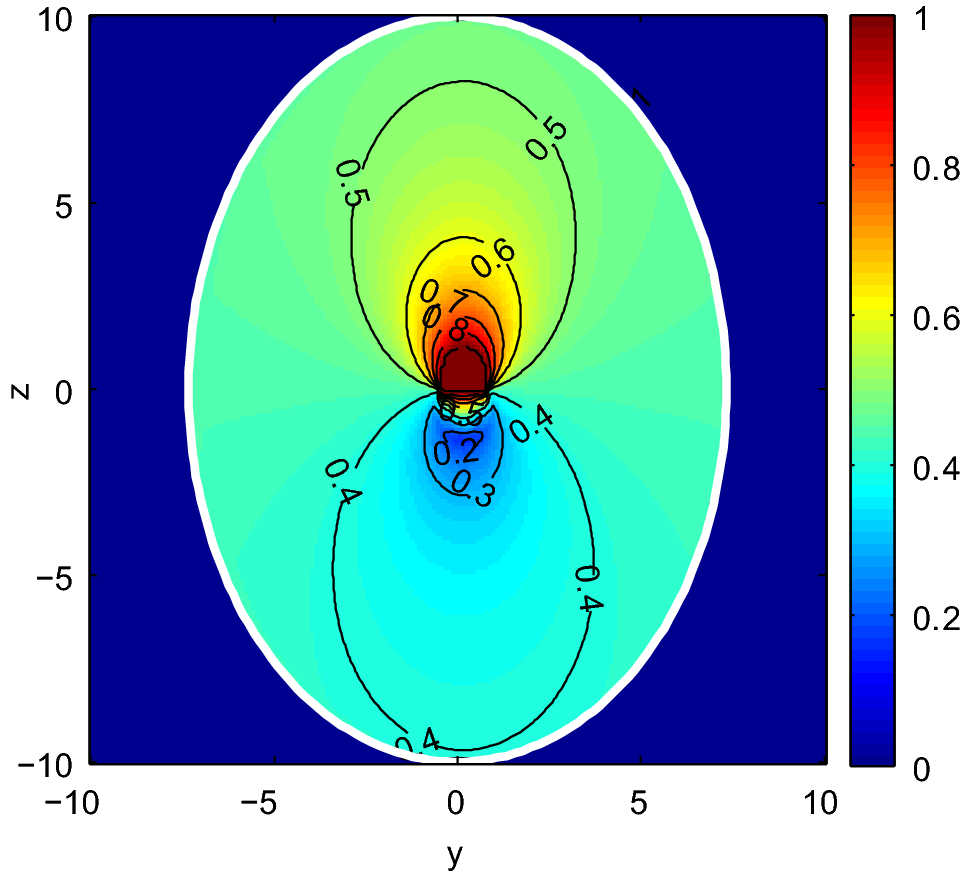


Figure 11. Probability contours for a downwind flight path where the orientation angle is 85° (approach angle is 43°), the bird’s ground velocity  is 15 m/s, and the wind velocity  is 10 m/s. Note that the oblique angle of approach leads to a reduced turbine profile. Also note, however, that the probability of collision increases because the bird spends more time in the rotor plane.

*Oblique Approach Turbine Collision Probabilities* — Contour plots of the collision probability contours were generated for the four approach angles described above: , , , and  (Figs. 8-11, respectively). These flight path approach angles correspond to bird orientation angles of , , , and due to the effects of the wind. For the  orientation, the contours are not symmetric about the horizontal axis (Fig. 8). Since the bird is moving to the left, it is traveling in the direction of the rotors in the top half of the turbine and against the direction of the rotors in the bottom half. As a result, the probability of a collision is higher in the bottom half. For the orientation (Fig. 9), this effect is amplified. The collision probabilities are higher for this case since the oblique angle of approach means that the birds spend more time in the plane of the rotors. For the  orientation (Fig. 10), the probabilities are identical to a  orientation flipped about the horizontal axis of the turbine. This is because the bird is now moving against the direction of the rotor rotation in the top half and with the direction of the rotor rotation in the bottom half. For the  orientation (Fig. 11), the highly oblique  angle of approach results in a high probability of collision across the entire face of the turbine. The profile of the turbine, as viewed by the bird, is significantly reduced, however, resulting in a more narrow range of flight paths that may result in a collision.

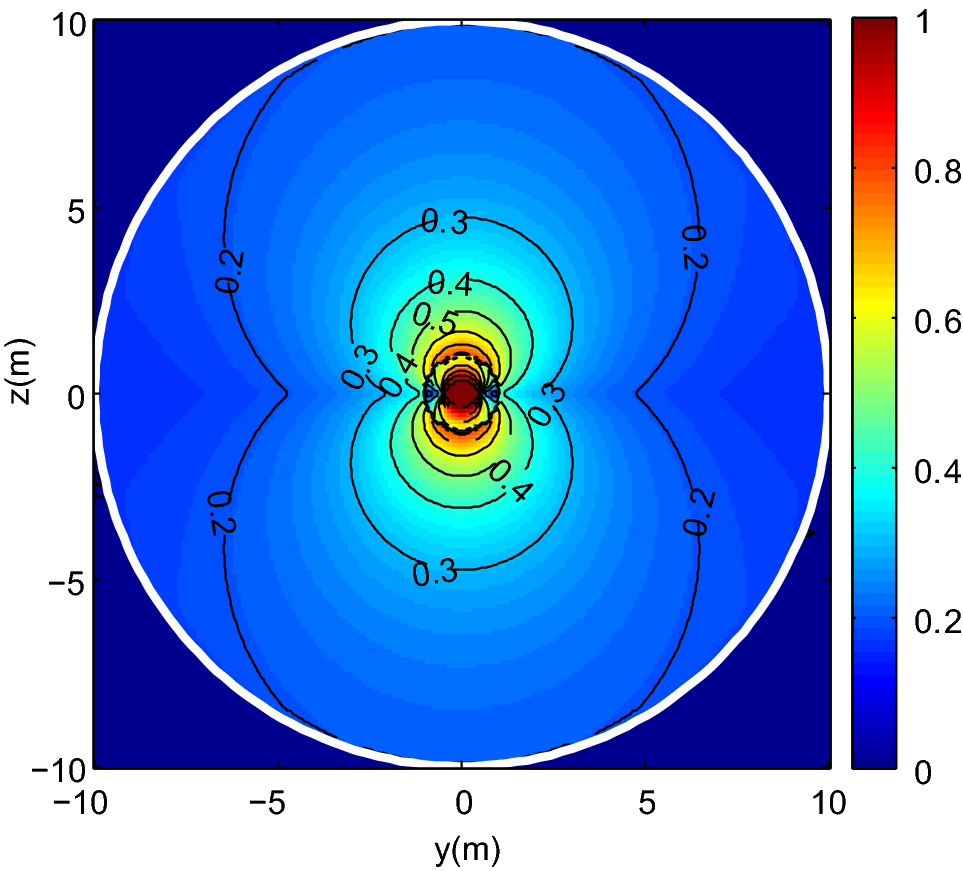


Figure 12. Probability contours for downwind flight accounting for 3-D rotors. The probabilities are elevated relative to the results assuming 2-D rotors.

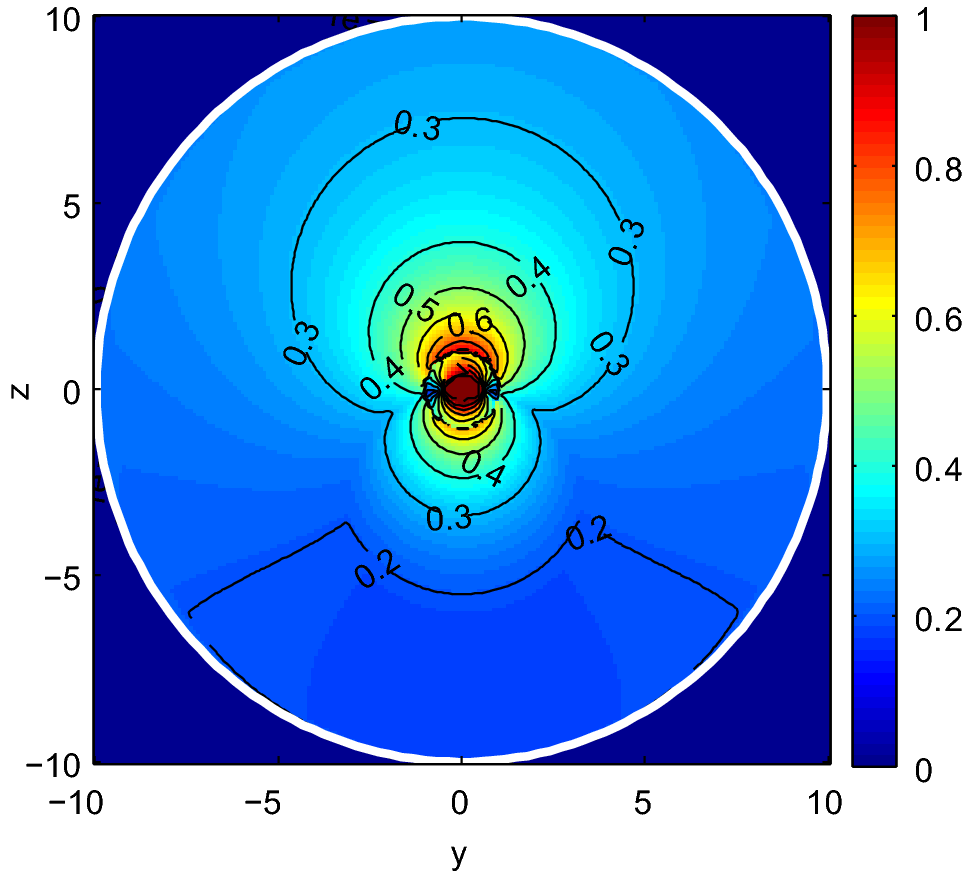


Figure 13. Probability contours for a flight path where the orientation angle is 15° (approach angle is 5°) accounting for 3-D rotors. These collision probabilities are elevated relative to the downwind, 3-D probability estimates. Note that the “boxy” shape of the contour on the bottom is due to the changing rotor chord length as the radius changes.

**3.2 Collision Probability Contours for 3-D Rotors**

A plot of the collision probability contours was generated for a downwind flight path for the case where  (Fig. 12). Otherwise, the parameters were identical to those used in the 1-D example (Fig. 7). The inclusion of the 3-D rotor characteristics results in a greater probability of collision across the entire turbine. These contours are identical to those predicted by the Tucker model using the same parameters.

A plot of the collision probability contours was generated for the same model parameterization, except an approach angle of  was used ( orientation angle) (Fig. 13). Similar to the 1-D case, the probability of collision is elevated across the entire turbine, due to the increased angle of approach.

**3.3 The Effect of Approach Angle on Collision Probability Estimates**

In contrast to the previous examples which were parameterized in order to compare the results with the reference Tucker Model, this example uses actual turbine parameters and avian flight path data collected in the field (see Data Collection for Raptor Risk of Collision Case Study in Central Washington in Methods). The turbine parameters chosen for this example correspond to a modern GE 1.5se turbine: =3 rotors, =35.25 m, =5 m, =16.6 RPMs, =0, =1.5 m.

We recorded 89 flight speeds for the Sharp-shinned Hawk. These were normally distributed with a mean of 16.1 m/s and a standard deviation of 3.4 m/s. We recorded 69 flight speeds for the Golden Eagle. These were also normally distributed and had a mean of 19.3 m/s and a standard deviation of 3.3 m/s. For the Sharp-shinned Hawk we used a body length of 0.29 m and a wingspan of 0.59 m, which are the mean values of the full range reported for males of the species (Dunn and Alderfer 2006). For the Golden Eagle we used a body length of 0.77 m and a wingspan of 2.03 m, which are the mean values of the full size range for both males and females of the species (Dunn and Alderfer 2006).

The scenario illustrated in this example is one in which the ground velocity of the bird is a known quantity (as a result of field surveys), but the wind speed and direction are not. The question being addressed is what effect does the wind speed and direction, and therefore the turbine orientation, have on the estimated collision probabilities for a bird moving at a fixed ground speed.

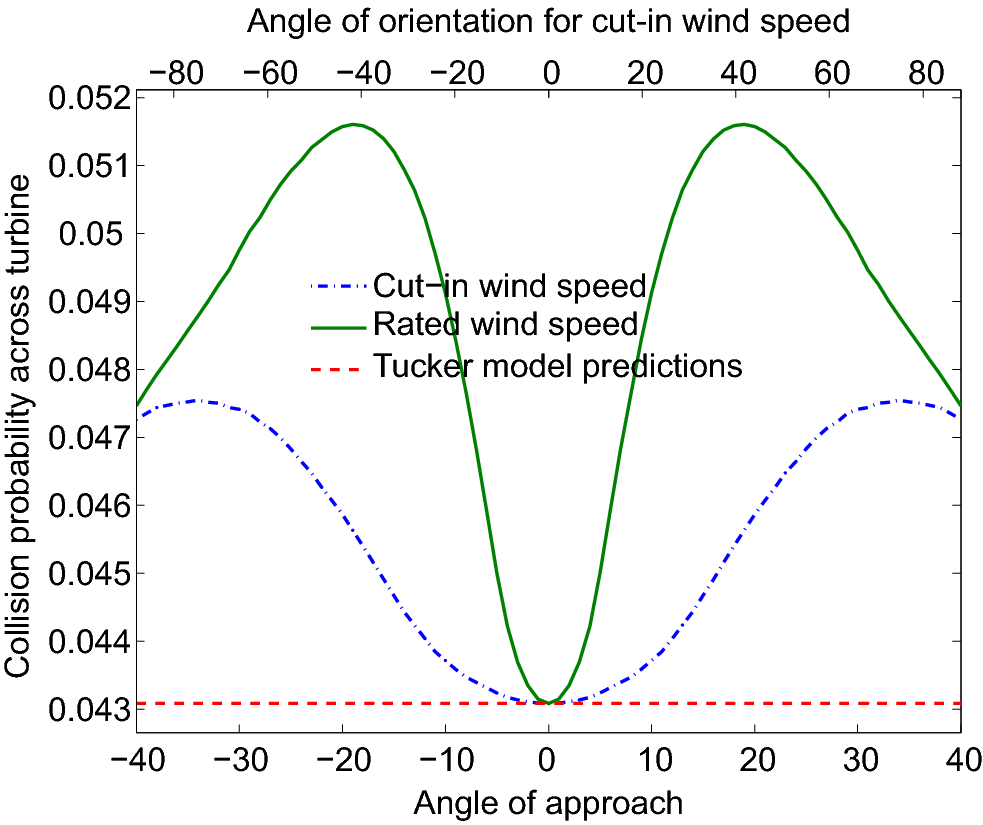


Figure 14. A comparison of average collision probabilities across a single GE 1.5se wind turbine for different Sharp-shinned Hawk flight path approach angles relative to downwind, using the mean recorded ground velocity of 16.1 m/s measured in the field study. The dashed, flat line indicates the collision probability assuming downwind flight, which is the equivalent result that would be obtained from an application of the Tucker model. The dot-dashed and solid lines indicate the estimated collision probabilities assuming the wind speed is equal to the cut-in wind speed (4 m/s) and rated wind speed (12 m/s) for the GE 1.5se wind turbine. The values on the x-axis across the top of the figure indicate the bird's angle of orientation as it approaches the wind turbine for the rated wind speed.

We calculated a comparison of average collision probabilities across a single GE 1.5se wind turbine for different Sharp-shinned Hawk flight path approach angles relative to downwind using the mean recorded ground velocity of 16.1 m/s measured in the field study (Fig. 14). To generate the collision probabilities for each wind direction, a uniform sampling of flight paths intersecting with the rotor plane was used across the entire surface of the area swept out by the turbine rotors. Each average collision probability was then adjusted to account for the reduced area that may result in a collision when the rotor is rotated with respect to the flight path. First, probabilities were calculated for downwind flight (the dashed, flat line at the bottom of Fig. 14), which produces the same result that would be obtained from an application of the Tucker Model.

Probabilities were also calculated for a number of different wind directions assuming that the wind speed was equal to either the cut-in wind speed of 4 m/s (the dot-dashed line in Fig. 14) or the rated wind speed of 12 m/s for the GE 1.5se wind turbine (the solid line in Fig. 14). The cut-out wind speed of 28 m/s for the GE 1.5se wind turbine was not used, because it would require that the bird was flying backwards. Due to the effects of wind, the orientation of the bird and the flight path direction are not, in general, the same (see top and bottom axes of Fig. 14). Our results show that even though the area that may result in a collision is reduced when the bird is not flying downwind, the increased possibility of collision across this area results in a net increase in collision risk. For this example, at angles of approach of  and a wind speed of 4 m/s, the probability of collision is at a maximum and results in a 10% increase over a downwind flight path. At angles of approach of  and a wind speed of 12 m/s, the probability of collision is at a maximum and results in a 20% increase over a downwind flight path. At angles of approach of  and a wind speed of 12 m/s, the bird's orientation angle is almost perpendicular to the plane of the rotor. Angles greater than this were not used because they resulted in scenarios where the angle of orientation is greater than , indicating that the bird is being pushed backwards by the wind and not considered a likely scenario.

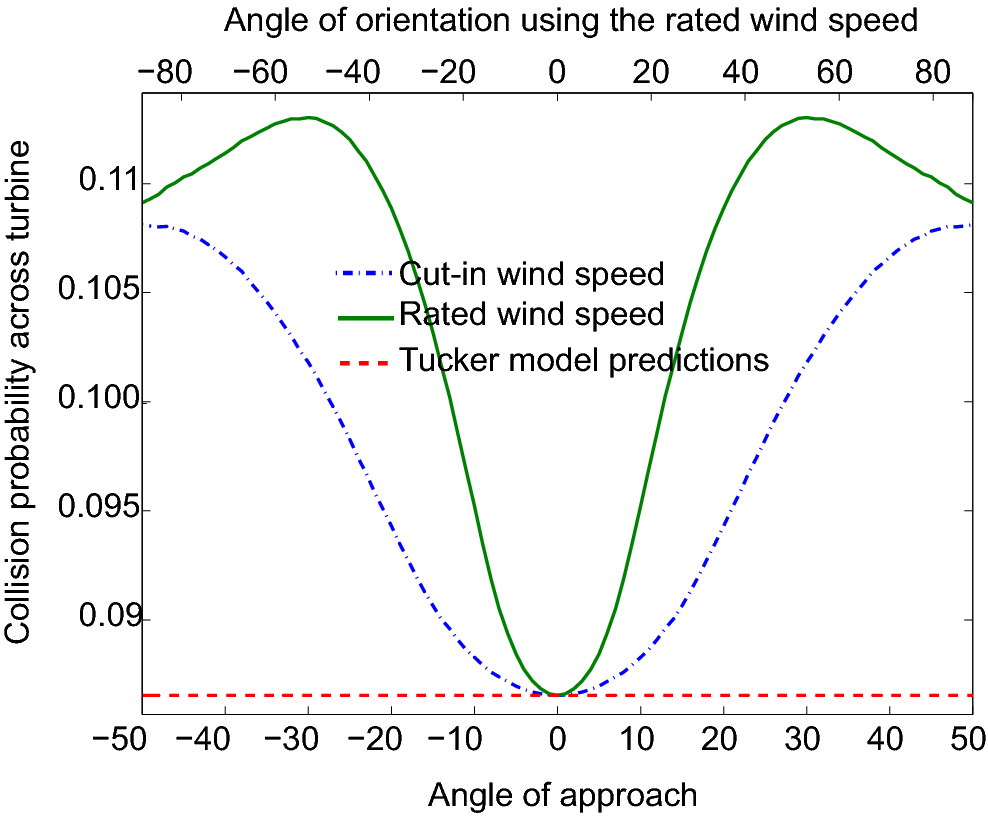


Figure 15. A comparison of average collision probabilities across a single GE 1.5se wind turbine for different Sharp-shinned Hawk flight path approach angles relative to downwind, using the mean recorded ground velocity of 19.3 m/s measured in the field study. The dashed, flat line indicates the collision probability assuming downwind flight, which is equivalent the result that would be obtained from an application of the Tucker model. The dot-dashed and solid lines indicate the estimated collision probabilities assuming the wind speed is equal to the cut-in wind speed (4 m/s) and rated wind speed (12 m/s) for the GE 1.5se wind turbine. The values on the x-axis across the top of the figure indicate the bird's angle of orientation as it approaches the wind turbine for the rated wind speed.

Next, we used the same approach to calculate a comparison of average collision probabilities across a single GE 1.5se wind turbine for different Golden Eagle flight path approach angles relative to downwind, using the mean recorded ground velocity of 19.3 m/s measured in the field study (Fig. 15). For this example, at angles of approach of  and a wind speed of 4 m/s, the probability of collision is at a maximum and results in a 25% increase over a downwind flight path. At angles of approach of  and a wind speed of 12 m/s, the probability of collision is at a maximum and results in a 31% increase over a downwind flight path.

**4.1 Management Implications**

Our results show that wind speed and direction are important and significant factors when estimating avian collision mortality rates at proposed wind farm sites. Not only should we measure bird and wind velocities at these sites, but we need to employ an avian collision model which accurately accounts for these variables to improve the quality of an impact assessment. The proposed Hamer model offers a more accurate tool to aid in educated land management decisions for renewable energy development.

**REFERENCES**

Chamberlain, D. E., Rehfisch, M. R., Fox, A. D., Desholm, M., Anthony, S. J., 2006. The effect of avoidance rates on bird mortality predictions made by wind turbine collision risk models. The International Journal of Avian Science 148, 198–202.

Desholm, M., Kahlert, J. 2005. Avian collision risk at an offshore wind farm. Biology Letters 1, 296–298.

Desholm, M, Fox, A. D., Beasley, P. D. L, Kahlert, J., 2006. Remote techniques for counting and estimating the number of bird-wind turbine collisions at sea: a review. Ibis 148, 76-89.

Dunn, J.L., Alderfer, J., 2006. National Geographic Field Guide to the Birds of North America, Fifth Edition. National Geographic Society, Washington, D.C., USA, 504 pp.

Kahlert, J., Petersen, I. K., Fox, A. D., Desholm, M., Clausager, I., 2003. Investigations of birds during construction and operation of Nysted offshore wind farm at Rodsand. National Environmental Research Institute, Ministry of the Environment, Tech. Rep. Copenhagen, Denmark.

Shire, G.G., Brown, K., Winegrad, K., 2000. Communication towers: a deadly hazard to birds. American Bird Conservancy, Washington, DC, USA.

Thelander, C., Smalwood, K., Rugge, L., 2003. Bird risk behaviors and fatalities at the Altamont Pass Wind Resource Area. National Renewable Energy Laboratory, Tech. Rep.

Tucker, V. A. 1996a. A mathematical model of bird collisions with wind turbine rotors. ASME Journal of Solar Energy Engineering. 118, 253–262.

Tucker, V. A. 1996b. Using a collision model to design safer wind turbine rotors for birds. ASME Journal of Solar Energy Engineering. 118, 263–270.

Williams, T. C., Williams, J. M., Williams, P. G., Stokstad, P., 2001. Bird migration through a mountain pass studied with high resolution radar, ceilometers, and census. The Auk 118, 389-403.



Wilson, R. E. 1994. Aerodynamic Behavior of Wind Turbines. ASME Press, New York, NY, USA, pp. 215–282.