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Research paper

A B-spline design model for propeller blades

F. Pérez-Arribas, R. Pérez-Fernández*

Universidad Politécnica de Madrid. (UPM), Avenida Arco de la Victoria 4, 28040 Madrid, Spain

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ABSTRACT

This work presents a new design methodology for modelling the blades of propellers using B-spline surfaces. Propeller blades are good examples of free form surfaces, designed specifically considering several parameters that control their performance. Traditional tools for surface design in CAD, such as control point manipulation, are not appropriated for blade design, and the designers prefer to work with design parameters that possess a clear aerodynamic / hydrodynamic meaning. This method uses common design parameters for the geometry of propellers and produces a final B-spline surface for the geometry of the blades that can be used for the visualisation, calculations, and construction of the propeller. The method starts with the definition of a 3D grid of points that form the propeller blades based on the 2D definition of a series of cross-sectional profiles at several radial locations. Propeller blades are very thin objects with great changes of curvature, and if standard B-spline techniques are used, they cannot be modelled well under a tolerance unless a large number of control points is used, producing very complex surfaces.

The inclination and twist of the blades are given by rake and pitch angles, quite common in the design procedures. The method stresses the fitting of the blade's leading edge which has great effect on the propeller behaviour and geometrically has a small curvature radius in comparison with the rest of the blades.

1. Introduction

Blades of airplane or ship propeller are familiar shapes for most people, and anyone has in mind its nice curved and slender shape. Geometrically speaking they are nice examples of functional free form surfaces that are designed by engineers for a practical purpose controlling their performance. Today, propellers are common in commercial drones that are easily available, and the use of 3D printers enables the construction of these geometries with the appropriate CAD files (Fig. 1). In the particular case of this figure, the propeller at the bottom can be printed without support surfaces.

Blades are typically defined by a series of cross-sectional profiles stacked at several radial locations. These sections can be developed on planes in the case of wings of foils, on concentric cylinders in the case of propellers, or in concentric cones in the case of turbo machinery (gas, steam, and Pelton turbines mainly). This paper is focused on propellers that consist of a number of identical twisted blades spaced equally around a hub. The blade shape is defined by a series of cylindrical cross-sections at specified radius ratios of the propeller. The inclination of the blades is given by the rake and there are other specific parameters, such as skew and twist distributions (Fig. 5).

A left-hand ship propeller is presented in Fig. 2, where the propeller plane is the XZ plane and the flow direction is along the Y axis, which is also the rotation axis. The hub is depicted as a cylinder and the base circles are presented. The blade sections of that figure are contained in concentric cylinders which are defined to represent the path of fluid through the propeller. This assumption simplifies the aerodynamic / hydrodynamic design procedure and calculations that also consider the 3D interaction between cylinders numerically.

The blade design and its geometrical definition are intrinsically related to the selection of a 2D profile and its geometrical characteristics mainly considering their aerodynamic or hydrodynamic performance. Therefore, the geometrical characteristics of the 2D sections must be accurately modelled in a 3D definition of the propeller blades.

So, the approach presented for defining the geometry of the rotor blades is based on a discrete approximation of a collection of space curves or cross sections, containing a 3D representation of the 2D profile points. The manner in which these points are obtained and the tolerances associated with the data, influence the presented method for the representation of the blades. This blade definition corresponds to the classical construction of a propeller based on a generator line and profiles attached to it. A classical ship's propeller lines drawing is shown in Fig. 3, where the expanded 2D profiles are presented at different stations and two projections are used to represent the complete propeller geometry. Propeller workshops use this kind of representations to construct ship propellers at full scale.

* Corresponding author.
E-mail address: rodrigo.fernandez@sener.es (R. Pérez-Fernández).

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Fig. 1. Example of propeller: air drone (up) and boat propeller (down).

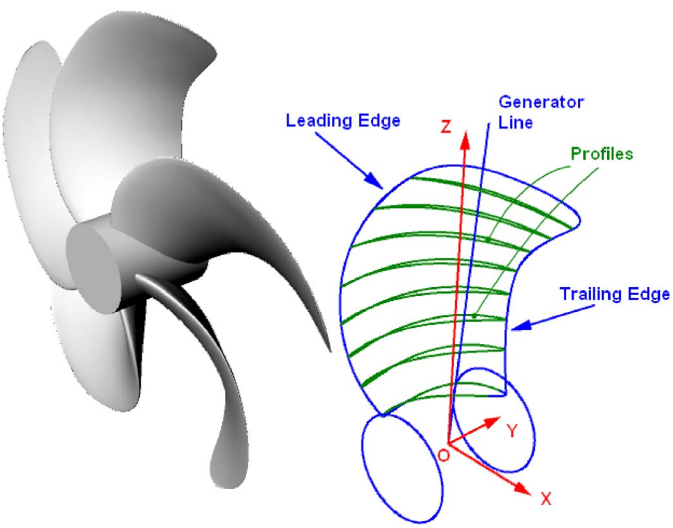

Fig. 2. Schematic propeller geometry.

Modelling the geometry of a propeller is different from modelling other industrial objects; for example, an accurate representation of the shape of the sections is required, and this requires working with a large amount of information because the representation of these curves is based on a discrete set of data points, usually more than 100 points per curve. If standard techniques are used, very complex surfaces with a large number of control points are obtained and will likely present poor smoothness in the resulting surface obtained from the interpolation of the data points.

The results defined by the blade design process have to be compatible with existing standard technology in CAD, and are difficult to solve by direct or manual manipulation of the control points in the surfaces. B-spline representation of blade surfaces is widely used, and enables subsequent steps in the product development such as manufacturing, finite element analysis, or Computer Fluid Dynamics (CFD) calculations. Techniques for propeller design have a long history with the first scientific works published in the 1960s. If the reader would like to know more about hydrodynamic / aerodynamic design of propellers and why the shape is different in the case of marine and airplane propellers, two good starting points are the readings in references [1,2].

In more recent years, the use of CAD methodologies and software products, opened new possibilities for blade design. Blades are typically defined by a series of cross-sectional profiles stacked at several radial locations. These sections can be developed on planes in the case of wings of foils, on concentric cylinders in the case of propellers, or in concentric cones in the case of turbo machinery (gas, steam, and Pelton turbines mainly). Thus there is a wide scope for blade representation, with common geometry basics, and there are different techniques for convenient shape modifications of the blade surfaces. Reference [3] presents a technique for designing functional surfaces including normal vectors as physical constraints of the surface. The method focused on propeller design based on hydrodynamic analysis but did not use B-spline representation. In reference [4], turbine blades are first reproduced via lofted B-spline surfaces from a set of given planar profile curves, also produced in B-spline representation. This reference does not consider how the profile curves are obtained, which is a key factor in propeller design. Reference [5] presents an approach for turbine blade that allows the designer to control certain geometric parameters of the blades, and include blade material. However, it does not consider the use of sections and needs an initial surface definition. Reference [6] uses B-spline curves to represent turbine blades, based on 2D blade sections. This reference uses a large number of data points to model the 2D sections, and uses the same points as the B-spline control points. It will be seen later that a reduced number of control points is desired, since a large number of control points will likely present poor smoothness in the resulting surface. This reference also used the lofting technique, so the blade can be produced with a single surface.

A constraint of the present problem is that the leading edge of the propeller (Fig. 2) must be accurately reproduced because most of the performance characteristics are induced by this region. This part of the surface presents high curvature values when compared with the rest of the shape of the blades and if it is modelled with a wrong definition of the leading edge, additional drag to the one that has been predicted will be present in the final design.

The first step of the presented method is to accurately model the 3D data points of propeller profiles, with special attention to their leading edge. An iterative least squares fitting process [7] with an original selection of the parameterisation based on the minimum of the maximum Euclidean distances, (Haussdorf metric) is described in Section 3 and also considers accurate modelling of the leading edge.

The proposed method allows a reduction in the number of control points of the profiles without reducing accuracy. Data reduction in an object representation speeds up most of the downstream processes, improves the fairing of the resulting surface and decreases storage requirements in following design stages. Once the profiles have been accurately modelled with B-spline curves, the next step is to construct a surface that contains them. The technique of lofting or skinning over B-spline curves was selected from the various numerical methods used for industrial surface definitions. This consists of fitting a surface through