

Design and Manufacturing of a Propeller for Axial-Flow Fan

D. Almazo, M. Toledo, and C. Rodríguez

Abstract—This work presents a methodology for the design and manufacture of propellers oriented to the experimental verification of theoretical results based on the combined model. The design process begins by using algorithms in Matlab which output data contain the coordinates of the points that define the blade airfoils, in this case the NACA 6512 airfoil was used. The modeling for the propeller blade was made in NX7, through the imported files in Matlab and with the help of surfaces. Later, the hub and the clamps were also modeled. Finally, NX 7 also made possible to create post-processed files to the required machine. It is possible to find the block of numbers with G & M codes about the type of driver on the machine. The file extension is .ptp. These files made possible to manufacture the blade, and the hub of the propeller.

Keywords—Airfoil, CAM, manufacturing, mathematical algorithm, numeric control, propeller design, simulation.

NOMENCLATURE

Tangential speed increase in the actuator disk	b'
Speed increase	
a'	
Lift Coefficient	C_L
Drag Coefficient	
C_D	
Chord	c
Magnitude of the relative wind	
V_0	
Speed of the propeller revolutions per second	n
Step angle	θ
Speed Angle	ϕ
Induced angle	ε
Angle of attack	
α	
Coefficient operation or factor of progress	
J	
Speed-induced	a
Speed-induced	b
Blade width	σ
Position along the chord	x
Half thickness	y
Radius	r

Maximum camber

m

Location of maximum camber

p

Tip twist

t_m

Root twist

t_M

Efficiency

η

I. INTRODUCTION

A PROPELLER is a mechanism designed to produce a attractive force or push, when submerged in a fluid medium. The propellers are aerodynamic elements, that are composed of a hub or central core and a number of blades, with helical surfaces that are united to it. Naturally, the characteristics of a propeller depend on: the speed of the plane in the direction of the axis of the propeller; the number of revolutions of the propeller, the unit of time; the diameter of the propeller; the number of blades; of the airfoils used; pressures; and the angles formed by the chord of the airfoils with the plane of rotation. Some applications of the propeller, in addition to the propulsion are: as part of a fan; by the turn of the propeller, produce wind having a difference of pressures, as it happens in the wind tunnel. Another case occurs when exploited and transformed the energy of the wind, into another type of energy as it could be mechanical or electrical, as it happens in a wind turbine.

The operating principle of axial-flow fans is simply deflection of airflow [1]. Past the blade, therefore, the pattern of the deflected airflow is of helical shape, like a spiral staircase. This is true for all three types of axial-flow fans: propeller fans, tubeaxial fans, and veneaxial fans. Accordingly, the design procedures and the design calculations are similar for all three types.

An airfoil is a streamline shape. Its main application is as the cross section of an airplane wing [2]. Another application is as the cross section of a fan blade [1].

This paper introduces computational tools to numerically solve some of the equations that were simplified before, in order to find an analytical solution [3].

II. COMBINED MODEL

There are two basic models that describe the operation of a propeller: the Rankine – Froude model and the blade element model [4]. From these models it is possible to get a non-linear system of equations for the angle and the speed induced in the disk of the propeller which are shown below:

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$$f(\varepsilon) = \tan(\varepsilon) - \frac{Jb + \pi\alpha a}{J(J+a) + \pi x(\pi x - b)} \quad (1)$$

$$a = \frac{\frac{8x}{\sigma} \sin(\phi + \varepsilon)(C_L \pi x - C_D J) - (C_L^2 + C_D^2) J}{\left[\frac{8x}{\sigma} \sin(\phi + \varepsilon) + C_D \right]^2 + C_L^2} \quad (2)$$

$$b = \frac{\frac{8x}{\sigma} \sin(\phi + \varepsilon)(C_L J + C_D \pi x) + (C_L^2 + C_D^2) \pi x}{\left[\frac{8x}{\sigma} \sin(\phi + \varepsilon) + C_D \right]^2 + C_L^2} \quad (3)$$

Seeking the solution of the equations 1, 2, and 3, to find the roots of these equations, using the classical Newton method. In this case it has been programmed in Matlab. Once the results are obtained by the equations above, it is possible to calculate the efficiency of the blade, by integrating the aerodynamic coefficients of the airfoils that comprise it and considering the geometrical characteristics of the blade itself as: chord length, step angle, thickness and mean camber.

10 parameters were defined to create a parametric family of airfoils for the propeller blade, which are: 1) root twist, 2) tip twist, 3) twist camber, 4) tip arrowed, 5) root arrowed, 6) arrowed camber, 7) chord root, 8) tip chord, 9) maximum chord, 10) location of point maximum chord.

The parameters are entered in the algorithm designed to automatically generate the text files that will contain the three-dimensional coordinates of the surface of the blade.

The airfoils generated from the previous program are divided into two parts that define the front and rear sides of the blade of the propeller: the airfoils are cut through the minimum and maximum coordinates in the transverse axis. Each airfoil consists of 401 points.

Fig. 1 shows the efficiency calculated for a propeller with a NACA 6512 airfoil compared with the experimental results [5].

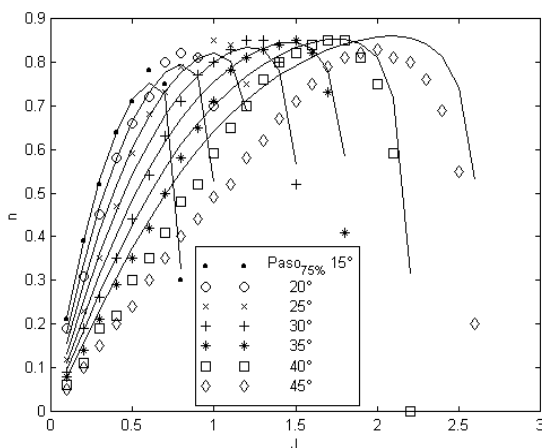


Fig. 1 Experimental results vs. Numerical estimates of the efficiency of a propeller

The Blade

The NACA airfoils are airfoil shapes for aircraft wings

developed by the National Advisory Committee for Aeronautics (NACA). The parameters in the numerical code can be entered into equations to precisely generate the cross-section of the airfoil and calculate its properties. The NACA four-digit wing sections define the profile by [6]:

First digit describing maximum camber as percentage of the chord.

Second digit describing the distance of maximum camber from the airfoil leading edge in tens of percent's of the chord.

Last two digits describing maximum thickness of the airfoil as percent of the chord.

The formula for the shape of 4-digit NACA airfoil, is:

$$y_t = \frac{t}{0.2} c \left[\begin{array}{l} 0.2969x\sqrt{\frac{x}{c}} - 0.1260\left(\frac{x}{c}\right) - 0.3516\left(\frac{x}{c}\right)^2 + \\ 0.2843\left(\frac{x}{c}\right)^3 - 0.1015\left(\frac{x}{c}\right)^4 \end{array} \right] \quad (4)$$

Camber Equation for the NACA Airfoil

The mean camber line is defined by two paraboles:

$$y = a1 * x^2 + b1 * x + c1 \quad (5)$$

$$y = a2 * x^2 + b2 * x + c2 \quad (6)$$

the first parable is defined by the equations:

$$0 = c1 \quad (7)$$

$$0 = 2 * a1p + b1 \quad (8)$$

$$m = a1 * p^2 + b1 * p + c1 \quad (9)$$

the second parable is defined by the equations:

$$0 = a2 * b2 + c2 \quad (10)$$

$$0 = 2 * a2 * p + b2 \quad (11)$$

$$m = a2 * p^2 + b2 * p + c2 \quad (12)$$

and the result of the previous process are the equations 13 and 14

$$y_c = m \frac{x}{p^2} \left(2p - \frac{x}{c} \right), \quad 0 \leq x \leq pc \quad (13)$$

$$y_c = m \frac{c-x}{(1-p)^2} \left(1 + \frac{x}{c} - 2p \right), \quad pc \leq x \leq c \quad (14)$$

where:

m is the maximum camber (is it the first of the four digits),
 p is the location of maximum camber (it is the second in the series of four digits [7]).

In Fig. 2 is possible to see the NACA 6512 airfoil that was obtained from the algorithm programmed in Matlab, this will serve for the creation of the second algorithm that will give you the blade for the propeller.

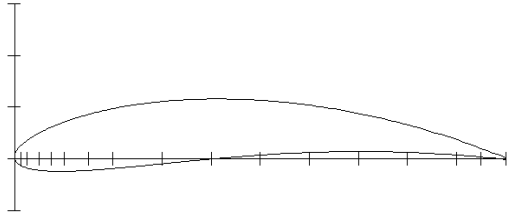


Fig. 2 NACA 6512 airfoil obtained from the first program in Matlab

The design process continues using a programmed algorithm in Matlab which output data contain the coordinates of the points that define the aerodynamic airfoils of the blade.

In order to be able to enter the parameters to the program in Matlab for the chord it is that:

The distribution of chord along the blade is defined also by two parables that are determined by the following parameters:

$$c_r = a_0 + a_1x_0 + a_2x_0^2 \quad (15)$$

$$c_m = a_0 + a_1r_m + a_2r_m^2 \quad (16)$$

$$0 = a_1 + 2a_2r_m \quad (17)$$

$$\begin{bmatrix} 1 & x_0 & x_0^2 \\ 1 & r_m & r_m^2 \\ 0 & 1 & 2r_m \end{bmatrix} \begin{bmatrix} a_0 \\ a_1 \\ a_2 \end{bmatrix} = \begin{bmatrix} c_r \\ c_m \\ 0 \end{bmatrix} \quad (18)$$

$$c_p = b_0 + 0.5b_1 + 0.5b_2^2 \quad (19)$$

$$c_m = b_0 + b_1r_m + b_2r_m^2 \quad (20)$$

$$0 = b_1 + 2b_2r_m \quad (21)$$

$$\begin{bmatrix} 1 & 0.5 & 0.5^2 \\ 1 & r_m & r_m^2 \\ 0 & 1 & 2r_m \end{bmatrix} \begin{bmatrix} b_0 \\ b_1 \\ b_2 \end{bmatrix} = \begin{bmatrix} c_p \\ c_m \\ 0 \end{bmatrix} \quad (22)$$

after making operations have the the following equation for the program in Matlab:

$$t = tm + (tM - tm) * ct * \left(\frac{1 - rx}{ct * (1 - rx) + (rx - X0)} \right) \quad (23)$$

If the above equation is plotted, it could be seen that at $x = x_0$ passes by $y = tm$ and $x = 1$ always passes through $y = tM$.

The equation 23 is used in the twisting and the arrowing of

the blade. In the programmed for Matlab tm it will be the twisted at tip and tM twisted in the root.

The arrowing on the blade, will be from low to high. As we want the biggest arrowing at the tip, arrowing is at the beginning and at the tip increases.

The result is the next blade with 50 airfoils and 401 points in each airfoil, as shown in Fig. 3:

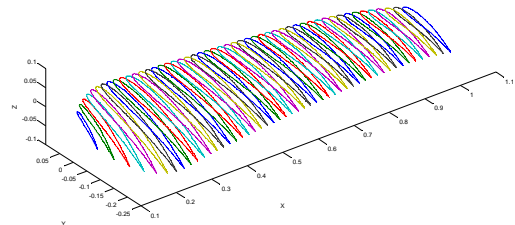


Fig. 3 Blade with 50 NACA airfoils modified

III. THE PROPELLER ON CAD

The Blade on Cad

From Matlab we can create text files with all the coordinates of each airfoil.

Once you have the files with the coordinates of the blade, they must go to a computer-aided design software for the generation of the model, in this case we used NX 7. It must scale the new geometries in NX 7, because in Matlab, the blade is measured as one unit.

Once you have the sections of airfoils, geometries must be closed, it is necessary to generate surfaces in NX. Fig. 4 shows how the airfoils are in NX 7.

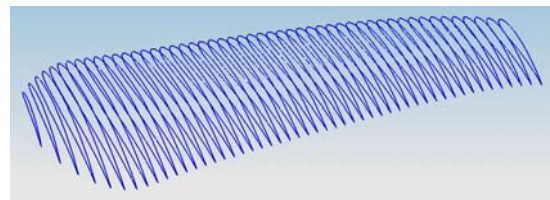


Fig. 4 50 NACA 6512 airfoils imported from Matlab

Once you have the closed airfoils in NX 7, the following step is to create , surfaces with the tools in the software, in this case the creation of splines.

Then we can create the solid with an operation, Known in CAD as "loft" or "swept". The tool, in NX 7 called "Trough Curves", uses a third-degree interpolation between airfoils to generate the solid.

Once you have the solid of the blade it is possible to insert the tube or the bar, as the case may be, linking the blade to the hub of the propeller.

The blade is as shown in Fig. 5:

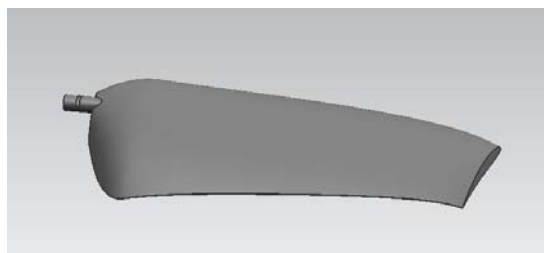


Fig. 5 Solid model of the blade generated with the software NX 7 based on the data obtained from the program, developed in Matlab

Now there is a need for a solid body that represents the block of the material that will contain the blade to be manufactured in a machine of C. N. C. This is accomplished extruding a rectangle in the suitcase position as shown in Fig. 6.

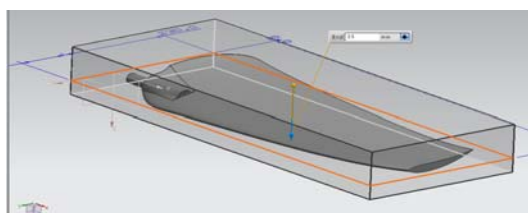


Fig. 6 Block that represents the material which you will get the blade

The Hub

The hub is simpler to make, it does not require too much mathematical development, programming or aerodynamic as when the blade was made. It Only requires the appropriate dimensions and shape. It is drawn in a CAD software, as shown in Fig. 7:

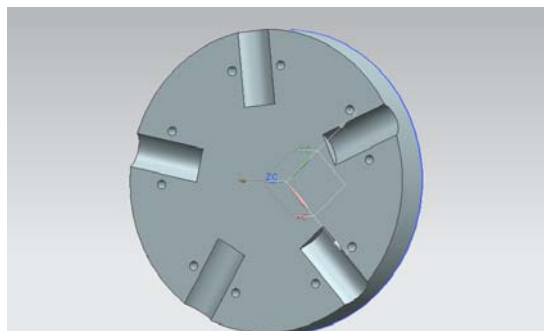


Fig. 7 0.2m hub diameter, with 5 slots for the blades and 10 holes for the 5 steel clamps

The Clamps

They only require drawing but, it is not necessary to manufacture them due to the large amount of them which are found on the market.

The clamp is as shown in Fig. 8:



Fig. 8 Clamp to secure the blade to the hub

CAD Assembly

Once you have the parts which comprise the propeller, you can do the assembly to see how it looks physically.

Fig. 9 shows the propeller's assembly.

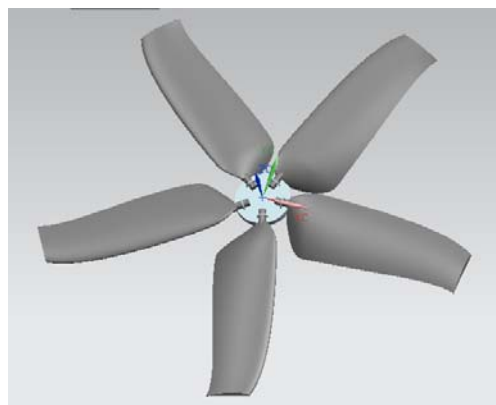


Fig. 9 The Propeller in CAD

Blade Manufacturing Simulation of Propeller

Once you have the CAD models, a simulation is performed about manufacturing in each of the parts of the propeller. The simulation's purpose is not to make mistakes in the manufacturing process. We'll use Manufacturing Module of NX 7 to generate CNC code for 3-Axis Vertical Machining Centers. The manufacturing module allows you to program and do some post-processing on drilling, milling, turning and wire-cut EDM tool paths. Fig. 10 shows how the trajectories of tool are generated.

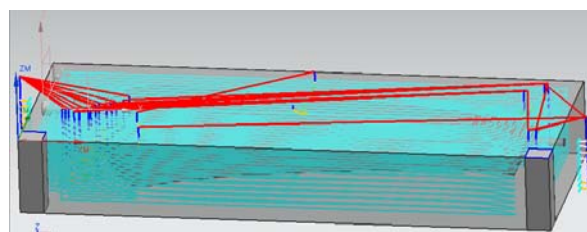


Fig. 10 Tool paths generated in NX 7

You can now observe the software slicing the model into depths of cuts and creating tool-path at every level. You can find cyan, blue, red and yellow lines on the model.

In Fig. 11, the face of Upper surface blade can be seen

once the main simulation was finished.

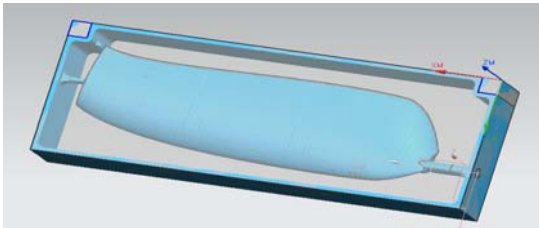
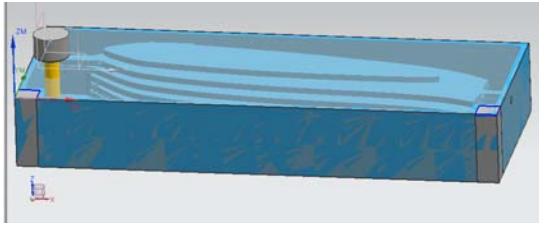


Fig. 11 Simulation of milling Upper surface

Post processing

The primary use of the Manufacturing application is to generate tool paths for manufacturing parts. Generally, we cannot just send an unmodified tool path file to a machine and start cutting because there are many different types of machines. Each type of machine has unique hardware capabilities, requirements and control systems. For instance, the machine may have a vertical or a horizontal spindle; it can cut while moving several axes simultaneously, etc.

CLSF (Cutter Location Source File)

After an operation is generated and saved, the resulting tool path is stored as part of the operation within the part file. CLSF (Cutter Location Source File) provides methods to copy these internal paths from the operations in the part file to tool paths within the CLSF, which is a text file. The values exported are referenced from the MCS stored in the operation.

The CLS file is the required input for some subsequent programs, such as postprocessors. The CLSF file will be created. The contents of the file contain the basic algorithm of the cutter motion without any information about machine codes and control systems. This file can be used for post-processing any machine control. The extension of the file is .cls.

NX 7 also allows you to create post-processed archives for the machine desired. You can find the block numbers with G and M codes concerning the machine controller type. The extension of the file is .ptp.

This entire sequence starting from the transfer of the model into the Manufacturing module to the transfer of the files to the machine and cutting the raw piece into the final part is called Computer Aided Manufacturing.

IV. BLADE MANUFACTURING

For the creation of the blade, a Canadian maple wood block is built first. The achieve the desired dimensions, plywood was used.

The model was made in Canadian maple wood by the

resistance to deformation when it is exposed to heat or moisture, for these reasons, this resist the curing and the whole process to make the mold of glass fiber.

This block with dimensions of 0.85m long x 0.33m wide x 0.12m thickness. The milling process began in one of its faces within the machining center actually in Upper surface. After the completion of the first side, it required to be filled with rigid polyurethane foam, on the rough side, so that when the second milling process starts on the lower surface, it wouldn't fall off the blade or suffer any movement that would change its way. Before placing the polyurethane foam it is important to place at least four layers of wax mold release and at least two layers of parting wax, the foregoing, so that the foam does not stick to the wood blade.

Fig. 12 shows a picture of leftover material after removing the blade. In the same figure we can see the lower surface of a blade of the same dimensions in polyurethane foam that was used as a test.



Fig. 12 Leftover material, with contains a test of manufacturing of the foam blade

Once that the manufacture of the wooden blade was completed, it was polished and ready to make a fiberglass mold with it, to obtain 5 five blades to the propeller. Although the blades can be made in carbon fiber or other materials, but the cost increases significantly.

In Fig. 13 we see a picture that shows the varnished blade extracted from the wood block.



Fig. 13 The polished and varnished blade that was removed from the wood block

It uses the fiberglass for the mold, since it is one of the most used products in the molding of the polyester resins [8]. It has a series of mechanical properties that make it an ideal reinforcement for the manufacture of different parts. The amount of glass fiber varies in weight percentage according to the mechanical characteristics of the part required to manufacture. In Fig. 14 shows a photograph of the mold in

fiberglass, which was used to make the final 5 blades.



Fig. 14 Inside of the mold made of glass fiber

It is important to mention that the blades can be built with or without the fill, depending on the application, but if they are made with fill is a little more expensive process, since it requires additional material and it requires tests so that the filling of the blade does not deform the blade itself. Fig. 15 is a photograph of the of glass fiber blades in the drying process.



Fig. 15 5 blades hanging

V. HUB MANUFACTURING

Of an aluminum bar, cut a 0.2m diameter disc and 0.0254m thickness. Milled in conventional lathe to make it flat and cylindrical. In Fig. 16 we see a photograph of the plane and cylindrical disk.



Fig. 16 0.2m diameter disk

After the disk in CAD modeling is generated, from NX 7 codes G&M are to be introduced in the machining center and you can begin to create the slots and holes in the hub, as well as the cavity attaching the engine to the hub.

Fig. 17 shows a photograph of the hub of the propeller.



Fig. 17 The hub

VI. PROPELLER ASSEMBLY

Fig. 18 shows a photograph of the propeller assembly.



Fig. 18 Propeller assembly

VII. RESULTS

From the aerodynamic point of view, it is a method for the prediction of the efficiency of a propeller.

On the other hand, the precision with which manufacture the propeller blade and anticipated behavior of the materials for the propeller proved to be a success since we didn't have behaviors in the material that were unexpected, so it is recommended to use the Canadian maple for the model, because it generates threads of wood and it does not tear when roughing in the center of machining and it does not burt. We found that the glass fiber to generate the mold is recommended as it can withstand without problems the curing process and the entire process of manufacturing of the blades.

VIII. CONCLUSION

From the perspective of aerodynamics, there is a methodology for the design and manufacture propellers, no matter what the application of this, since the method described in this work can be used to design and manufacture propellers for different applications. It is documented how to design and manufacture a form as complex as the blade of a propeller

from an airfoil, with the accuracy required to obtain the desired characteristics.

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