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User's guide for smooth-prop

A program for smoothing propeller tip geometry

David Hally

Defence R&D Canada – Atlantic

Technical Memorandum
DRDC Atlantic TM 2013-179
October 2013

Canada

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Abstract

The traditional method of specifying propeller geometry is to define a series of airfoil sections each of which is modified by local values of the chord length, pitch, skew angle and rake. Near the tip of the propeller, where the chord length reduces rapidly to zero, a blade defined in this way often has surface irregularities which make meshing for flow solvers difficult. This report is a user's manual for a program that will smooth the irregularities near the tip and save the resulting propeller geometry in the IGES format which can be read by most flow solvers.

Résumé

La méthode classique pour établir de manière détaillée la géométrie d'une hélice consiste à définir une série de sections de surface portante, chacune d'entre elles étant modifiée en fonction des valeurs localisées de la longueur de corde, du pas de l'hélice, de l'angle oblique et de l'angle d'inclinaison. Près des extrémités de l'hélice, où la longueur de corde diminue rapidement et atteint zéro, la pale définie à l'aide de ces éléments présente souvent une surface irrégulière, ce qui rend complexe le maillage dans le cas des solutionneurs d'écoulement. Le présent rapport constitue le manuel de l'utilisateur pour un programme qui permet de lisser les irrégularités près des extrémités de l'hélice et de sauvegarder les résultats obtenus en matière de géométrie de l'hélice en format IGES, lequel peut être lu par la plupart des solutionneurs d'écoulement.

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Executive summary

User's guide for smooth-prop: A program for smoothing propeller tip geometry

David Hally; DRDC Atlantic TM 2013-179; Defence Research and Development Canada – Atlantic; October 2013.

Background: The design of propellers affects ship performance in many ways including maximum speed, fuel consumption, wear on shafts and machinery, on-board vibrations and radiated noise. The evaluation of propeller designs will be an important part of the projects to acquire the Arctic/Offshore Patrol Ship (AOPS), the Joint Support Ship (JSS) and other vessels for the Royal Canadian Navy.

The use of Reynolds-averaged Navier-Stokes (RANS) flow solvers for evaluating propellers is becoming increasingly common as they have the potential to be more accurate than older panel-based methods. However, before they can be used, an accurate propeller geometry must be available so that an appropriate computational mesh can be created around the propeller.

Principal results: This report is a user's manual for a program, `smooth-prop`, that fixes problems in the propeller geometry near the tip which can arise when traditional methods of describing a propeller are used. The resulting geometry is smooth, has no coordinate singularities, and has surfaces with edges that match to very high accuracy, all properties that are required when creating grids for flow solvers. Tight control is maintained over the amount by which the smoothed surface can deviate from the original, ensuring that the new geometry remains an accurate representation of the real propeller.

Significance of results: Use of `smooth-prop` will allow analyses of propellers to be performed with a minimum of effort. The analysis procedure will be more robust and the results more reliable. It is expected that it will be used to support the acquisition of propellers for AOPS, JSS and other vessels for the Royal Canadian Navy.

Sommaire

User's guide for smooth-prop: A program for smoothing propeller tip geometry

David Hally ; DRDC Atlantic TM 2013-179 ; Recherche et développement pour la défense Canada – Atlantique ; octobre 2013.

Introduction : La conception des hélices a de nombreux effets sur le rendement d'un navire, y compris sur des facteurs comme la vitesse maximale, la consommation de combustible, l'usure des arbres et des machines, et l'ampleur des vibrations produites à bord du navire et du bruit rayonné. L'évaluation des modèles d'hélice constituera un élément important des projets d'acquisition de navires de patrouille extracôtiers de l'Arctique (NPEA), de navires de soutien interarmées (NSI) et d'autres bâtiments de la Marine royale canadienne.

L'utilisation de solutionneurs d'écoulement basés sur l'analyse d'équations de Navier Stokes avec moyennisation des nombres de Reynolds (RANS) est de plus en plus courante dans le cadre d'évaluations d'hélices, car ils pourraient offrir des résultats plus exacts que les anciennes méthodes basées sur la modélisation de panneaux. Avant de pouvoir employer efficacement de tels solutionneurs, il faut toutefois pouvoir établir de manière exacte la géométrie de l'hélice afin de pouvoir garantir la justesse du maillage numérique créé autour de l'hélice.

Résultats : Le présent rapport constitue le manuel de l'utilisateur du programme `smooth-prop`, qui permet de régler les problèmes associés à la géométrie de l'hélice près de ses extrémités, qui peuvent se présenter lorsque des méthodes classiques sont employées. La géométrie de l'hélice résultante est lisse et ne comporte pas de singularité en matière de coordonnées, et de plus, les bords de ses surfaces s'ajustent avec une très grande exactitude. Les propriétés de ce type sont toutes cruciales lors de la création de grilles pour un solutionneur d'écoulement. La méthode assure aussi une régulation serrée de la variation de la surface lissée par rapport à celle d'origine, ce qui permet de garantir que la nouvelle géométrie de l'hélice représente avec exactitude celle de l'hélice réelle.

Portée : L'utilisation du programme `smooth-prop` permettra d'effectuer, avec un minimum d'efforts, l'analyse d'hélices. La technique d'analyse sera plus robuste et les résultats plus fiables. On prévoit que la nouvelle méthode facilitera le processus d'acquisition, par la Marine royale canadienne, d'hélices de NPEA, de NSI et d'autres bâtiments.

Table of contents

List of figures

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1 Introduction

Traditionally the geometry of a propeller blade is defined by specifying a series of airfoil sections from the root of the blade to its tip. Each section is modified by the local values of the chord length, pitch, skew angle and rake. The resulting curves can be interpolated to provide a full geometric description of the blade. Software has been developed at DRDC Atlantic for reading section data for a blade and generating a geometric representation that can be used in a variety of applications [1].

Two problems arise when the propeller geometry generated in this way is used in Computational Fluid Dynamics (CFD) programs for calculating the flow around the propeller:

1. Commercial CFD programs do not use the DRDC Atlantic representation of the propeller; it must be converted to a form that they can use.
2. The modulation of the blade sections by the chord length, rake, etc. can result in very rapidly varying geometry near the blade tip where there is a coordinate singularity. The geometry in this region must be smoothed to prevent problems when generating meshes for the CFD calculations and problems with the results of the calculations themselves (e.g. spurious pressure peaks caused by flow over geometric irregularities that would be smoother on a real propeller).

The program `smooth-prop` addresses both these problems. It reads the propeller geometry using existing DRDC Atlantic software, modifies the geometry to avoid the coordinate singularity at the tip and to smooth it in a controlled way, and saves it in the IGES [2] format that can be read by most commercial CFD programs.

2 Overview of blade smoothing

In order to make best use of `smooth-prop`, you should have a basic understanding of how the program generates the blade surfaces. We provide a quick overview here: full details are provided in Ref. 3.

1. The surface of the reference blade is split into five separate surfaces as shown in Fig. 1. The tip, leading edge and trailing edge surfaces each wrap around the leading/trailing edge from the pressure side to the suction side.
2. A series of curves on the blade surface is calculated; each curve passes around the leading edge or trailing edge. See Fig. 2.
3. The curves are sampled and a weighted Laplace filter is applied to smooth the points near the leading and trailing edges.

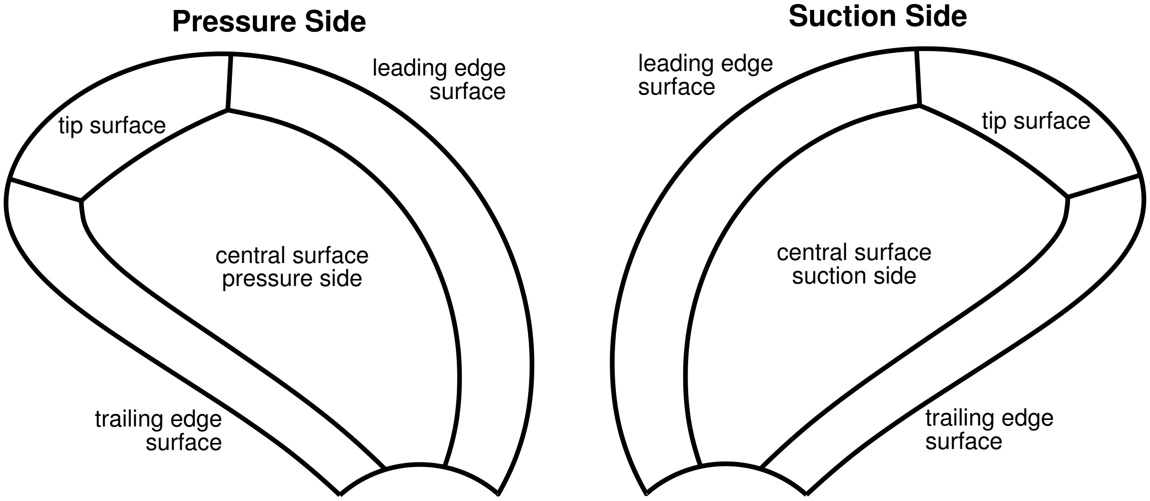


Figure 1: *The five surfaces on the reference blade.*

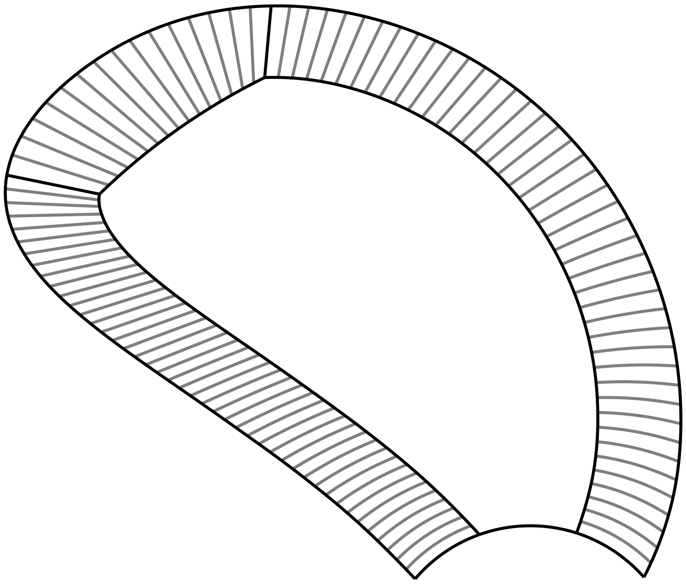


Figure 2: *The series of curves on the blade surface passing around the leading and trailing edges.*

4. Splines through the smoothed points are calculated to generate a new sequence of curves.
5. The spline coefficients of the new curves are themselves splined to generate new blade surfaces.

In `smooth-prop` only the pressure side of the blade is shown.

2.1 Defining the blade surfaces

The five surfaces into which the blade is split are defined using six points:

1. $\mathbf{x}_{LL}$, a point on the blade-hub intersection at the lower left hand corner of the central surface on the pressure side of the blade. Because it is constrained to lie on the blade-hub intersection, the location of this point is specified using a single value giving its distance along the intersection curve.
2. $\mathbf{x}_{LR}$, a point on the blade-hub intersection at the lower right hand corner of the central surface on the pressure side of the blade.
3. $\mathbf{x}_{UL}$, a point at the upper left hand corner of the central surface on the pressure side of the blade.
4. $\mathbf{x}_{UR}$, a point on the blade hub intersection at the upper right hand corner of the central surface on the pressure side of the blade.
5. $\mathbf{x}_{LE}$, a point on the leading edge.
6. $\mathbf{x}_{TE}$, a point on the trailing edge.

The six points are shown in Fig. 3. Each of these points can be moved in `smooth-prop`.

2.2 The curves around the leading and trailing edges

Most of the curves around the leading and trailing edges in the tip surface are generated as the intersections of planes with the blade (for details see Ref. 3). The plane is chosen so that its normal is nearly tangent to the blade surface. The intersection curve, called a blade cut, then provides a cross section of the blade near the leading or trailing edge. The upper curves on the leading and trailing edge surfaces are generated in the same way. However, this cannot extend all the way to the hub as the intersection of the blade and the hub does not lie in a plane. Therefore on both the leading edge and trailing there is a point at which the curves change from being generated as a plane intersection to being generated by a different method (trans-finite interpolation). The choice of these points can affect the quality of the leading and

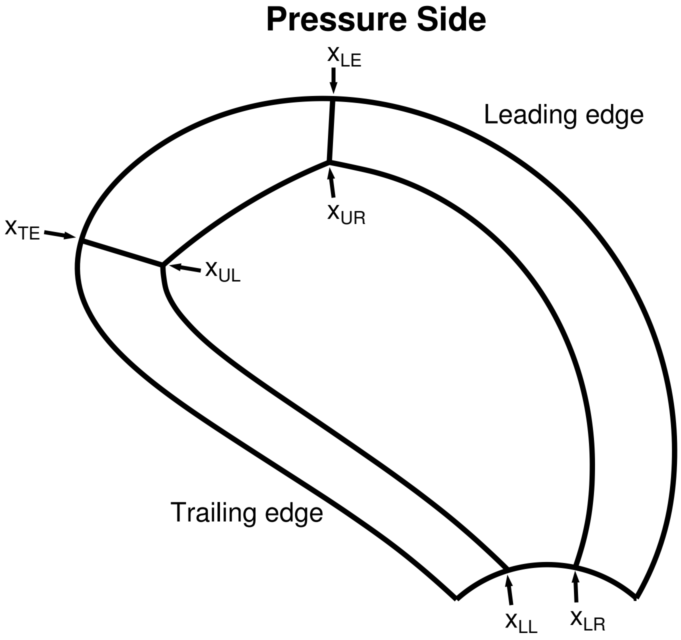


Figure 3: *The points used to split the blade into separate surfaces.*

trailing edge curves. If they are too close to the tip, the curves will show excessive curvature: for example, see Fig. 4. Choosing the points to be about half-way along the leading or trailing edge usually works well. You have control over the location of the transition point in `smooth-prop`.

The number of curves around the leading and trailing edge is determined by a single spacing parameter, Δc. The distance between two successive curves measured along the leading or trailing edge will not exceed $D\Delta c$ where D is the propeller diameter; however, the distance may be somewhat smaller than $D\Delta c$ as it is required that the number of curves on the leading edge is the same as on the trailing edge (see Ref. 3, Sec. 9). For highly skewed blades, the arclength along the leading edge is usually significantly longer than along the trailing edge, so the curves will have smaller spacing on the trailing edge. You have control over the value of Δc in `smooth-prop`.

2.3 Smoothing

The propeller tip is smoothed by sampling points on the blade cuts, applying a weighted Laplace filter to generate new points, then splining the smoothed points to generate a new curve. Only blade cuts near the tip are smoothed. The smoothed curves, along with those curves that weren't smoothed, are then also splined to generate the smoothed surface.

The amount of smoothing is controlled by a smoothing factor, α. The actual smooth-

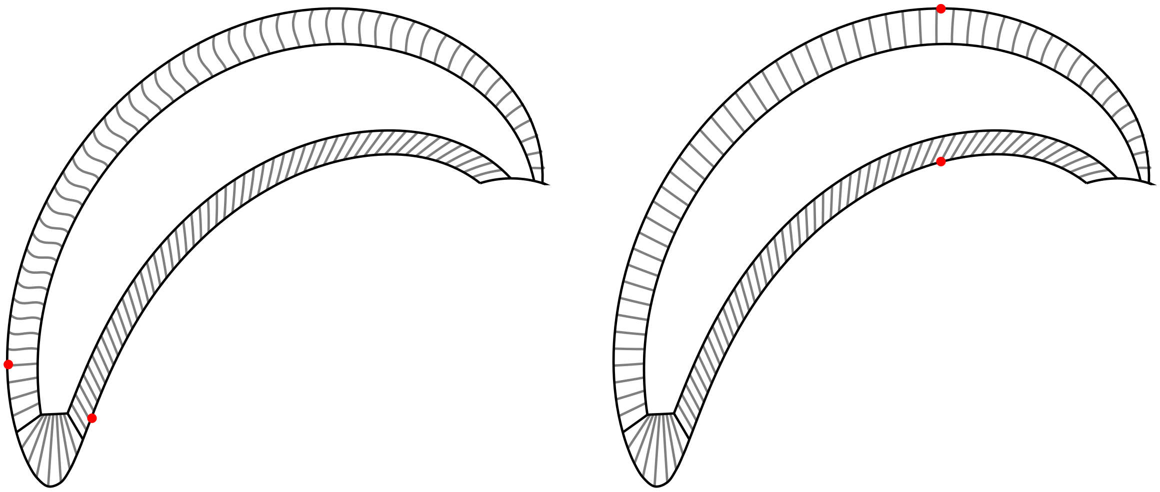


Figure 4: *The effect of the location of the transition points (shown by the red dots) on the leading and trailing edge curves of a highly skewed blade. When the points are close to the tip (left) the curves can show excessive curvature; lowering them (right) makes a significant improvement.*

ing applied varies from point to point so that the smoothing only occurs within a distance d_e of the leading or trailing edge and within a distance d_t from the tip. In `smooth-prop` you can adjust the values of α, d_e and d_t and examine the smoothing applied to any of the section curves. You can also choose the number of times that the smoothing filter will be applied.

The effectiveness of the smoothing also depends on the separation of the sampled points on the cut. This can also be controlled in `smooth-prop` using the maximum separation of the points, d. The maximum separation occurs at the base of the cut with the separation near the leading or trailing edge being much smaller. Smaller values of d will mean that fewer iterations of the filter will be necessary, but will decrease the accuracy of the curve in the locations that aren't smoothed.

3 The programs smooth-prop and prop2iges

The programs `smooth-prop` and `prop2iges` implement the algorithms described in the previous sections. The program `prop2iges` calculates the split blade surfaces and writes them to an IGES file. The program `smooth-prop` provides a graphical user interface (GUI) for `prop2iges`; it provides a convenient method for choosing the locations of the points defining the corners of the surfaces and the amount of smoothing that needs to be applied near the tip. The GUI is implemented using X Windows, available on most Linux and Unix systems. Normally `prop2iges` will only be called via `smooth-prop`, but it is possible to call it directly as well (for example, if X Windows is not available).

To run `smooth-prop` give the following command in a Linux/Unix shell:

```
smooth-prop prop-file -a acc
```

where *prop-file* is the name of a file defining the propeller using the format used by the DRDC propeller classes (see Ref. 1, Sec. 9.4). The value of *acc* sets the propeller accuracy non-dimensionalized using the propeller diameter (see Ref. 1, Sec. 2.5). If you omit the accuracy (and the `-a` preceding it) from the command line, the accuracy will be set to $10^{-6}D$.

Two windows will appear. The one called *Controller* (see Fig. 5) contains widgets for manipulating the way in which the blade is split and smoothed. Each of these is described below.

The window called *Blade* (see Fig. 6) shows the outline of the propeller blade. The red lines show the edges between the surfaces into which it will be split. The small triangle shows the location of the blade tip. The blue line passing through the tip shows the extent of the smoothing that will be applied; only blade curves whose mid-points lie in the blue region will be smoothed. The straight blue line shows the location of a blade cut that can be examined to check the effectiveness of the smoothing. The two black circles on the leading edge and trailing edge show the transition points between blade cuts and non-planar leading or trailing edge curves.

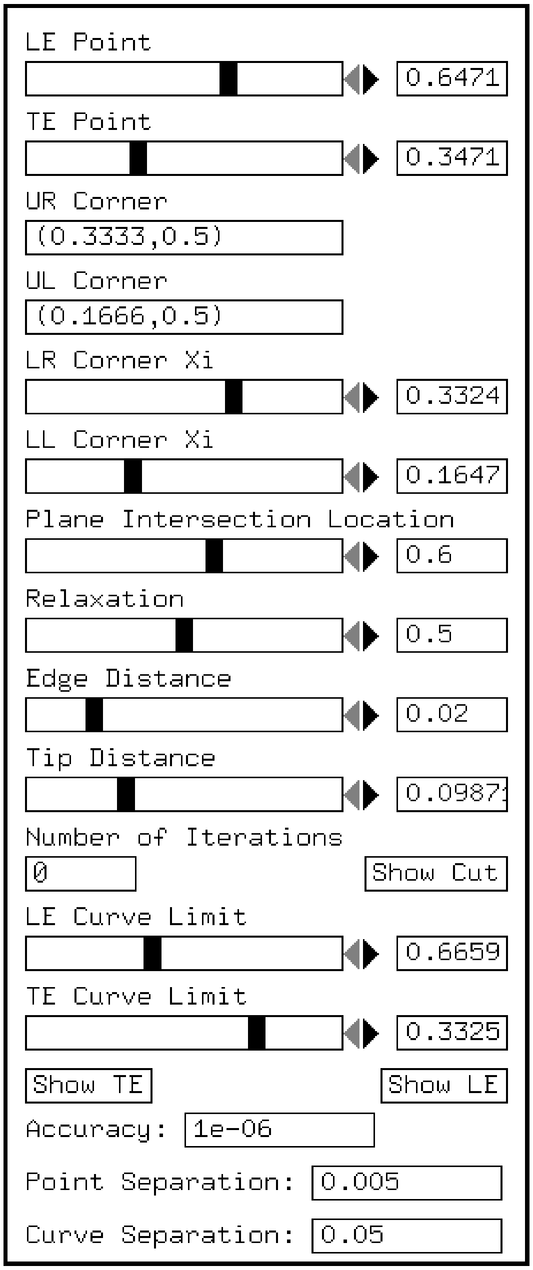
A third window becomes visible if you press the `Show Cut` button in the *Controller* window; it is named *Plane Intersection* and shows the blade cut at the location of the straight blue line in the *Blade* window: see Fig. 7. This curve is the projection of the blade cut in the intersection plane: i.e. it is a cross-section of the blade where it intersects the plane.

3.1 Basic window commands

Each of the windows responds to key presses and button clicks. The *Blade* and *Plane Intersection* windows use a similar set of commands; the *Controller* window uses a different set. To find out what commands are available in any window, place the cursor over the window and type a `?` character. A new window will appear with a description of the options.

3.1.1 Exiting from the program

You can exit from `smooth-prop` by typing the escape key when the cursor is over the *Controller* window. If you have not yet saved the propeller in an IGES file, a dialog


LE Point 0.6471

TE Point 0.3471

UR Corner (0.3333,0.5)

UL Corner (0.1666,0.5)

LR Corner Xi 0.3324

LL Corner Xi 0.1647

Plane Intersection Location 0.6

Relaxation 0.5

Edge Distance 0.02

Tip Distance 0.0987

Number of Iterations 0

Show Cut

LE Curve Limit 0.6659

TE Curve Limit 0.3325

Show TE

Show LE

Accuracy: 1e-06

Point Separation: 0.005

Curve Separation: 0.05

Figure 5: The *Controller* window.

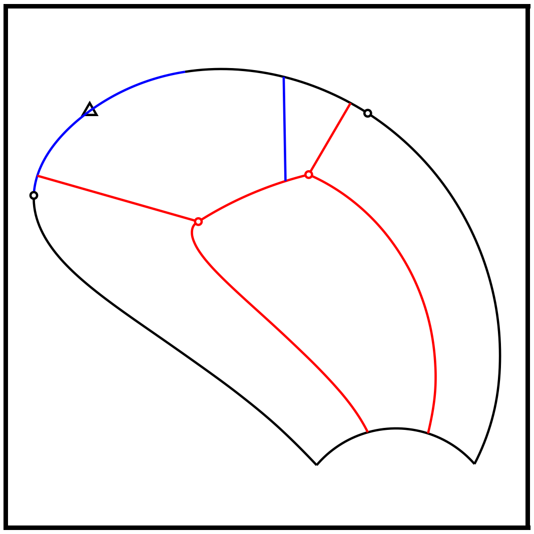


Figure 6: The *Blade* window.

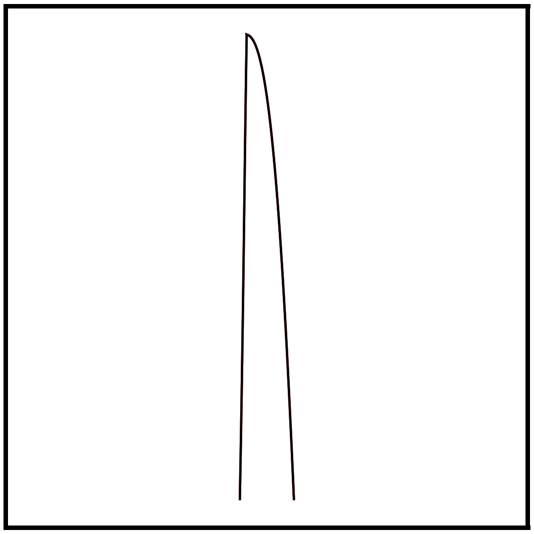


Figure 7: The *Plane Intersection* window.

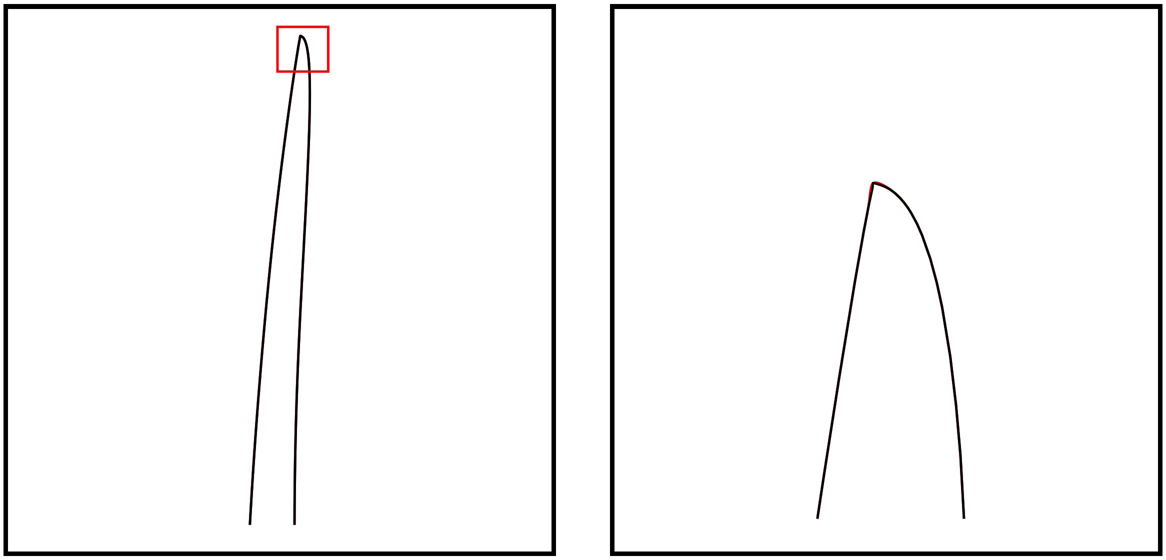


Figure 8: *Zooming in on the tip region of the blade in the Plane Intersection window. Left: during zooming. Right: after zooming.*

box will appear asking whether you really want to quit. Press the `Exit` button if you do want to exit, the `Continue` button if you do not.

3.1.2 Zooming in on a window

You can magnify any region of the *Blade* or *Plane Intersection* windows by clicking and dragging with the left mouse button. A red rectangle will appear to show you the region which you have selected. When you release the mouse button, the region you have selected will magnify to fill the window. You can zoom in more by making another selection. Click the right mouse button to undo the last zoom. Type a caret (^) to undo all the zooms at once. See Fig. 8.

3.1.3 Sliders in the *Controller* window

The *Controller* window contains ten sliders which are used to modify different elements of the display. Each slider is a long rectangle containing a smaller black box: see Fig. 9. The black box is a handle that can be dragged back and forth along the slider to change its value; any mouse button can be used. The value of the slider is shown in the box to the right of the slider.

Each slider has a range of allowed values which it covers as the handle is moved from the far left to the far right. The sensitivity of the slider is dependent on the range and the number of pixels available in the display (currently 180). You can increase the sensitivity by a factor of ten, with a corresponding decrease in the range of the slider, by pressing the rightward pointing triangular button to the right of the slider. The new range will be centred on the current location of the slider handle. You can press this button as many times as you want to continue to restrict the range. Press the left-facing triangular button to decrease the sensitivity, and increase the range, by a factor of ten. This button is originally grey to indicate that the sensitivity cannot be decreased past its original value.

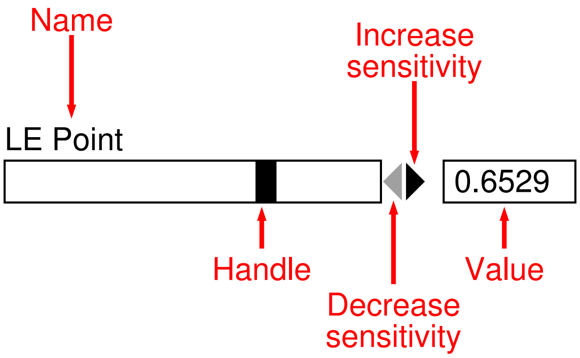


Figure 9: *A slider in the* Controller *window.*

The value of the slider may change as the sensitivity is decreased. This is because the value is always set to one of the 180 values that correspond to the pixels in the slider. Normally the slider values do not have to be very precise, so this will not cause a problem. If you do wish to specify a precise value, increase the sensitivity of the slider.

The value can also be changed by editing the number in the value box, then hitting the `Enter` key. You will probably notice that the value then changes slightly from the one you typed as it is adjusted to match the current sensitivity.

3.2 Modifying the blade surfaces

The way the blade is split into surfaces can be modified by moving the six points defining the surface. To move the upper corner points of the central surface, place the cursor over the small circle at the corner you wish to move; the circle will turn blue. Drag the circle to its new location using the left mouse button.

Each point on the blade surface can be identified using the blade parameters (ξ, η). The parameter ξ is 0.0 at the trailing edge, increases along the pressure side of the blade to 0.5 at the leading edge, then increases to 1.0 along the suction side of the blade back to the trailing edge. The parameter η increases from the root of the blade to the tip: at the root it is typically between 0.2 and 0.3; at the tip it is 1.0.

The blade parameters, (ξ, η), of the upper right corner are shown in the `UR Corner` input box in the *Controller* window. You can also edit these values in the input box to change the upper right corner if you wish. The change will not be implemented until you type `Enter`. Since it is the pressure side of the blade that is displayed, the value of ξ must be in the range $[0, 0.5]$. Similarly, the upper left corner can be moved by editing the `UL Corner` input box.

The point on the leading and trailing edges are controlled using the `LE Point` and

`TE Point` sliders in the *Controller* window. For each point, the value of the slider is the fractional arclength, s, around the blade outline starting where the trailing edge meets the hub ($s = 0$) and moving to where the leading edge meets the hub ($s = 1$). The value of s at the tip will usually be close to 0.5. Notice that it is possible to move the leading edge point past the tip onto the trailing edge; similarly, the trailing edge point can be moved to the leading edge.

The points where the sides of the central surface meet the hub are controlled using the `LR Corner Xi` and `LL Corner Xi` sliders in the *Controller* window. The values of these sliders are the values of the blade parameter ξ along the blade-hub intersection.

3.3 Modifying the blade cut

The *Plane Intersection* window is originally hidden. To make it appear, press the `Show Cut` button. The window will appear and the `Show Cut` button will change to `Hide Cut`; it can be pressed to make the window disappear again.

The location of the blade cut displayed in the *Plane Intersection* window is shown by the straight blue line in the *Blade* window. It can be changed using the `Plane Intersection Location` slider. The blade cut shown in the *Plane Intersection* window will not be updated until the mouse button used to move the slider handle is released.

The value of the slider is in the range [0,1] with 0 corresponding to the blade-hub intersection near the trailing edge, 0.3333 corresponding to the left edge of the upper surface, 0.6666 corresponding to the right edge of the upper surface, and 1 corresponding to the blade-hub intersection near the leading edge. If the blade does not extend beneath the hub, setting the value too close to 0 or 1 will cause an error when the cut is calculated.

3.3.1 Modifying the smoothing

As described in Sec. 2.3, the smoothing of the blade cut is controlled by five parameters:

d_t: The maximum distance to the blade tip along the leading and trailing edge over which smoothing occurs. This distance is displayed in the *Blade* window by the blue section of the blade outline near the tip.

d_e: The maximum distance along the blade cut to the leading or trailing edge over which smoothing occurs. This distance can be displayed in the *Plane Intersection* window by typing the character `r`. Three square symbols will appear (unless you are zoomed in so far that they are outside the plot). The two lower ones show the ends of the range over which smoothing occurs; the third shows the location of the blade tip. Type `r` again to make the symbols disappear.

The value of d_e is changed using the `Edge Distance` slider. The square symbols respond immediately to the slider so that you can see what the new range will be; however, the smoothing itself will not be updated until you release the mouse button used to move the slider handle.

α: The level of relaxation. Its value is set using the `Relaxation` input box.

d: The maximum separation of the smoothed points. Its value is set using the `Points Separation` input box. Increasing the value reduces the accuracy of the smoothed curve but increases the effectiveness of the relaxation factor α: i.e. for the same value of α one gets more smoothing if d is increased.

N_s: The number of smoothing iterations. Its value is set using the `Number of Iterations` input box.

As described in Sec. 2.3, the smoothing is implemented by applying a Laplace filter to a series of points around the blade cut. These points can be displayed in the *Plane Intersection* window by typing the character `d`. Type `d` again to make them disappear.

3.3.2 Showing axes

You can get a quantitative estimate of how much the smoothing has altered the blade geometry by adding axes to the display in the *Plane Intersection* window. To do this move the cursor over the window and type the character `a`. Typing `a` again will cause them to disappear. The coordinate origin is always at the tip of the blade cut. When the axes are shown, you can also make a grid appear on the plot by typing the character `g`. Remove it by typing `g` again. Axes and a grid can also be added to the display in the *Blade* window, but they have less utility there.

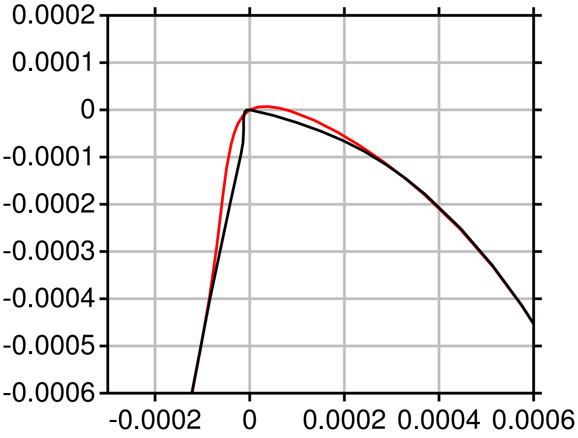


Figure 10: *The tip of the plane intersection with axes and grid.*

Fig. 10 shows the *Plane Intersection* window zoomed in to show only the immediate vicinity of the tip of the blade cut. The black curve is the unsmoothed cut, the red curve the smoothed cut. The axes and grid indicate that the difference between the two curves is less than $0.0001D$. Notice that the location of the tip is always maintained; that is, the smoothed cure will always pass through the original tip location.

3.4 Displaying the non-planar curves around the leading and trailing edge

The small black circles on the leading and trailing edges mark the transition between the planar blade cuts and the non-planar curves around the leading and trailing edges: see Sec. 2.2. These points can be moved using the `LE Curve Limit` and `TE Curve Limit` sliders. Their values are similar to those of the `LE Point` and `TE Point` sliders in the *Controller* window: i.e. the fractional arclength around the blade outline starting where the trailing edge meets the hub ($s = 0$) and moving to where the leading edge meets the hub ($s = 1$). Therefore, for the point on the leading edge, lowering the value moves it toward the tip; raising it moves it toward the hub. For the trailing edge point, lowering the value moves it toward the hub; raising it moves it toward the tip. The transition points cannot be moved off the leading or trailing edge surfaces.

Several non-planar curves around the leading or trailing edge will be displayed if you press the `Show LE` or `Show TE` button in the *Controller* window. If you move the transition point while these curves are displayed, they will not be updated until you release the button used to move the slider.

3.5 Changing the accuracy

When the leading and trailing edge curves are converted to splines, their knot sequences are chosen so that the spline curve matches a curve on the blade surface to within a specified accuracy. By default the accuracy is set to the propeller accuracy specified from the command line when `prop-smooth` is run (see Sec. 3), but it can be changed using the `Accuracy` input box in the *Controller* window. Changing the accuracy will not normally cause any visible difference in the displays; however, it will affect the accuracy of the IGES representation of the propeller as well as the size of the IGES file.

3.6 Changing the distance between the curves around the leading and trailing edges

The maximum distance between the curves around the leading and trailing edges is $D\Delta c$ (see Sec. 2.2). The value of Δc can be changed using the `Curve Separation` input box in the *Controller* window. Reducing the value will increase the overall accuracy of the spline approximations of the blade, and increase the size of the resulting IGES file. However, it will not cause any visible difference in the displays; the number of curves shown when the `Show LE` or `Show TE` buttons are pressed is always the same and is independent of Δc. These curves are intended as a check that their curvature is not too extreme, not as a display of the curve spacing.

3.7 Saving the propeller in an IGES file

When you are satisfied with the partition of the blade into surfaces and the amount of smoothing, you can save the propeller in an IGES file by typing `i` or `I`. You will be prompted for the name of the IGES file. The program `prop2iges` is then called to create the IGES file; the command used to run `prop2iges` is written to the shell which you used to run `smooth-prop`. For example:

```
prop2iges P4382.prp -a 0.0001 -t -LE 0.547059 -LL 0.1666 -LR 0.3333
-TE 0.317647 -UL 0.0962073 0.569585 -UR 0.305925 0.638316
-plim 0.182057 0.743736 -smooth 0.01 0.00352941 100
-relax 0.735294 0.0526471 -d 0.025 -o P4382.igs
```

You can follow the progression of the program in this shell; the data shown are described in Sec. 3.8. The cursor will also turn to the shape of a watch until `prop2iges` is finished.

3.8 Running prop2iges from the command line

Occasionally it will be useful to run `prop2iges` directly from the command line without resorting to the GUI. For example, one may wish to test the effect of the relaxation factor α by changing only its value and nothing else. The syntax of the call is as follows:

`prop2iges` *prop-file* `-a` *acc* `-d` Δc `-LE` s_{LE} `-TE` s_{TE} `-UR` ξ_{UR} η_{UR} `-UL` ξ_{UL} η_{UL}
`-LR` ξ_{LR} `-LL` ξ_{LL} `-plim` $s_{\min}$ $s_{\max}$ `-smooth` d d_e N_s `-relax` α d_t `-o` *IGES-file* `-t`

where

prop-file	is the name of the file specifying the propeller geometry;
acc	is the accuracy of the splines relative to the propeller diameter;
Δc	is the distance between the curves around the leading and trailing edges (relative to the propeller diameter).
s_{LE}	is the value of the `LE Point` slider;
s_{TE}	is the value of the `TE Point` slider;
Δc	is the separation of the leading and trailing edge curves normalized using the propeller diameter;

(ξ_{UR}, η_{UR}) is the blade parameter for the upper right corner of the central blade surface (also the value of the `UR Corner` input box);

(ξ_{UL}, η_{UL}) is the blade parameter for the upper left corner of the central blade surface (also the value of the `UL Corner` input box);

ξ_{LR} is the blade ξ parameter of the lower right corner of the central surface (also the value of the `LR Corner` slider);

ξ_{LL} is the blade ξ parameter of the lower left corner of the central surface (also the value of the `LL Corner` slider);

s_{min} is the value of the `LE Curve Limit` slider marking the transition from planar to non-planar curves around the leading edge;

s_{max} is the value of the `TE Curve Limit` slider marking the transition from planar to non-planar curves around the trailing edge;

d is the maximum distance between sampled points on a blade cut;

d_e is the distance from the leading or trailing edge over which smoothing will occur on a blade cut;

N_s is the number of smoothing iterations;

d_t is the the maximum distance to the blade tip along the leading and trailing edge over which smoothing occurs;

α is the smoothing relaxation factor;

IGES-file is the name of the file to which the output is written.

The option `-t` causes the hub surface to be trimmed where it intersects the blade. If this option is not present the hub will not be trimmed; it will then have to be trimmed manually in the program used to create the grid on the propeller. This option will always be present when `prop2iges` is called from `smooth-prop`.

While `prop2iges` is running, it reports to the shell on its progress beginning with a message describing the input file:

```
Reading propeller data from P4382.prp
  Making propeller blade...
  Done
  Origin: DTMB   Designation: P4382

  Number of blades: 5
  Diameter        : 0.3048
  Closed trailing edge
```

```
  Dull trailing edge
  Closed tip
  Dull tip
  Hub extent: -0.09144 to 0.09144
Done
```

It then reports on the locations of the points used to split the blade into five surfaces:

```
UL params =   9.620730e-02   5.695850e-01
UR params =   3.059250e-01   6.383160e-01
LL params =   1.666000e-01   1.281884e-01
LR params =   3.333000e-01   1.281884e-01
```

```
LE parameter = 0.547059
TE parameter = 0.317647
```

Then the number of curves around the tip and the leading and trailing edges are given:

```
22 curves around the TE
12 curves around the tip
22 curves around the LE
54 curves in total
```

It then makes the curves reporting the number of each curve as it goes:

```
Making curves on tip surface: 21 22 23 24 25 26 27 28 29 30 31 32
Making smoothed curves on trailing edge surface: 20 19 18 17 16 15 14
13
Making smoothed curves on leading edge surface: 33 34 35 36 37 38 39
40 41
Making remaining curves on trailing edge surface: 0 1 2 3 4 5 6 7 8 9
10 11 12
Making remaining curves on leading edge surface: 42 43 44 45 46 47 48
49 50 51 52 53
```

The knot sequences for the surface splines are then determined by approximating each curve with a spline. As the calculation progresses, the number of the curve being approximated is written followed by the number of knots required to achieve the desired accuracy; this will increase monotonically since each curve starts with the knot sequence from the previous curve.

```
Finding knot sequence for curves around LE and TE:
  0(13) 1(13) 2(15) 3(17) 4(17) 5(17) 6(17) 7(19) 8(19) 9(19) 10(19)
  11(19) 12(19) 13(19) 14(21) 15(21) 16(21) 17(21) 18(21) 19(21)
  20(21) 21(21) 22(21) 23(23) 24(23) 25(23) 26(23) 27(23) 28(23)
  29(23) 30(23) 31(23) 32(23) 33(23) 34(23) 35(23) 36(23) 37(23)
  38(23) 39(23) 40(23) 41(23) 42(23) 43(23) 44(23) 45(23) 46(23)
```

```
  47(23) 48(23) 49(23) 50(23) 51(23) 52(23) 53(23)
  22 segments around leading and trailing edges.
```

Finally, each surface is sampled at points in between the spline knots. The maximum deviation from the original blade surface is reported for each surface. Check these values carefully to ensure that the approximation of the blade surface is within your desired tolerance. If it is not, you may have to reduce the separation of the leading and trailing edge curves (Sec. 3.6), reduce the accuracy of the spline approximations (Sec. 3.5), or reduce the amount of smoothing applied near the tip.

```
Surface Trailing-Edge-Surface
  Accuracy: 2.00801e-05*D at (0.2,0.0)
  Blade point:    -1.163650e-02   2.817130e-02   1.347667e-02
  Surface point:  -1.163087e-02   2.817369e-02   1.347706e-02

Surface Pressure-Side-Central-Surface
  Accuracy: 1.95285e-05*D at (0.55,0.3)
  Blade point:    -7.415274e-03   6.146324e-02   1.049978e-02
  Surface point:  -7.410989e-03   6.146433e-02   1.050377e-02

Surface Leading-Edge-Surface
  Accuracy: 2.59837e-05*D at (0.55,0.15)
  Blade point:     1.503065e-02   5.160815e-02  -2.207236e-02
  Surface point:   1.502870e-02   5.161038e-02  -2.207970e-02

Surface Suction-Side-Central-Surface
  Accuracy: 2.15036e-05*D at (0.95,0.65)
  Blade point:    -5.038174e-02   7.334052e-02   3.315584e-02
  Surface point:  -5.037859e-02   7.334356e-02   3.316072e-02

Surface Tip-Surface
  Accuracy: 0.000144108*D at (0.05,0.5)
  Blade point:    -1.014473e-01   8.949024e-02   4.263725e-02
  Surface point:  -1.014841e-01   8.947206e-02   4.265285e-02
```

The hub is then calculated, its spine (the curve rotated around the propeller axis to form the surface) first being approximated by a spline.

```
Converting hub spine to a spline.
  12 polynomial segments.
Done
```

The intersection of the blade and hub is then found, converted to a spline and used to trim the hub.

```
Converting blade footprint to a spline.
  272 polynomial segments.
Done
```

Finally, the IGES file is written.

```
Writing P4382.igs
Done
```

The parameters used in the call to `prop2iges` are listed at the top of the IGES file in the comments section. For example, the file created by running `prop2iges` as above begins with the following lines:

```
DTMB  P4382                                                             S      1
IGES file created using prop2iges:                                      S      2
File: P4382.prp                                                         S      3
(xi,eta) UL:   9.620730e-02   5.695850e-01                              S      4
(xi,eta) UR:   3.059250e-01   6.383160e-01                              S      5
xi LL: 0.1666                                                           S      6
xi LR: 0.3333                                                           S      7
Param LE: 0.547059                                                      S      8
Param TE: 0.317647                                                      S      9
Planar cut range: 0.182057,0.743736                                     S     10
Accuracy: 0.0001*D                                                      S     11
Smoothing: 0.01 0.00352941 100                                          S     12
Relaxation: 0.735294 0.0526471                                          S     13
Max.Dist.between curves: 0.025                                          S     14
```

4 Concluding remarks

The programs described in this report circumvent a common problem when a propeller is generated in the traditional way from a series of airfoil sections: a coordinate singularity causes the geometry to be poorly defined near the tip so that it is not suitable for use in Reynolds-averaged Navier-Stokes (RANS) flow solvers. The algorithms remove the coordinate singularity and smooth the tip in a controlled way. The smoothed geometry is written in the IGES format which can be used by most commercial flow solvers. The improvements in propeller geometry allow analyses of propellers to be performed with a minimum of effort. The analysis procedure will be more robust and the results more reliable.

References

[1] Hally, D. (2013), C++ classes for representing propeller geometry, (DRDC Atlantic TM 2013-177) Defence Research and Development Canada – Atlantic.

[2] (1988), Initial Graphics Exchange Specification (IGES) Version 4.0, US Dept. of Commerce, National Bureau of Standards. Document No. NBSIR 88-3813.

[3] Hally, D. (2013), Smoothing propeller tip geometry for use in a RANS solver, (DRDC Atlantic TM 2013-178) Defence Research and Development Canada – Atlantic.

List of symbols

α	The smoothing relaxation factor.
(ξ, η)	Parameters for the blade surface.
(ξ_{UL}, η_{UL})	The blade parameters for the upper left corner of the central blade surface.
(ξ_{UR}, η_{UR})	The blade parameters for the upper right corner of the central blade surface.
Δc	The maximum distance between curves around the leading and trailing edges.
D	The propeller diameter.
d	The maximum separation of the points used for smoothing a blade cut.
d_e	On a blade cut, the distance from the leading or trailing edge over which smoothing occurs.
d_t	The distance from the tip, measured as arclength along the leading and trailing edge, over which smoothing occurs.
N_s	The number of smoothing iterations.
s	The fractional arclength around the blade outline.
s_{LE}	The value of the `LE Point` slider.
$s_{\max}$	The value of the `TE Curve Limit` slider.
$s_{\min}$	is the value of the `LE Curve Limit` slider.
s_{TE}	The value of the `TE Point` slider.
$\mathbf{x}_{LL}$	The point on the blade-hub intersection at the lower left hand corner of the central surface.
$\mathbf{x}_{LR}$	The point on the blade-hub intersection at the lower right hand corner of the central surface.
$\mathbf{x}_{UL}$	The point at the upper left hand corner of the central surface.
$\mathbf{x}_{UR}$	The point on the blade hub intersection at the upper right hand corner of the central surface.

$\mathbf{x}_{LE}$	The point on the leading edge between the leading edge surface and the tip surface.
$\mathbf{x}_{TE}$	The point on the trailing edge between the trailing edge surface and the tip surface.

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User's guide for smooth-prop: A program for smoothing propeller tip geometry

4. AUTHORS (Last name, followed by initials – ranks, titles, etc. not to be used.)

Hally, D.

5.	DATE OF PUBLICATION (Month and year of publication of document.) October 2013	6a.	NO. OF PAGES (Total containing information. Include Annexes, Appendices, etc.) 32	6b.	NO. OF REFS (Total cited in document.) 3

7. DESCRIPTIVE NOTES (The category of the document, e.g. technical report, technical note or memorandum. If appropriate, enter the type of report, e.g. interim, progress, summary, annual or final. Give the inclusive dates when a specific reporting period is covered.)

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9a.	PROJECT OR GRANT NO. (If appropriate, the applicable research and development project or grant number under which the document was written. Please specify whether project or grant.) Project 01gl08	9b.	CONTRACT NO. (If appropriate, the applicable number under which the document was written.)
10a.	ORIGINATOR'S DOCUMENT NUMBER (The official document number by which the document is identified by the originating activity. This number must be unique to this document.) DRDC Atlantic TM 2013-179	10b.	OTHER DOCUMENT NO(s). (Any other numbers which may be assigned this document either by the originator or by the sponsor.)

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The traditional method of specifying propeller geometry is to define a series of airfoil sections each of which is modified by local values of the chord length, pitch, skew angle and rake. Near the tip of the propeller, where the chord length reduces rapidly to zero, a blade defined in this way often has surface irregularities which make meshing for flow solvers difficult. This report is a user's manual for a program that will smooth the irregularities near the tip and save the resulting propeller geometry in the IGES format which can be read by most flow solvers.

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