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SHORT ORIGINAL PAPER

Design for manufacturing with tool paths adapted to marine propeller

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Abstract Marine propellers are complex surfaces that are usually machined with a perfect roughness not to disturb the theoretical flow. Because this requirement is penalizing from a manufacturing point of view, the global objective of the study is to propose an approach in which the machining parameters are linked to functional properties of the blade in order to cancel the polishing phase. Indeed, the flow around the blade, associated with the performance of the propeller, is characterized with stream lines. The approach that is presented in the paper links the tool trajectories to flow specifications, specifically by following those stream lines. To benefit from a rotational axis on a five-axis-machine-tool, the idea is to compose a continuous trajectory, especially at the leading edge, to mill the surface. As the tool paths follow specific hydrodynamical lines, the geometrical information such as peak heights vary along the blade. Finally, the strategy allows multiaxial milling of a blade surface in the context of design for manufacturing.

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1 Introduction

This research fits in with a multi-step improvement of marine propeller manufacturing process. When producing the propeller, obtaining a mirror polished roughness represents approximately 15 % of the total cost and of the total production time [5]. A controlled loss of the roughness parameters may reduce those costs/times. Unlike the bidimensional foil [2], where the flow can be considered as planar, the blade is naturally characterized with a three dimension flow. The presented approach links the tool trajectories to flow specifications. The solution considers that the streak lines can be used to control the orientation of the tool paths.

The streak lines are tangent to the wall and to the speed vector; they can be obtained from computer-fluid-dynamic computation. (see Fig. 1). Whereas the stream lines cannot exist exactly at the wall because of friction effect, streak lines can also be considered as the extrapolation of these stream lines at the surface.

Two studies are planned. The first concerns the obtaining of a surface pattern that has a lesser impact on hydrodynamical performances, (see Fig. 2), [2,4]. The second objective is to develop a new machining methodology allowing a reduction of time and/or cost machining. This latter point can be seen as an improvement in itself or a consequence of the former.

Thus, blades machining is supported with three-dimensional streak lines in order to obtain a machined propeller which will not require being polished before use.

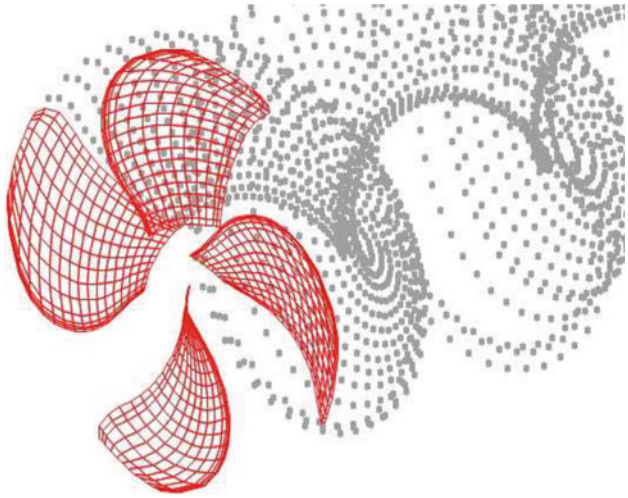


Fig. 1 Propeller and associated flow in a boundary element method code

2 Functional description of the propeller

Considering the propeller as a functional device, the main characteristics specifying its performances and efficiency are thrust, yield and cavitation behavior. These global parameters are distributed on each blade, on which it is possible to measure drag and lift parameters to characterize the chosen profile. Similarly to a bidimensional foil, the profile can be described with a pressure side and a suction side. What happens at leading edge is relevant from a hydrodynamical point of view because the speed and pressure behavior is separated into two parts.

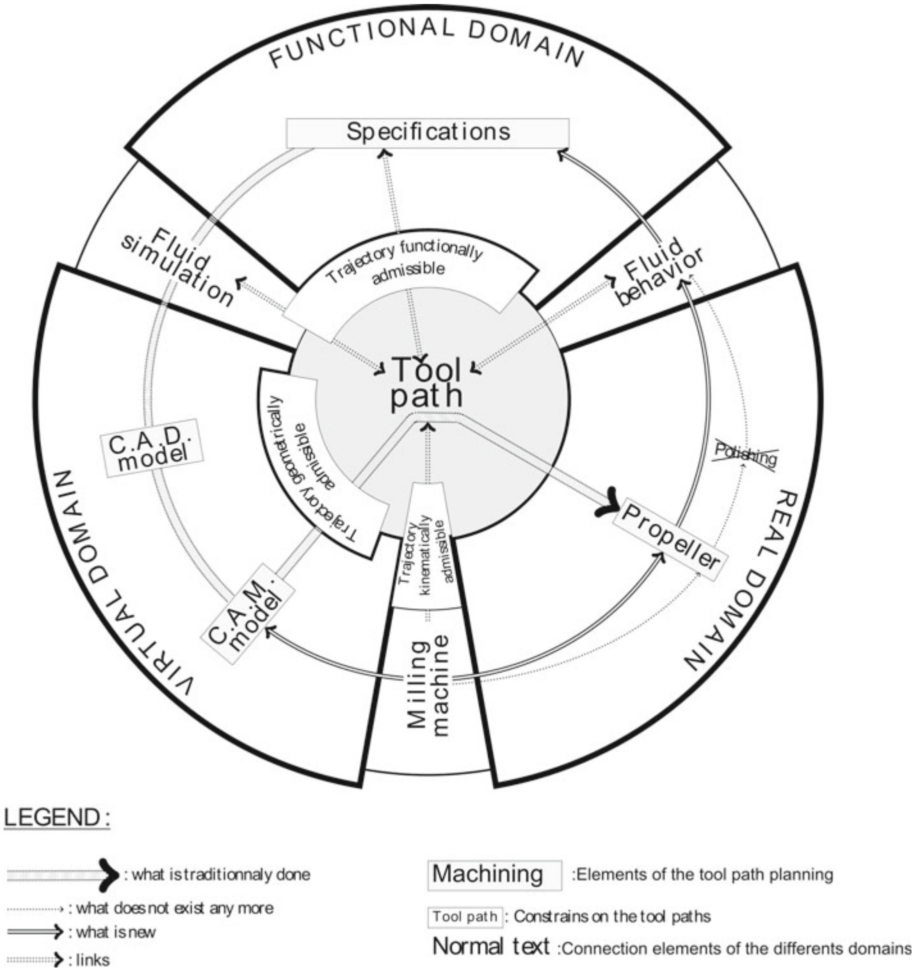
The cavitation phenomenon, appearing because of a too important variation of pressure, has to be avoided as it degrades the performances and can damage the structure. To quantify these properties of foils, tests in cavitation channel are under consideration to measure drag, lift and cavitation characteristics.

3 C.A.M. path planning preparation

3.1 Machining objectives

This work proposes to develop a machining approach that leads to such a roughness that the polishing phase could be avoided without any substantial degradation of performances. Those performances come from the local pressure and the local skin friction repartition in both sides of the

Fig. 2 Process of propeller machining in a functional way



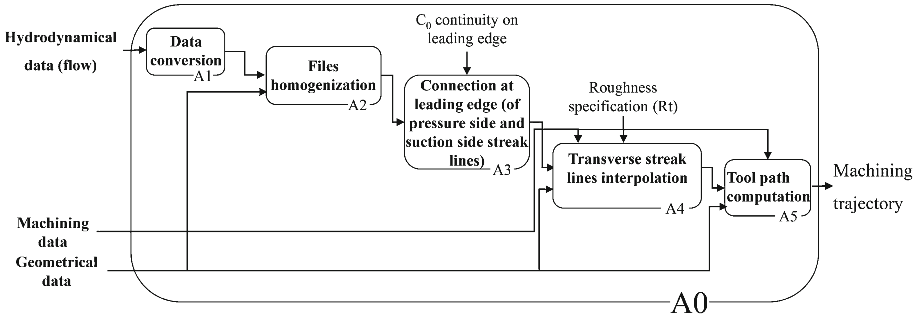


Fig. 3 Used Algorithm to compute tool path

blade (suction side and pressure side); they are obtained from experiments performed in a hydrodynamic tunnel. Cavitation is another problem which must be taken into account particularly near the leading edge of the blades and at the tip of the blades. But it is important to note that all this factors are sensitive to surface roughness. From a hydrodynamical point of view, roughness can be considered as "small obstacles" for the near-wall flow that increases the skin friction. However, the flow direction around the blade is organized and is characterised by streak lines. The main idea in this work is to manufacturing propellers that are not polished, with a residual roughness that is organized in the direction of the flow in the close vicinity of the wall, to not disturb the stream.

Actually in the industry, propellers are manufactured on dedicated machine-tool. They are mostly milled into two phases because of their weight (several tons), they cannot be positioned on a displacement axis. Hence there is a machining recovery at this frontier between pressure side and suction side, whereas the leading edge is an area where pressure strongly varies. If cavitation appears in this part, it may propagate along the surface.

Consequently, grooves may stay on propeller after machining, but it should be reasonable to observe a continuous ridge on leading edge. That is the reason why, in this approach, the four blades are machined separately on a five-axis-machine with a rollover axis perpendicular to the spindle axis (see Sect. 4). Algorithms are developed to obtain machining trajectories based on continuous hydrodynamical data.

3.2 Adaptation of hydrodynamical data regarding to machining objectives

The developed approach [1] allows to avoid the polishing phase, keeping oriented machining grooves thanks to the algorithm (see Fig. 2). Because streak lines are going to be used as a support for machining trajectories, they have to be continued and smooth [3] on the leading edge. In this part, a methodology to obtain machinable streak lines is presented.

Streak lines representing the flow are constituted with a starting point on the leading edge and an end point on the trailing edge. But, those streak lines (each side) are discontinued on the leading edge because of the numerical approach that is used. As proposed in the introduction, one of the goals of this study is to machine the leading edge without discontinuities not to create grooves that can make cavitation appearing. So, an algorithm which connects the streak lines on the leading edge is developed (see Fig. 3 step A3 and Fig. 4). To machine precisely the surface this algorithm also densifies the number of points in each streak lines.

Streak lines cannot be used directly because the way they are generated causes a discontinuity at leading edge. The solution is to keep the streak lines on one side of the blade (on suction side because most influent on hydrodynamic performances) and to interpolate the complementary part on the other side. Data of the geometrical sections is added in such a way that the interpolated streak lines are as close as the blade surface (see Fig. 5). In a first time, the radius (defined from the propeller axis) of the first points from all suction side streak lines are computed. Then, a CAD section is interpolated at this radius from original CAD sections. Because CAD sections are cylindrical, the points of the pressure and suction sides are located at same radius. After this step, the suction side streak lines are determined to interpolate new pressure side streak lines. Those new streak lines have first points that are similar with the interpolated CAD sections. The step of CAD section interpolation is used to optimise the location of the pressure side streak lines. So, continuous streak lines, composed with original suction side streak lines and interpolated pressure side streak lines are obtained (see Figs. 4, 5).

Then, two solutions are tried out to obtain tool paths (see Fig. 6). The original files contain about twenty streak lines. So, the first solution is to machine the propeller as a facetted surface. In one direction the facet's boundaries are part of leading and trailing edge, and in the other direction there are two streak lines (see Fig. 4). Then the machining trajectories are obtained with the CAM software CATIA. Each facet is swept using the boundary streak lines. The tool orientation is

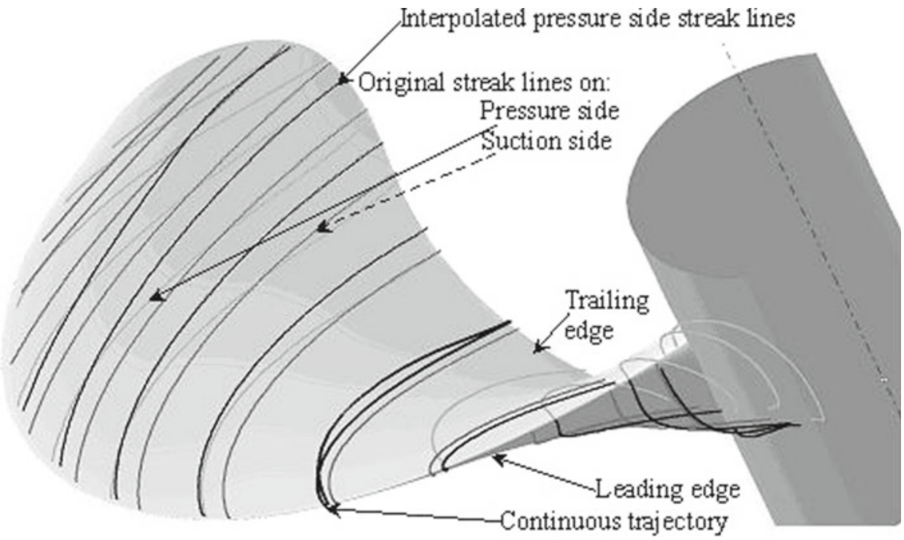


Fig. 4 Streak lines interpolation on the pressure side

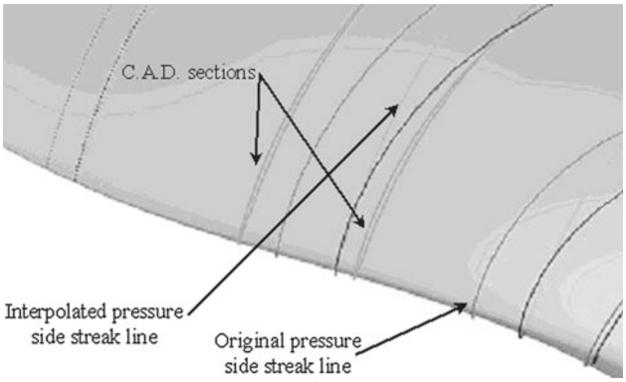


Fig. 5 Zoom on streak line interpolation at the leading edge

perpendicular to the surface and a maximum cusp height of 0.22 mm is computed. This parameter was chosen in a similarity study with a real propeller which diameter is 1,710 mm [5]. Moreover, with this approach, the step A5 on the algorithm (see Fig. 3) is directly computed after step A3 because step A4 is achieved by the CAM software CATIA.

But, with this approach the cusp height is determined by the software as a maximum allowed value and the precise location of this maximum is not known.

To control the direction of the surface pattern, a second algorithm which directly computes the tool paths from the data is developed. For each facet, the boundary streak lines (original on suction side and interpolated on pressure side, see Fig. 4) are used as input to interpolate the new trajectories. The distance between two adjacent trajectories, to respect a maximum cusp height of 0.22 mm on the leading edge, is computed and used as width between tool paths (see Fig. 3 step A4).

Roughness is analysed transversally to the grooves, from the boss to the top of blade. The maximum cusp height is so computed along the leading edge, which seems to be significant from a geometrical point of view.

4 Machining, geometrical and functional measuring, tests and performances

To benefit from rotational axis (A) which is perpendicular to the spindle axis (Z), the position and orientation of the blade on a five-axis machine tool are determined to propose a continuous trajectory. Actually, the setup work-piece fits the blade so that the propeller rotational axis is quite perpendicular to the machine tool rotational axis A (see Fig. 6). More precisely, the piece is balanced in such a way that the extremity point of the blade belongs to this rotational axis. The tail stock is rigidifying the structure to limit deformation due to flexion and to minimize vibration during the milling. Unlike a two phases machining, the developments and the new approach allows a one phase milling.

The trajectory are designed for manufacturing without discontinuity at leading edge from hydrodynamical data and sometimes from geometry for zones in which there is a lack of these data (see Sect. 3). In this orientation, due to the blade geometry, the most requested displacement axis is perpendicular to A, it is Z axis. In fact, considering the kinematics of the machine, Z is the fastest axis according to acceleration performances.

The comparative analysis is based on geometrical measurement on one side, and on functional measurement on the other side. Tests in hydrodynamic channel, to characterize the performances of the developed solution, are planned.

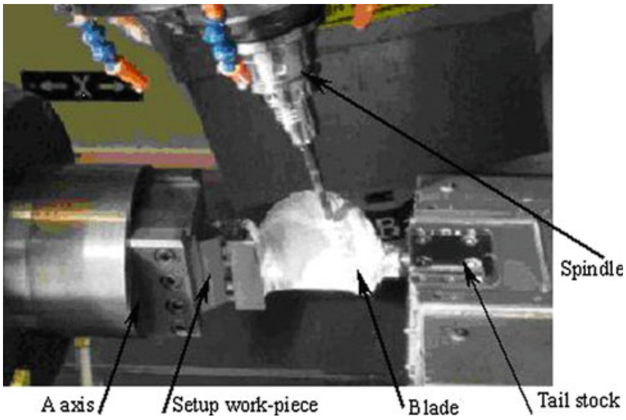


Fig. 6 Milling of an aluminium blade

5 Conclusion

The specific requirement consisting in polishing the blades of marine propellers is a constraint that may lead to over quality. The approach developed in this paper allows a milling of the blade in which the machining parameters are linked to functional properties. The flow at the surface should not be perturbed because the proposed tool path is a trajectory supported by stream lines. Thus the polishing phase may be avoided which represents a significant profit of cost and time to the manufacturer.

Considering the machining strategy, the contribution of the used methodology is based on a tool path planning generated with both hydrodynamical and geometrical data. Indeed, some specific zones on the blade present a lack of information concerning stream line (leading edge, extremity,…). The approach interpolates lines on both suction side and pressure side, thus setting a continuous way for a five axis milling with a rollover rotational axis.

The cusp height, which is a relevant parameter from geometrical choices of the strategy, is chosen according to former studies. A specific work concerning this point constitutes the future orientation of the topics research. A great interest to the study is showed by the industrialists both working on the propeller definition—data is given by the BEC—and on the propeller machining—contracts were led with the French naval architect DCNS [2].

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