A Simple and Effective Method for Analyzing Propeller Marks on Manatees in Brevard County, Florida, USA

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ABSTRACT

There appears to be a general assumption that vessel speed is a major factor in accidents that involve vessels striking marine mammals, but the lack of suitable methods for determining the types of vessels that are most often involved in these accidents has prevented researchers from properly testing this hypothesis. The methods presented here allow researchers to use gross measurements of propeller marks on marine mammals to help determine the types of vessels that created the marks. Once the types of vessels generally responsible for these accidents are determined, researchers can examine the physical characteristics of these vessels and the operational procedures that would most likely be employed in the locations where these accidents occur and determine if a specific cause effect relationship can be identified. The Florida manatee (Trichechus manatus latirostris) and the vessels operating in the Indian River Lagoon in Brevard County, Florida, USA are used as models for developing these methods, but the resulting methods can be applied to marine mammals in general and to most geographic locations.

When marine mammals are struck by vessels, the results are at best annoying to the animal and at worst fatal. Strikes on the Florida manatee (Trichechus manatus latirostris) are no exception. The general assumption appears to be that the speed of the vessel is a significant factor in the cause of these accidents (O'Shea 1995). Though this assumption may be true in some specific cases where the details of the incident have been reported to researchers, the lack of suitable methods of analysis has prevented researchers from testing this hypothesis in the general sense. Many of these accidents are the result of impact with the hull of the vessel and do not include any discernible marks from the propeller or other structures that would lend themselves to detailed analysis (Wright et al. 1995). However, when propeller marks are present, they provide researchers with an opportunity to determine the types of vessels involved in the accidents. Once the types of vessels are determined, it may be possible to examine the physical characteristics of these vessels and the operational procedures that would most likely have been employed in the location where the accidents occur to determine if a specific cause effect relationship can be identified.

One of the more obvious methods for analyzing propeller cuts on manatees is to predict the patterns of marks a specific vessel could create under various circumstances. Such methods are likely to fail simply because the vast number of variables required for such an analysis would be difficult if not impossible to quantify accurately. A more manageable approach to this problem is to identify and analyze the physical characteristics of a specific set of propeller marks which are the direct result of the cumulative effects of all of these variables. Even though the full array of forces that existed when the propeller marks were created is not known, their cumulative effect is readily measurable in the physical dimensions of the resulting marks.

The method of analysis presented here is a two step process that looks at propeller marks where the length and depth of individual cuts and the distance between successive cuts in a series of propeller marks can be physically measured. These marks are analogous to footprints in the sand on a beach. Any attempt to predict the size and spacing of the footprints that an individual might leave in the sand would require specific knowledge of the individual and the conditions that exist when the footprints are made. However, once the footprints have been left in the sand, measuring the length and depth of each foot print and the distance between successive footprints is a very simple task that does not require any knowledge of how they got there. It can be stated with certainty that the person that left the footprints had feet of a general size capable of producing the observed footprints and moved the distance between successive footsteps in the time required to take one step.

So it is with the propeller marks on manatees. The size and spacing of the propeller marks can be measured without any knowledge of how they got there. Once the measurements have been made, it can be stated with certainty that the vessel that left the marks is capable of producing the observed marks under whatever conditions existed at the time. The length, depth and shape of each cut as well as the separation between these propeller marks is dependant on the size of the propeller, the shape of the blades, rotational speed of the propeller, pitch of the propeller, design of the hull, slippage in the system, the shape of the surface being cut and a multitude of other variables that may not be known. However, the ability to determine the physical dimensions of the propeller marks is simply a matter of measuring them.

ANALYZING A SERIES OF PROPELLER MARKS

Propeller mark patterns distinguished by a series of marks spaced at intervals provide a means of identifying the types of vessels that could have created the marks, provided the types of vessels under consideration have distinctly different operating characteristics. The vessels that frequent the Indian River Lagoon in Brevard County, Florida, USA can be used as an example of vessels with distinctly different operating characteristics. The vessels that operate in the lagoon, a body of water which is also frequented by manatees, can be divided into two groups based on the characteristic rotation speed of their propellers when they are traveling at specific speeds, and a chart can be used to illustrate these differences.

Categorizing Vessels

A simple method of defining the operational characteristics of a vessel is to consider the rotational speed of its propeller when the vessel is operated at idle speed and when the vessel is operated at cruising or working speed. This relationship between propeller rotation speed and boat speed can be illustrated by plotting these two points on a chart of boat speed in miles per hour (mph) versus propeller rotation speed in revolutions per minute (rpm). It can be temporarily assumed that the relationship between the vessel's propeller rpm at other speeds can be illustrated by drawing a straight-line plot defined by these two points. It should be noted that most performance data available for general watercraft of the size being considered here are presented as vessel length in feet and vessel speed in mph; therefore, the inch/pound/second units will be used as the primary units of measure.

This assumed straight-line relationship between propeller rpm and vessel speed is not strictly true. Chart-1 is an actual performance curve produced from boat performance data reported as engine rpm at specific boat speeds. The engine gear ratio is then used to calculate a corresponding propeller rpm, and the results are plotted as boat speed verses propeller rpm. Even though the actual performance curve is not a straight line, Chart-1 does illustrate that a straight line can be used to approximate the general performance characteristics of the vessel.

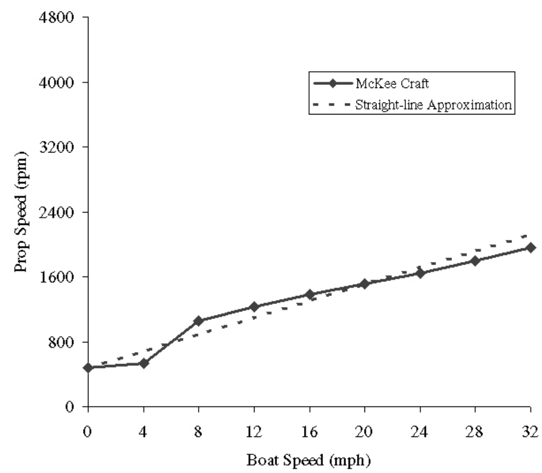

Chart-1: A boat's performance curve can be approximated by a straight line.

Even though an actual performance curve is not generally a straight line, Chart-2 illustrates that a straight-line approximation of an actual performance curve can be used to define the upper and lower limits for the operating range of a category of vessels. The dashed lines in Chart-2 represent straight-line performance curves of two general purpose watercraft that operate in the Indian River Lagoon. These straight-line performance curves are obtained by determining the engine rpm for each boat at idle speed and at cruising speed. The reduction gear ratio for each boat is used to convert the engine rpm at each speed to the appropriate propeller rpm. The results for each vessel are plotted as propeller rpm verses boat speed.

The upper line in Chart-2 represents a small skiff, about 12 feet (3.7 meters) long, powered by a small, 7.5 horsepower, outboard motor. This boat operates at idle speed with a propeller rotation of about 500 rpm and at a cruising speed of 16 mph (14 Kts) with a propeller rotation of about 2100 rpm (personal experience). It is important to note that the idle speed is not actually zero. The idle speed is some value slightly above zero, but, for this analysis, the errors introduced in this region by substituting zero are not significant. The lower line represents a large cruiser, 50 feet (15.2 meters) long, powered by large diesel engines connected to a screw and rudder propulsion system. This boat operates at idle speed with a propeller rotation of about 400 rpm and at a cruising speed of 20 mph (17.4 Kts) with a propeller rotation of about 1200 rpm (communication with vessel Captain).

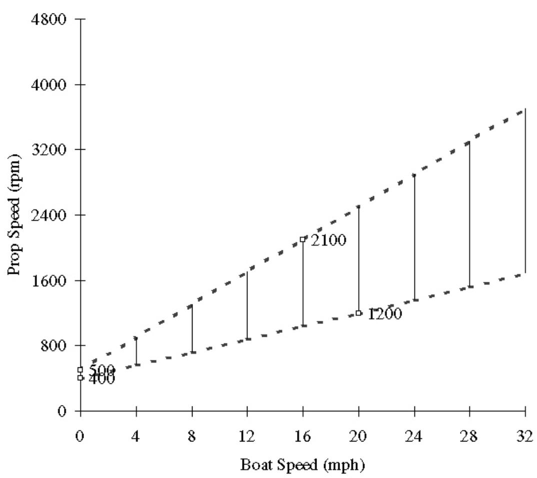

Chart-2: The operating range of general watercraft can be established by using straight-line approximations of the performance curves of two boats representing opposite ends of the spectrum of general watercraft operating in the study area.

These two boats can be used to represent the opposite ends of the spectrum of general purpose watercraft operating in the Indian River Lagoon, and the performance curves for most other general watercraft should fall within the region between these two lines. While it is true that there may be boats operating in this area that are either larger or smaller than these two examples, it can be temporarily assumed that their performance curves will not vary significantly from the region within the chart that is defined by these two examples.

The dashed lines in Chart-3 represent an approximation of the upper and lower performance curves of tugs operating in the Indian River Lagoon. These tugs operate at idle speed, again arbitrarily assumed to be zero, with a propeller rotation between 80 and 100 rpm. They operate at a working speed of between five and eight mph (four and seven Kts) with a propeller rotation of 120 to 300 rpm (communication with vessel Captains). As with the general purpose watercraft, the area between these two lines should fairly approximate the performance curves of the tugs operating in this area. It should be noted that these performance curves for the tugs are extended out to 32 mph (28 Kts). This has been done for visual clarity and to be consistent with the operating range of general watercraft represented in Chart-2. It is not intended to suggest that the tugs actually operate at this speed.

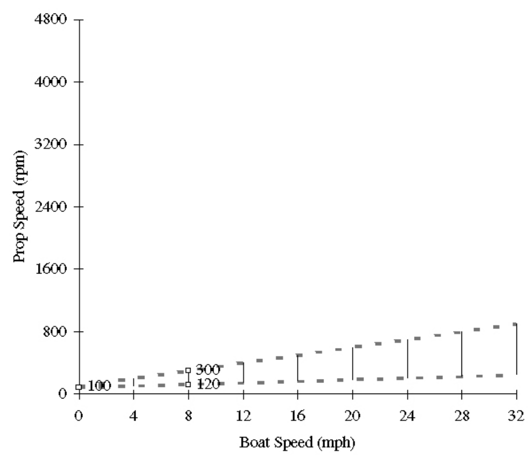

Chart-3: The operating range of tugs can be established by using straight-line approximations of performance curves. These straight-line approximations have been extended to 32 mph for visual clarity and consistency with Chart-2.

Chart-4 combines the relationships illustrated in Chart-2 and Chart-3. The most notable feature illustrated in this chart is that the operating range for general watercraft is distinctly different from the operating range for tugs. This distinct difference between these two categories of boats is a direct result of their design characteristics. Tugs are designed to move heavy loads of materials at slow speeds. They use powerful engines connected to large propellers that turn at low rpm. General watercraft are designed to

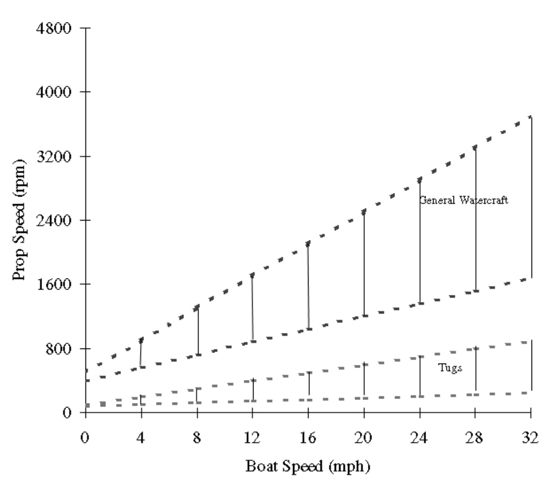

Chart-4: The operating ranges of general watercraft and tugs are distinctly different.

transport smaller loads of people or materials at moderate speeds. They use much smaller engines connected to smaller propellers that turn at relatively high rpm. It is this fundamental difference between the operating characteristics of these two categories of boats that makes it often possible to distinguish between patterns of propeller marks that each can make.

Characterizing Propeller Marks

The distance between successive marks in a series of propeller marks ("χ" in Figure-1) is of particular interest since it is a direct result of the cumulative effects of the forces present at the time the marks were made. The illustration of propeller marks presented in Figure-1 can be used to derive a simple equation defining the relationship between the separation between the cuts in an observed set of propeller marks, the relative speed of a boat that produced the propeller marks and the rotational speed of the propeller. The derivation for this equation is presented in Appendix-A, and the resulting equation is presented below.

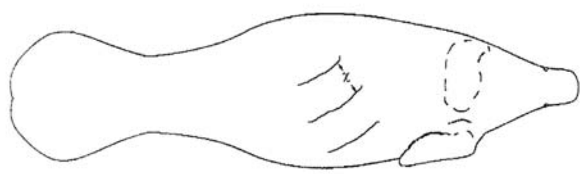

Figure-1: The distance between marks in a series of propeller marks is of particular interest.

$$S = (n\chi\lambda) / 1056$$

Where:

- S = boat speed relative to surface where propeller marks occur in miles per hour (mph)
- n = a constant representing the number of blades on the propeller
- χ = a constant representing the distance between adjacent propeller marks in inches
- λ = rotation speed of the propeller in revolutions per minute (rpm)
- 1/1056 = a constant used to convert from inches per minute to miles per hour (mph)

This formula is not intended to be a method of measuring boat performance or propeller efficiency. However, it can be used to create a chart of propeller speed and boat speed combinations that are capable of producing propeller marks separated by specific distances. Chart-5 shows the boat speed and propeller rotation combinations, for a three-blade propeller, capable of producing propeller marks separated by distances ranging from two inches (five cm) to 20 inches (51 cm). It is important to note that these plots are not measures of boat performance or of the efficiency of the propeller. These are simply a graphical representation of the combinations of boat speed and propeller rotation speed that are capable of producing propeller marks separated by a specific set of distances. It is possible that some of the combinations of boat speed and propeller revolutions that are used are physically impossible to attain by any type of watercraft.

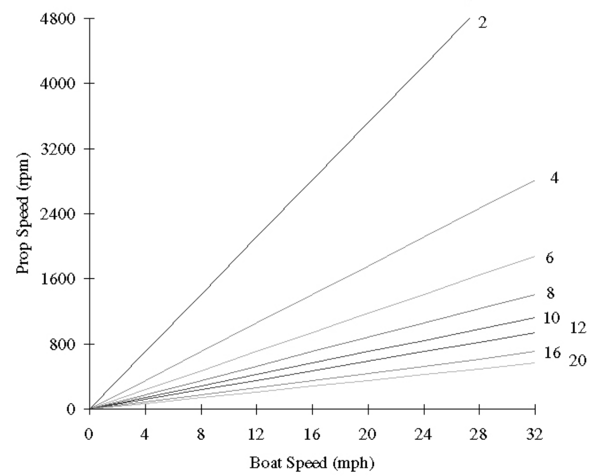

Chart-5: Boat and propeller speed combinations that can produce propeller marks separated by specified distances (in inches) for a three-blade propeller can be plotted.

Boat Type and Prop Marks

Chart-6 combines the relationships illustrated in Chart-4 and Chart-5 to determine if either of the types of watercraft being considered can produce propeller marks separated by the specified distances. This chart

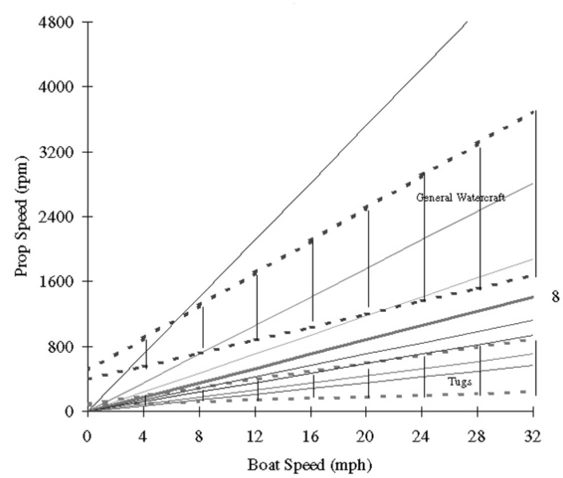

Chart-6: The operating range of general watercraft does not include boat and propeller speed combinations that will produce propeller marks separated by eight inches or more.

illustrates that the operating range of general watercraft includes boat speed and propeller rpm combinations that can produce propeller marks separated by two, four, and six inches (five, 10, and 15 cm). However, the operating range of general watercraft does not include boat speed and propeller rpm combinations that can produce propeller marks separated by eight inches (20 cm) or more. On the other hand, the operating range for tugs includes boat speed and propeller rpm combinations that can produce propeller marks with separations from two inches (five cm) to over 20 inches (51 cm).

Chart-7 is a simplified version of Chart-6 with all of the unnecessary plots removed. It illustrates the basic conclusion of this part of the analysis. PROPELLER MARKS SEPARATED BY EIGHT INCHES (20 cm) OR MORE COULD NOT HAVE BEEN PRODUCED BY GENERAL WATERCRAFT AND MOST PROBABLY WERE CREATED BY A TUG.

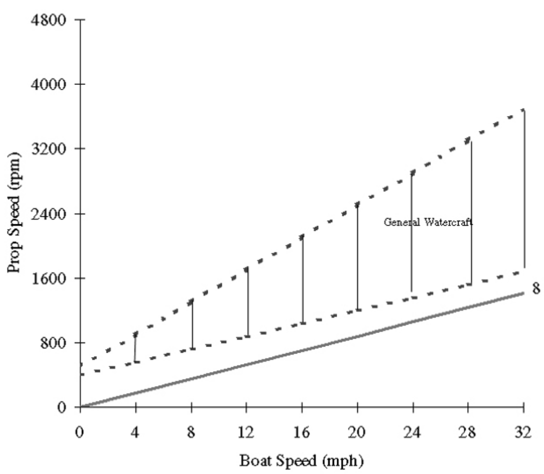

Chart-7: Propeller marks created by general watercraft will be separated by less than eight inches.

The validity of this statement can be tested by looking at actual performance curves for a variety of general watercraft. Chart-8 through Chart-11 shows actual performance curves for 57 general watercraft ranging in size from 16 feet (4.8 meters) to 54 feet (16.5 meters) in length. The data used to create these charts is derived from engine and boat performance data published on several websites (www.boatingmag.com, www.boattest.com, www.johnson.com, and www.honda-marine.com).

Chart-8 presents performance curves for boats less than 23 feet (seven meters) in length and equipped with three-blade propellers. Chart-9 presents performance curves for boats less than 23 feet (seven meters) in length and equipped with four-blade propellers. In both charts, the performance curves are in the lower part of the region defined as general watercraft with only a few of the performance curves dropping below the straight line performance curve for the vessel that was used to define the lower boundary of the region. More importantly, none of the performance curves intersects the line representing an eight inch (20 cm) separation between cuts for the type of propeller being represented.

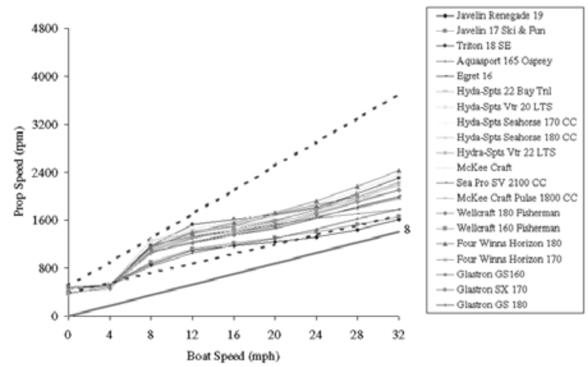

Chart-8: Performance curves for boats less than 23 feet in length equipped with three-blade propellers do not intersect the line representing cuts separated by eight inches.

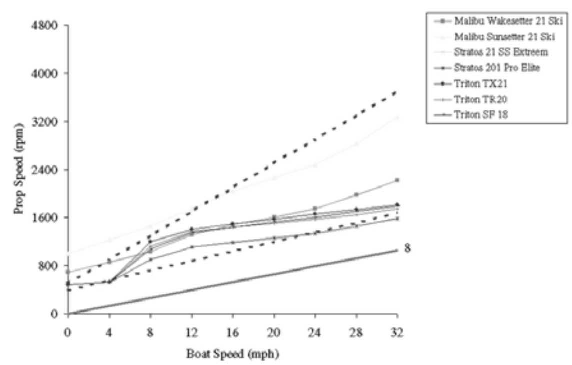

Chart-9: Performance curves for boats less than 23 feet in length equipped with four-blade propellers do not intersect the line representing cuts separated by eight inches.

Chart-10 presents performance curves for boats 23 feet (seven meters) or greater in length and equipped with three-blade propellers. These performance curves also are in the lower part of the region defined as general watercraft, and none of them intersects the line representing an eight inch (20 cm) separation between cuts for a three-blade propeller. Chart-11 presents performance curves for boats 23 feet (seven meters) or greater in length and equipped with four-blade propellers. Several of these performance curves are below the lower boundary for the region defined as general watercraft, but none of them intersects the line representing and eight-inch (20 cm) separation between cuts for a four-blade propeller. This would indicate that the vessel used to temporarily define the lower boundary of the range of general watercraft may not be representative of all of these types of vessels. However, its use does serve to demonstrate the principles employed in this method, and the assertion that general watercraft do not produce propeller marks separated by eight inches (20 cm) or more appears to be valid.

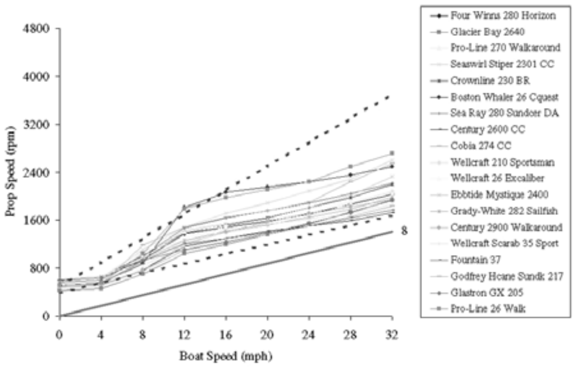

Chart-10: Performance curves for boats 23 feet in length and over equipped with three-blade propellers do not intersect the line representing cuts separated by eight inches.

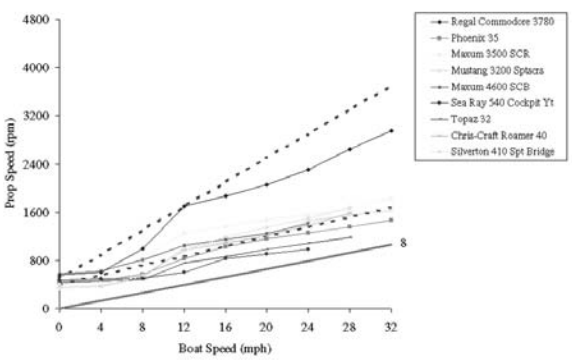

Chart-11: Performance curves for boats 23 feet in length and over equipped with four-blade propellers do not intersect the line representing cuts separated by eight inches.

It is important to note that by using this method of analysis researchers can not determine which specific boat actually caused a specific set of propeller marks or how fast the boat was actually traveling when it created the marks, but they may be able to exclude one category of boats from consideration. If the separation between propeller marks is eight inches (20 cm) or more, it can be reasonably concluded that general watercraft did not produced the marks, and the marks probably were produced by a tug. However, if the separation between propeller marks is less than eight inches (20 cm), it is possible that either category of boat could have produced the marks, and another means of distinguishing between the two categories of boats must be used. Using the length and depth of the cuts to calculate the diameter of the propeller that created them can be useful in these circumstances.

This situation is similar to the early days of DNA analysis when it was possible to exclude a group of individuals from consideration as suspects, but it was not possible to confirm a group of individuals as suspects. In spite of this apparent lack of certainty, the analysis is simple and useful. It does not depend on highly accurate or subjective measurements, and it can help identify the types of vessels involved in these accidents. It can be executed using gross measurements taken directly from a manatee, from photographs that include an accurate reference of size, or from existing necropsy reports, and it does not depend on quantifying the array of forces present during the incident.

Individual Propeller Cuts

Another interesting phenomenon is when there is only one propeller mark on the manatee. It could be reasoned that this is a result of the animal being hit by the first propeller blade and then, in response to that impact, moving out of reach of the next propeller blade. Considering that a three-blade propeller rotating at only 600 rpm will strike a manatee three times in 0.1 of a second, the duration of the blink response of the human eye, it is unreasonable to assume that an animal as large as a manatee could react quickly enough and then move far enough to avoid the second blade. It could also be reasoned that the force of the first blade may have pushed the animal out of reach of the second blade. Single propeller cuts causing fatal injury have been observed on manatees that were 10 feet (306 cm) in length (Necropsy Report UCF9141). A manatee this size usually weighs more than 1000 pounds (454 Kg). It is probably not reasonable to assume that a strike of a single propeller blade could move an animal that large any significant distance within the blink of an eye.

A more plausible explanation is that the vessel involved in this type of collision was moving at a speed and with a propeller rotation that would cause propeller marks separated by a distance greater than the distance from the observed cut to the edge of the animal's body, or the distance between passes of the blades and the contour of the animal's body combine to prevent the second blade from striking the animal. In either case the vessel will strike the manatee with the first blade and then move far enough forward so that the second blade will simply miss the animal. Indeed, propeller marks separated by 20 inches (50 cm) have been reported in necropsy reports (Necropsy Report MEC9315). Therefore, it is reasonable to assume that single propeller marks may be one in a series of potential marks that are separated by a distance greater that the distance from the observed mark to the edge of the animal's body. Of course, it is also possible that a single cut may not be from a propeller at all.

Accounting for the Manatee's Speed

In this analysis, boat speeds are measured relative to the surface of the manatee, and it is generally assumed that the majority of the motion is attributed to the watercraft and not the animal. If the manatee is moving very slowly or if the watercraft strikes the animal from the side, this assumption is valid. However, if the watercraft strikes an animal from the front and the animal is moving at high speed, then the relative speed of the watercraft is increased significantly, and the separation between propeller marks will increase. This is usually not a problem with manatees because they usually move very slowly. However, they are capable of bursts of speed of about 14 mph (12.2 Kts) (Hartman 1979). Even though they can only sustain this speed for very short periods of time, it is important to consider the implications of the manatee's ability to move at this speed.

The maximum separation of propeller marks under these conditions can be established by utilizing the data presented in Chart-6. The plots that bound the region used to characterize a type of watercraft's performance can be shifted along the x-axis until the idle rpm of the watercraft corresponds to the maximum speed of the manatee. Chart-12 shows this relationship for general watercraft. Plots that are not necessary for this evaluation have been eliminated. This chart shows that if a manatee is struck directly from the front when the animal is moving at top speed (14 mph) then, for general watercraft, the maximum separation of propeller marks increases to somewhere between 10 and 12 inches (25 to 30 cm). This amount of increase in the separation between cuts would only occur if the animal is struck directly from the front and if the animal is moving forward at its maximum speed.

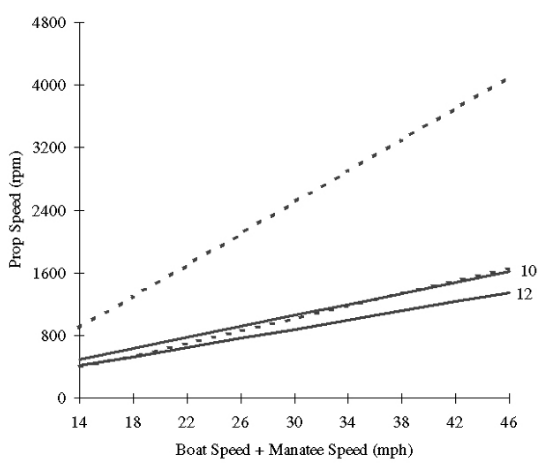

Chart-12: The maximum speed of the manatee must be added to the vessel speed when the shapes of the propeller marks indicate that the animal was struck directly from the front.

The information presented in Appendix-B demonstrates that it is often possible to determine the direction a boat was traveling when it hit a manatee. It is usually possible to tell the direction the watercraft was traveling across the surface of the manatee by looking at the shape of the propeller marks. They often form a characteristic arc that points in the direction the watercraft was moving. For example "(" indicates the watercraft was moving from right to left, and ")" indicates the watercraft was moving from left to right. This pattern is most discernible in very shallow cuts. The deeper cuts tend to form a symmetrical "S" shape that does not help identify the boats direction of travel. However, if there is a series of propeller marks, then the first or last cut is usually the shallowest in the series and therefore the most likely to form an arc that points in the direction the boat was moving.

If the shape of the propeller marks indicates that the animal was struck directly from the front and the separation of the propeller marks is between eight and 12 inches (20 and 30 cm), then it should be considered that the manatee may have been moving at high speed and the marks could have been created by a general watercraft. Under these circumstances, other factors, such as the length and depth of the cuts, can be used to help determine the type of watercraft involved. These conditions appear to be rare with the manatees. A cursory examination of the necropsy reports for propeller-related manatee deaths in northern Brevard County did not reveal any incidents where the speed of the manatee would be a factor in determining the type of watercraft involved. However, researchers should be mindful of this possibility.

ANALYZING INDIVIDUAL PROPELLER CUTS

The preceding method demonstrates a way of distinguishing between propeller mark patterns that are created by vessels with distinctly different operating characteristics. That method becomes less effective when the vessels under consideration have similar performance curves or when there is only one propeller mark present. Even vessels that vary greatly in size can have performance curves that are quite similar. Therefore, using the separation between propeller marks to distinguish between these groups may not be effective.

In this case, it is possible to use the length and depth of the propeller cuts to estimate the minimum size of a propeller that could have created the cuts. The derivation of an equation for performing this analysis is presented in Appendix-C, and the resulting equation is presented below.

$$\text{Diameter of Propeller} > L/(\sin(180 - 2(\operatorname{atan}(L/(2d)))))$$

Where: L = Length of the longest propeller cut
d = Depth of the deepest propeller cut

It is important to note that this formula uses the length of the longest cut in a series of cuts and the depth of the deepest cut in a series of cuts even though these measurements may not be taken from the same cut in the series. This is because these cuts occur on a surface that is not flat and the contour of the surface itself will cause some very deep cuts to be shorter than the propeller would have created on a flat surface. It should be apparent that the propeller is capable of producing cuts at least as long as the longest cut in the series and as deep as the deepest cut in the series even though the contour of the surface may prevent it from producing these dimensions in the same cut. The curved surface of the manatee's body contributes to the inability to obtain accurate length and depth measurements in another way.

The most accurate results from the use of this equation are attained if the length of the cut is measured along the chord of the arc formed by the propeller and the depth of the cut is measured from this chord to the bottom of the cut. This would require measuring a straight-line distance through the cut from one end of the cut to the other rather than along the surface of the manatee's body. This would also require measuring the depth of the cut from the chord of the arc rather than from the surface of the manatee's body. In actual practice these measurements are almost always taken relative to the surface of the manatee's body rather than relative to the chord of the arc. Therefore, it should be understood that this method produces an approximation of the minimum size propeller that could have produced the measured cuts, and the actual propeller size is always larger than the calculated size.

This method does not allow the researcher to identify a specific propeller size that produced the cut being analyzed. It does allow the researcher to determine that the propeller that produced the cut was at least the calculated diameter, and any vessel with a propeller smaller than that diameter could not have produced the cut. Once again, this method can exclude a group of watercraft from consideration. It does not depend on highly accurate or subjective measurements, and it can be executed using gross measurements taken directly from a manatee or from data presented in existing necropsy reports. The basic conclusion for this part of the analysis can be presented in one simple statement. WATERCRAFT EQUIPPED WITH PROPELLERS SMALLER THAN THE CALCULATED DIAMETER COULD NOT HAVE PRODUCED THE MEASURED PROPELLER CUTS.

CONCLUSIONS

This two step method of analyzing propeller marks on manatees can be summarized in two simple statements.

PROPELLER MARKS SEPARATED BY EIGHT INCHES (20 cm) OR MORE COULD NOT HAVE BEEN PRODUCED BY GENERAL WATERCRAFT AND MOST PROBABLY WERE CREATED BY A TUG.

WATERCRAFT EQUIPPED WITH PROPELLERS SMALLER THAN THE DIAMETER CALCULATED USING THE FOLLOWING FORMULA COULD NOT HAVE PRODUCED THE MEASURED PROPELLER CUTS.

Diameter of Propeller > L/(sin(180 – 2(atan(L/(2d)))))

Where: L = Length of the longest propeller cut
d = Depth of the deepest propeller cut

These methods can be modified for use on other marine mammals and in specific geographic locations where distinctly different categories of vessels are operating. Studies employing these methods can be completed with a minimum expenditure of manpower or funds, and the data that is produced by such studies can provide valuable information about the types of vessels that have actually been involved in propeller strikes on marine mammals within the study area. Researchers can then examine the physical characteristics of these vessels and the operational procedures that would most likely have been employed in the locations where the accidents occurred, and this information can be used to determine if there is a specific cause-and-effect relationship that can help identify why these animals are being struck. Once specific reasons for these accidents have been identified, it is very probable that counter measures can be developed that will prevent these accidents altogether.

ACKNOWLEDGMENTS

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APPENDIX-A: DETERMINE COMBINATIONS OF BOAT SPEED AND PROPELLER ROTATION THAT CAN PRODUCE PROPELLER MARKS SEPARATED BY A SPECIFIED DISTANCE

When a boat moves past a surface at a constant speed and the propeller of the boat touches the surface, it will leave a series of propeller marks similar to those illustrated below. It is possible to derive a formula that can determine combinations of boat speed and propeller revolutions that are capable of producing the observed separations.

This formula is not a method of measuring boat performance or propeller efficiency. It is possible to use combinations of boat speed and propeller revolutions that are physically impossible to attain by any type of watercraft. However, it does calculate the separation of propeller marks that would be produced for the specified combination of values.

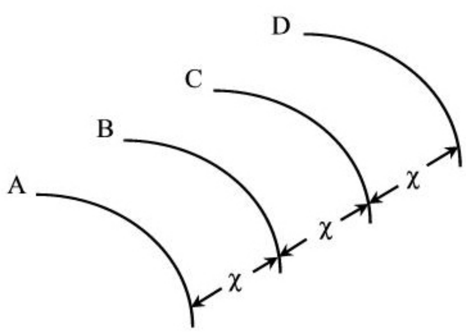

Figure-A1: One complete revolution of a three-blade propeller moving forward at a constant speed will create four cuts separated by three equal distance spaces.

By definition:

This analysis will assume that the boat is equipped with a three-blade propeller.

A = point of initial contact
by first propeller blade
B = point of initial contact
by second propeller blade
C = point of initial contact
by third propeller blade
D = point of second contact
by first propeller blade

From point A to point D represents one full rotation of the propeller.

If:

d = distance in inches (in) traveled in one revolution (rev) of the propeller
n = number of blades on the propeller
χ = distance traveled during the time interval from one blade strike to the next

Then:

$d = n\chi$ = in/rev

By definition:

Speed = distance/time

And If:

λ = rotational speed of propeller in revolutions per minute (rev/min)

Then:

Speed = $n\chi\lambda$ = (in/rev)(rev/min) = in/min

Converting (in/min) to miles per hour (mi/hr):

Speed=$n\chi\lambda$(in/min)(ft/12in)(mi/5280ft)(60min/hr)

Speed= $(n\chi\lambda)/1056$ (mi/hr)

Therefore:

$$S = (n\chi\lambda)/1056$$

Where:

S = boat speed relative to surface where propeller marks occur in miles per hour (mph)
n = a constant representing the number of blades on the propeller
χ = a constant representing the distance between adjacent propeller marks in inches
λ = rotation speed of the propeller in revolutions per minute (rpm)
1/1056 = a constant used to convert from inches per minute to miles per hour (mph)

APPENDIX-B THE SHAPES OF INDIVIDUAL PROPELLER CUTS

A simple geometric method can be used to determine the shapes of individual cuts a rotating propeller will make on a surface. This method uses a two-dimensional diagram of a propeller cutting through a surface which is then projected onto a plane view of the surface. The rotation of the propeller is divided into incremental segments. Each segment represents an equal angle of rotation. A line showing the contour of a cross section of the object being cut is positioned on the diagram so that it fairly represents the depth of the cut. The contour can be any shape. This example uses a simple convex curve to represent the body of a marine mammal.

A second diagram is drawn below the first. This second diagram is a rectangle representing a flat plane projection of the surface of the object being cut. It is divided into horizontal segments representing incremental forward movements of the propeller. It is apparent that for each incremental rotation of the propeller it will move forward some incremental distance. In the examples presented here, it is generally assumed that each increment of rotation will correspond to one arbitrarily defined increment of the forward movement of the propeller.

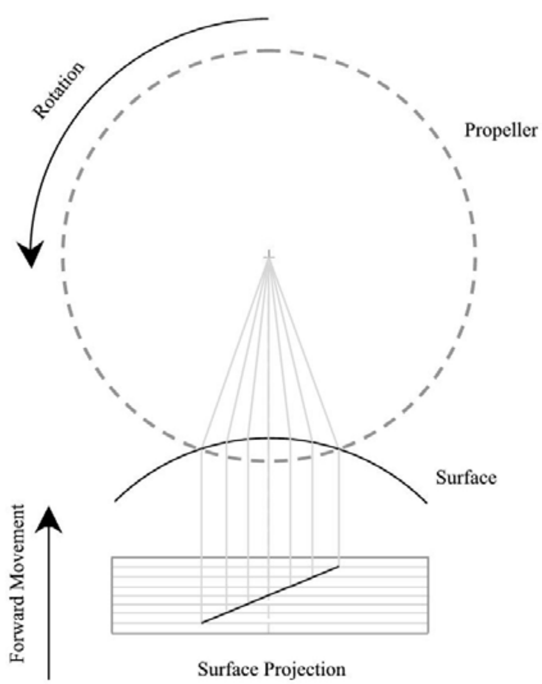

Figure-B1: A shallow cut created by an imaginary propeller with a straight vertical cutting edge will form a straight line shape.

At each point where a line representing an incremental segment of rotation intersects the contour of the surface being cut in the first diagram, a vertical line is projected down to the corresponding line representing forward movement on the second diagram. After all points of intersection in the first diagram have been projected to the second diagram, straight lines are used to connect the projected points on the second diagram. These lines form a shape that fairly represents the shape of the cut created by the propeller.

Figure-B1 represents a shallow cut created by an imaginary propeller blade with a shape that is nothing more than a straight vertical edge. It forms a straight line. It has been observed that propeller cuts of moderate depth do sometimes approximate straight lines. However, with most shallow cuts, there is another phenomenon that must be considered, and it is a result of the actual shape of the cutting edge of a real propeller blade.

Figure-B2 shows a frontal view of a propeller blade. The portion of the blade that is of particular interest is the contour of the leading edge of the tip of the blade. Because the leading edge of the blade is most often rounded, it first contacts the surface being cut at some point "A" forward of the apex of the blade. As the cut progresses the blade cuts in the direction of propeller rotation and away from the direction of rotation, toward the apex of the blade, simultaneously. This action continues until the apex of the blade penetrates the surface. At that point, the surface cutting action continues only in the direction of the propeller rotation. The significance of this dual cutting action is most evident when the propeller blade is viewed in profile.

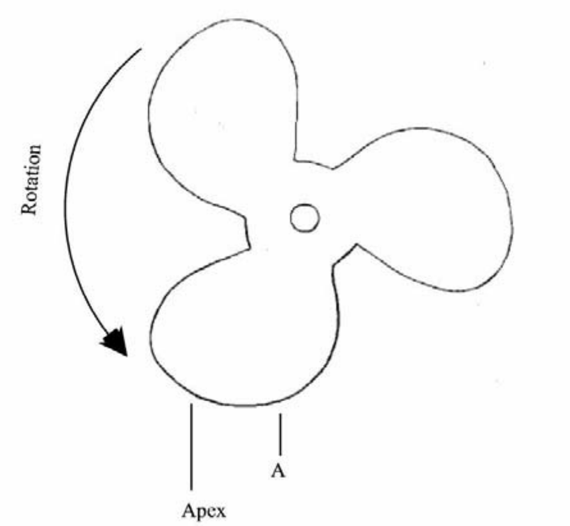

Figure-B2: A rotating propeller first strikes a surface at some point "A" rather than at the apex of the blade.

Figure-B3 shows a profile view of one blade of a propeller. As seen in the frontal view of the propeller blade, in shallow cuts the propeller blade first contacts the surface at some point "A". As the cut progresses, the blade cuts in the direction of the forward motion of the propeller and away from the forward motion, toward the apex of the blade, simultaneously. By the end of the first increment of rotation, the cutting edge of the propeller blade has effectively moved a distance equal to its actual forward movement plus the distance from some point "A" on the profile of the propeller to some point "B". The distance from point "A" to point "B" is a function of the curvature of the leading edge of the blade. On the tip of the blade, which forms shallow cuts, the leading edge of the blade is a relatively long, gentle slope of significant length when compared to the total forward movement of the propeller during the segment of rotation that creates the initial portion of the cut. The length of the cutting action from some point "A" to some point "B" must be added to the forward motion of the propeller when determining the shape of the cut the propeller will create.

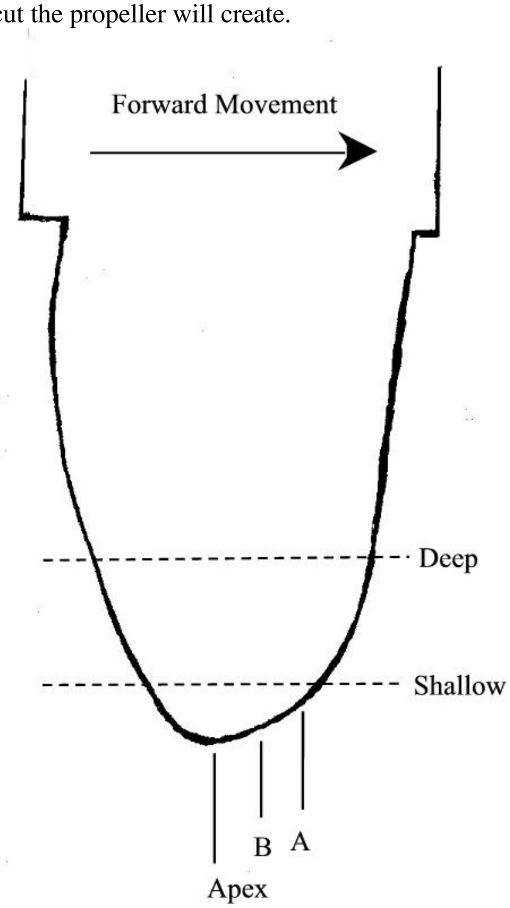

Figure-B3: A profile view of a propeller blade shows point "A" forward of the apex of the blade. Shallow cuts begin at some point "A" and proceed to cut in the direction of forward movement and from point "A" to point "B" simultaneously. This dual cutting action continues until the apex of the blade penetrates the surface being cut.

This pattern of the cutting action continues until the apex of the blade penetrates the surface. This means that during the initial portions of the cut, the effective forward movement of the cutting edge of the blade is greater than expected. Because of the shape of the leading edge of the blade, this effect is most significant during the first segment of the cut and then rapidly decreases until the forward movement of the blade is again a regular interval approximately equal to the interval that was employed in Figure-B1. This effect is most pronounced in the region of the tip of the blade that forms shallow cuts. As the cuts become deeper, the cutting edge moves farther up the blade where the profile of the leading edge becomes almost vertical and this effect becomes negligible.

In Figure-B4 it can be seen that the shape of a shallow cut when the shape of the tip of the propeller is taken into account forms an arc with the convex side of the arc pointing in the general direction of the forward motion of the propeller. It is important to note that the cut is not perpendicular to the direction of motion. Therefore, an individual cut can only indicate the general direction of the motion of the boat that created it, but a series of cuts can provide a very good approximation of the direction the boat was traveling. It has been observed that shallow cuts very often form this shape.

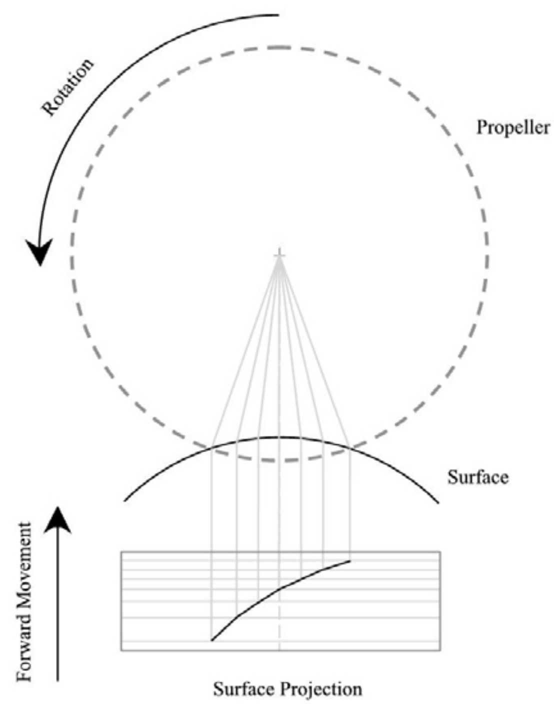

Figure-B4: The shape of the tip of a propeller blade will cause shallow cuts to form arc shaped cuts with the convex side of the arc pointing in the general direction of the forward movement of the blade.

Figure-B5 represents the shape of a propeller mark created by a relatively deep cut. In deep cuts, the cutting edge is almost vertical and its shape is no longer a significant factor in the forward movement of the cutting edge. Therefore, the forward movement is at regular intervals throughout the duration of the cut. The deep cut forms an elongated “S” shape with the side of the cut where the propeller enters the body forming a concave curve and the side of the cut where the propeller exits the body forming a convex curve. It has been observed that deep cuts do indeed form this shape. This unusual shape is the result of the point on the cutting edge of the blade that actually cuts the surface moving closer to and then farther away from the axis of rotation. As the cutting edge moves closer to the axis of rotation, each incremental rotation of the propeller translates into a shorter segment of the cut on the surface. Conversely, as the cutting edge moves farther from the axis of rotation, each incremental rotation of the propeller translates into a longer segment of the cut on the surface. These variations in the length of the cut for each increment of rotation and forward movement of the propeller form the observed “S” shape.

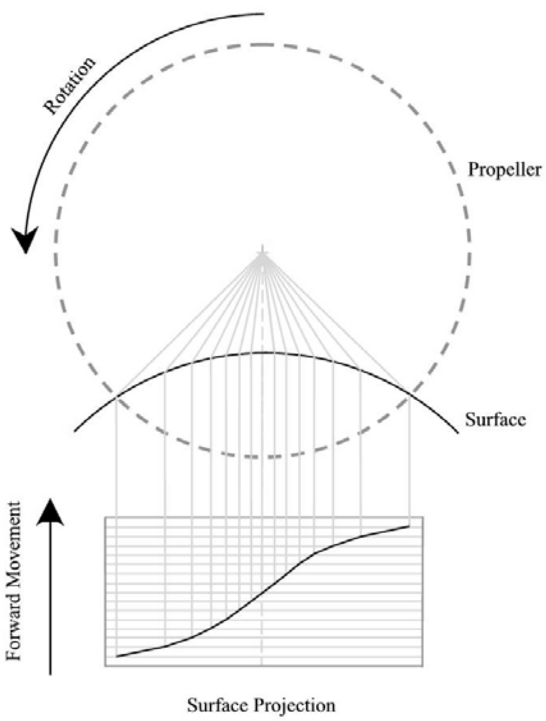

Figure-B5: Deep cuts form an “S” shaped curve with the concave side of the curve on the end of the cut where the propeller first contacts the surface being cut.

Deep cuts with this “S” shape are very symmetrical and do not provide an indication of the direction the boat was traveling. However, these types of cuts usually occur as a series of cuts, and the first or last in the series are usually much shallower. These beginning and ending cuts in the series usually form the arc shape that is characteristic of shallow cuts. The convex surface of these cuts point in the direction the boat was traveling. If the shallow cuts are present and indicate the direction the boat was traveling, then the deep cuts can be used to establish the direction of rotation of the propeller. The propeller enters the surface on the side of the deep cut that is concave relative to the direction the boat was traveling.

APPENDIX-C: ESTIMATE PROPELLER DIAMETER FROM LENGTH AND DEPTH OF CUT

This is a derivation of a formula used to estimate the diameter of a propeller by measuring the length and depth of a cut made by the propeller. It is assumed that the length of the cut is measured along a straight-line chord between the entry and exit points of the propeller and that the depth of the cut is measured along a line perpendicular from this chord to the bottom of the arc formed by the cut. This is not usually the case in practical applications. The length is actually measured along the surface where the cut occurs, and the depth is actually measured from the surface where the cut occurs to the bottom of the arc. Using these measurements in the application of the formula derived here will yield a propeller diameter that is the minimum diameter that could have produced the cut. The actual size of the propeller will always be larger than the calculated size.

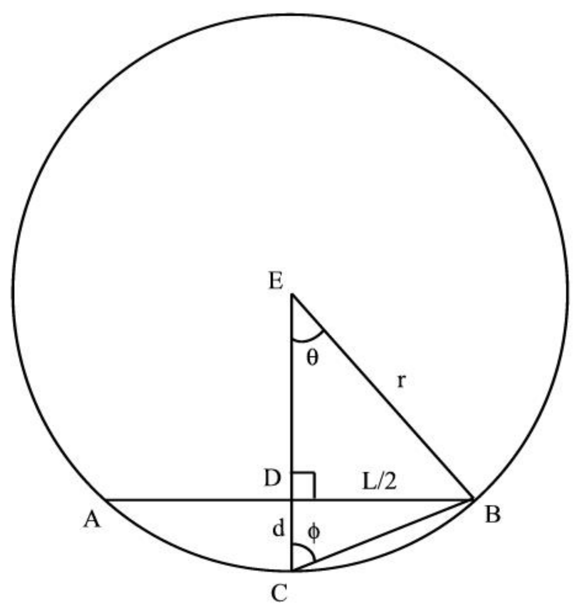

Figure-C1: A propeller that cuts a flat surface will form a cut that can be defined by some chord “AB” of the circle formed by the path of the tip of the propeller blade.

By definition:

AB = L = Length of cut
DB = L/2
CD = d = Depth of cut

By definition:

$\tan\phi = (L/2)/d$

Solving for ϕ and simplifying the equation yields:

(1) $\phi = \text{atan}(L/(2d))$

By definition:

EC = EB = r = radius of propeller

(2) $\theta = 180 - 2\phi$

By definition:

$\sin\theta = (L/2)/r$

Solving for r yields:

(3) $r = L/(2\sin\theta)$

Substituting (2) into (3) yields:

(4) $r = L/(2\sin(180 - 2\phi))$

Substituting (1) into (4) yields:

(5) $r = L/(2\sin(180 - 2(\text{atan}(L/(2d)))))$

By definition:

(6) Diameter of Propeller = DiaOfProp = 2r

Substituting (5) into (6) and simplifying the equation yields:

(7) $\text{DiaOfProp} = L/(\sin(180 - 2(\text{atan}(L/(2d)))))$

Since, as stated earlier, the practical application of this formula limits the finding to the minimum size of propeller that could have caused the cut being measured, it is correct to restate (7) as:

$\text{DiaOfProp} > L/(\sin(180 - 2(\text{atan}(L/(2d)))))$