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A NEW STRATEGY OF TOOL PATH PLANNING BASED ON HYDRODYNAMIC DATA TO MACHINE MARINE PROPELLER.

Marine propellers are complex surfaces that are usually machined with a perfect roughness in order 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 remove the polishing phase.

To reach this objective, hydrodynamic data are used: streak lines, that are computed during the propeller design phase, characterize the fluid behavior at the close vicinity of the blade. Those lines, which are theoretically continuous at the leading edge, turn out to be discontinuous, due to the computing method.

To be consistent with the fluid behavior as much as possible, the idea presented in the paper is to compose a continuous trajectory, especially at the leading edge, to mill the surface. Thus, an algorithm is developed to plan tool paths which are smoothed at leading edge using Bezier curves. Moreover, this algorithm allows to quantify the cusp height at the leading edge to avoid a drop in performance using criteria linked to the dynamical behavior of a five axis machine tool. In this work, a strategy is developed and enables multiaxial milling of a blade surface by using geometric and hydrodynamic data and by respecting the associated constraints.

1. INTRODUCTION

Nowadays, marine propellers make up the most common means of ship propulsion. Their sizes, shapes and numbers of blades vary as much as the boat types. But, propellers have one common characteristic: their surface roughness, which is usually mirror polished. This requirement, which is specified to minimize the power loss due to friction between the fluid and the propeller, is of primary importance. In fact, the mirror polishing step

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corresponds to fifteen percent of the time and cost of fabrication [2]. The following work aims at reducing those time and cost rates without decreasing the propeller performances.

During propeller production, the surface roughness is taken into account into the machining phase, before the polishing phase. Subsequent to the sand cast that leads to the first form, the machining enables the approach of the nominal surface. By introducing hydrodynamic considerations in connection with the propeller geometry, the presented work allows an orientation of this roughness default. Through this organisation, although it is not equal to zero, the residual roughness should not penalize the hydrodynamic performances. Consequently, the step of mirror polishing should become unnecessary.

In a first part the interactions between the propeller roughness and the fluid behavior at the close vicinity of the blades are studied. Some criteria are established, that must be respected to have a non-zero rugosity that does not penalize the propeller performances. Then, a machining strategy based on those criteria is developed in a second part. Finally, a third part highlights the specificities of the propeller machining with the developed strategy and outlines the perspectives offered by the hydrodynamic tests.

2. SET UP OF THE PROBLEM

2.1. PROPELLER PRODUCTION.

The first step of the propeller production is the definition of the propeller specifications. Then comes the design of the propeller, which is based on a model simulation with an associated flow. At last, this model is successively sand cast to obtain a first form that approximates the final propeller volume and milled with a numerical command (N.C.) machine. This machining step is performed to control the final propeller form and to limit the cusp height [8]. Finally, to reach the required roughness specification, the propeller is hand polished.

In this study, to present the propeller production, the different steps of the propeller life cycle are stored in three domains (see Fig. 1). The first domain is the functional domain constraining with the propeller specifications. The second one is the virtual domain, in which the propeller is virtually designed with a C.A.D. software. Computational Fluid Dynamics (C.F.D.) software are also used at the interface of this domain with the first one to validate the designed propeller. The third domain is the real one in which the propeller is machined and polished. The N.C. machine allows the transfer from the second to the third domain.

As shown on Fig. 1., in the third domain, it is the polishing phase that impacts on the final roughness and therefore one the fluid behavior. Roughness specification is specified by the propeller class and the manufacturing standard ISO 484. To have an easiest polishing phase, the same class is specified on the whole surface, but researches [7] highlight that the propeller areas have different impacts on the propeller performances and can be polished with different roughness classes. Taking into account this information, it seems possible to machine the propeller with different methods according to the required precision of the local zone.

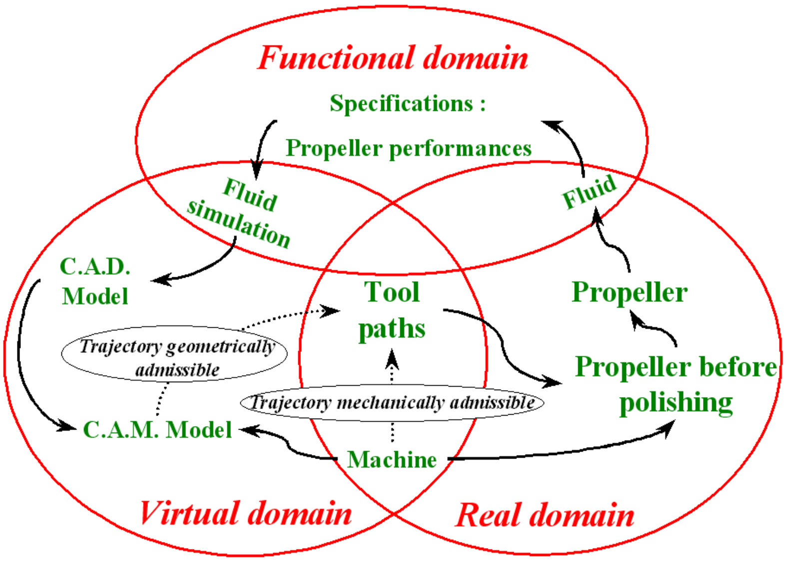


Fig. 1. Classical approach of propeller production.

2.2. PROPELLER LIFE CYCLE

During the propeller life cycle in the marine environment, the surface roughness is damaged and leads to an increase of fuel consumption due to the loss of propulsive power [7]. Those roughness damages are not homogeneous on the whole surface [3] due to different phenomena like cavitation and fouling (weed growth and barnacle deposit, Fig. 2).

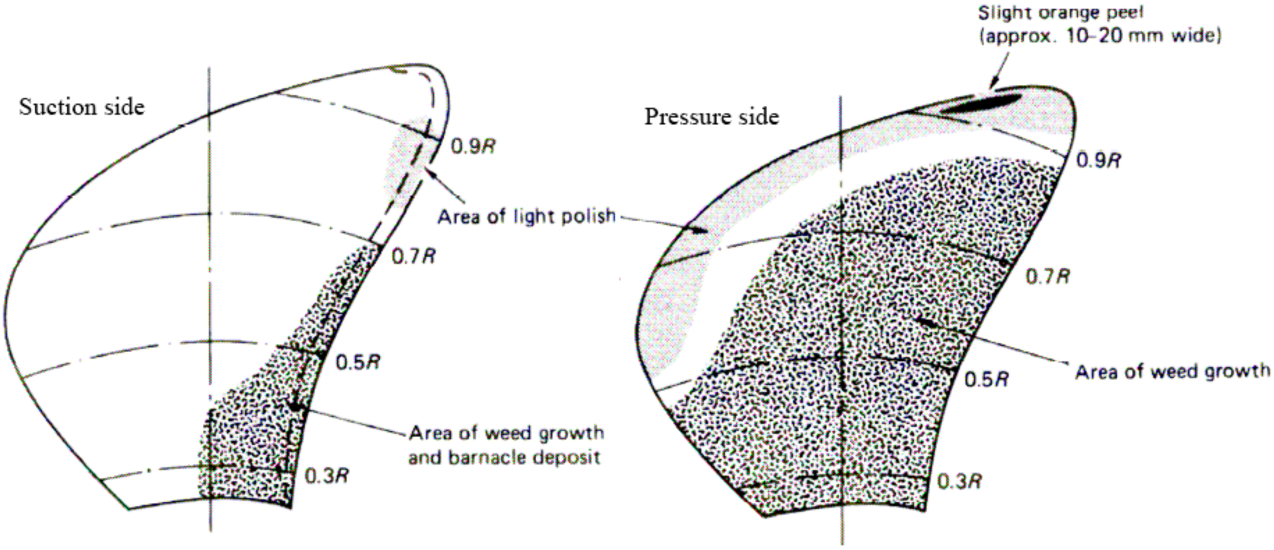


Fig. 2. Zones of roughness damages due to cavitation and fouling. [3]

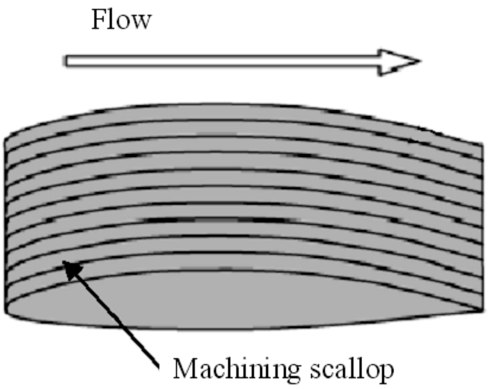


Fig. 3. Roughness oriented according to the fluid behavior on a 2D Foil [2]

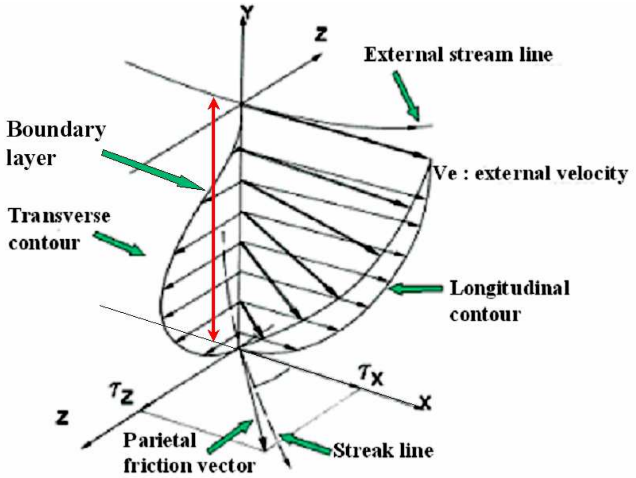


Fig. 4. Fluid behavior at the close vicinity of the blade

Considering this information and the time and cost rates taken by the polishing phase in the propeller fabrication [2], the methodology presented in this article aims at studying the influence of the propeller polishing on the performances. Is it possible to produce a propeller that does not require any polishing, and whose finition is acceptable with respect to hydrodynamic criteria?

2.3. LINKS BETWEEN HYDRODYNAMIC PHENOMENA AND PROPELLER MANUFACTURING

Researches lead on two-dimensional foils [2] highlighted that a roughness (the machined scallop) which is parallel to the flow has almost no impact on the hydrodynamic performances (Fig. 3). It is therefore decided to machine the blade of the propeller according to the fluid behavior at the close vicinity of the blade, in the boundary layer (Fig. 4). Outside the boundary layer the flow is characterized by stream lines that support the fluids speed vector. Those lines, extrapolated on the surface, are named streak lines and characterize the direction and the intensity of the roughness (see Fig. 4). They will be used to orientate the final roughness and so, to support the machining trajectories during fabrication.

Machining a roughness according to the fluid behaviour is not the only criterion to ensure the smooth running of the propeller. In his researches [3], J. Carlton analysed the propeller roughness after running (Fig. 2) and observed that the cavitation did not have an homogeneous effect on the whole surface. The damages due to cavitation are particularly important on the leading edge. Other researches on 2D foils [2] demonstrated that an increase of rugosity increased cavitation, that often appears near the leading edge. For those reasons, the roughness of this area must be regular and must not present grooves due to machining discontinuities. As the leading edge, that will be as regular as possible, the area of the suction side is as important as the leading edge one. In fact, this zone ensures the most important part of the thrust during running. So, the rugosity lines must be as consistent as possible with the streak lines on this blade face not to disturb the fluid and not to decrease the performances.

2.4. MULATION

From the above observations about the fluid behavior at the close vicinity of the blade, the presented work aims at developing a new methodology of tool path planning. Not to disturb the hydrodynamic performances of the propeller, the generated tool paths must be continuous at the leading edge and consistent with the fluid behavior. So, if the same hydrodynamic performances are obtained while avoiding the mirror polishing of the propeller, the objective of those researches should be achieved.

3. NEW APPROACH FOR PROPELLER PRODUCTION

In the industry, propellers are currently manufactured on dedicated machine-tools. They are mostly milled into two phases because of their weights (several tons), which prevent them from being positioned on a displacement axis. Hence there is a machining recovery at the frontier between pressure and suction sides, whereas the leading edge is an area where pressure strongly varies (see §1.3.). If cavitation appears there, 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 the leading edge. That is the reason why, in this approach, the blades are machined separately on a five-axis-machine with a rollover axis perpendicular to the spindle axis.

Thus, because this study aims at obtaining a propeller that does not require any polishing, the whole issue of the cycle of propeller production will have to be rethought. It can no longer remain sequential but transversal links must be created between the three domains shown in §1.1.. As seen in the last paragraph, the choice of the machine tool kinematics impacts on the propeller performances and it is therefore necessary to link the machine tool and the behavior of the fluid.

The machining phase consists in describing the surface with a tool to remove material on the blade. In his researches [1], Bernardos proposes a Fishbone diagram of the parameters affecting surface roughness (Fig. 5). As presented on the bone of machining parameters, the tool orientation and the stepover impact the surface roughness. The tool location on the surface is important for both parameters because they depend on the local curvature (see Fig. 6). Generally, classical methods of tool path planning only take into account geometric parameters to ensure that the specified maximum cusp height is respected. But, with such methods, the location of the maximum cusp height, the width between two adjacent cusps and the cusp direction are unknown and can lead to a decrease of the propeller performances. Thus, to have a surface roughness consistent with the fluid

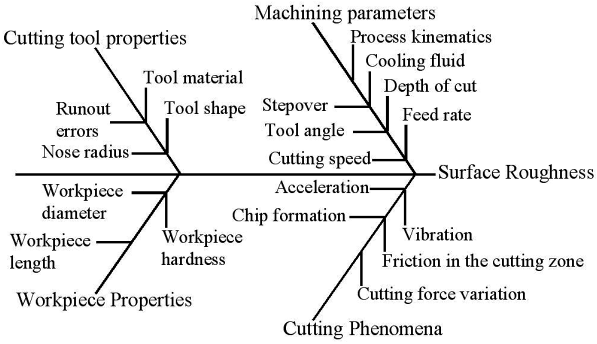


Fig. 5. Fishbone diagram with the parameters that affect surface roughness. [1]

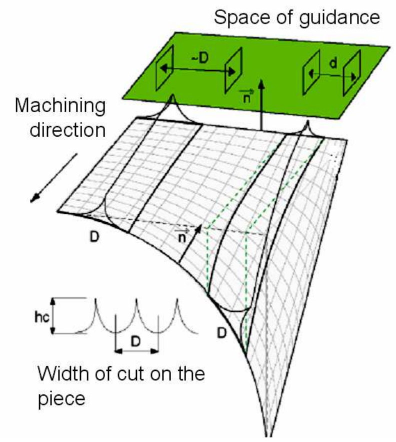


Fig. 6. Influence of the width of cut on the cusp height. [8]

behavior as much as possible, a method that uses not only the geometric parameters of the propeller but also hydrodynamic data is developed.

3.1. METHODOLOGY FOR A NEW CONCEPT OF PROPELLER PRODUCTION

On Fig. 1., it can be seen that the classical approach of propeller production is quite sequential and that links exist only between two successive phases. It has no transversal links.

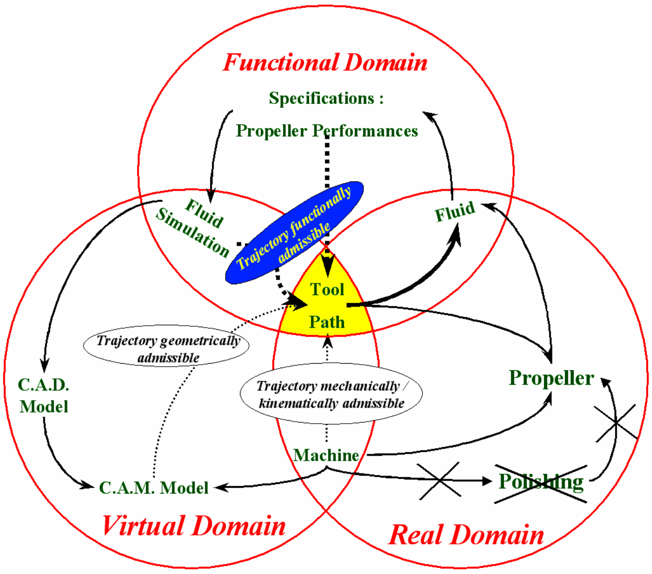


Fig. 7. New approach to produce a propeller

In this study, the tool path planning methodology, which contributes to the final geometry and to the surface roughness of the propeller, is set at the center of the production cycle: see Fig. 7. Indeed, the tool path planning methodology orientates the final roughness and the defined criteria (maximum cusp height, stepover,…) contributes to quantify the final roughness. During the propeller design, the transfer from the functional domain (propeller specifications) to the virtual domain (propeller C.A.D. model) is validated by a C.F.D. simulation. This fluid simulation, that computes trajectories for the fluid at the close vicinity of the propeller (the streak lines), allows to know the blade performances. As presented on Fig. 7, the developed methodology manages to place the tool paths at the interface of the functional, virtual and real domains and finally avoids the polishing phase. So, functional information is added to the geometric data to compute tool paths. The main added information is the orientation of the fluid at the very surface of the blade. In fact the final tool trajectories, and therefore the final roughness, are consistent with the streak lines. With this methodology, the roughness of the propeller should not disturb the fluid behavior and the polishing phase should be avoided.

3.2. USE OF HYDRODYNAMIC DATA FOR TOOL PATH PLANNING.

To have an oriented roughness after milling, the streak lines are used as supports of the tool trajectories (see Fig. 10.). Moreover, to avoid the cavitation appearance, streak lines have to be continuous and smooth on the leading edge.

Stemed from numerical simulations, streak lines representing the flow can not be used directly for tool path planning. In fact, because of the numerical approach that is used, streak lines are all composed of different parts of folders for both faces of the blade. This drawback is overcome with a homogenization presented on step A2 of the algorithm (Fig. 8). The second technical obstacle to use them as support for the tool paths is the discontinuity at the leading edge between pressure an suction sides, which is also due to the numerical simulation. Moreover, streak lines are too distant from eachother to obtain an acceptable roughness after machining. For example, for a 246.93 mm diameter propeller, the computed streak lines are 20 mm spaced. This distance is too high to obtain a 0.22 mm (based on a previous similarity study on this blade, [4]) maximum cusp height.

To overcome those obstacles, an algorithm that connects the streak lines at the leading edge and makes the number of streak lines denser is developed, see Fig. 8, step A3.

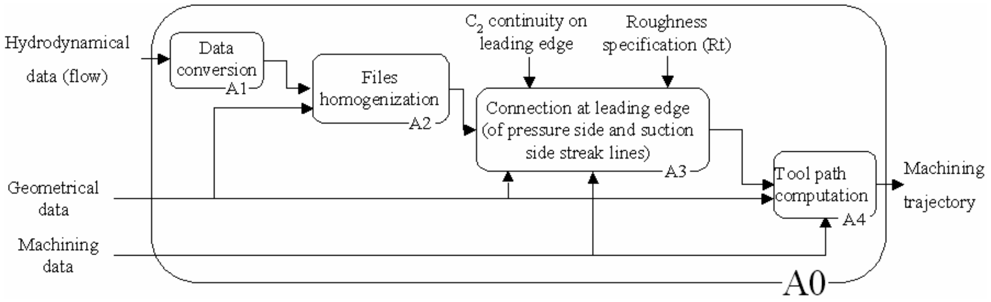


Fig. 8. Used Algorithm to compute tool paths

3.3. CONNECTION AT LEADING EDGE

The original streak lines are discontinuous at the leading and trailing edges and to respect their characteristics, they can not be connected on both edges (Fig. 9.1). Because the leading edge has more impact on the cavitation appearance, it has been decided to make the connection at this edge.

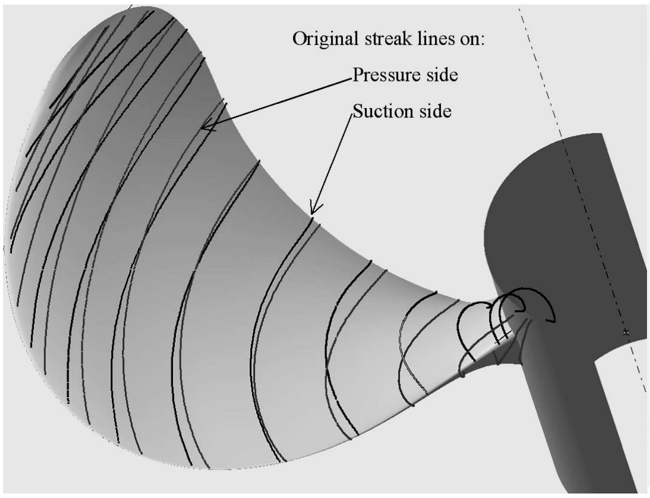
The solution consists in keeping the streak lines on one side of the blade (namely the suction side, because this side is more influential on hydrodynamic performances) and in interpolating the complementary part on the other side. Moreover, as streak lines are not defined on the leading edge which is a zone of great curvature, a basic interpolation should not respect the geometry. So, data of the geometrical sections are added in such a way that the interpolated streak lines are as close as possible to the blade surface. (see Fig. 9.2.).

First, the radius (defined from the propeller axis) of the first points from all suction side streak lines are computed. Then, CAD sections are interpolated at those radius from original CAD sections. Because CAD sections are cylindrical, the first points of the pressure and suction sides of a given section are located at the same radius. After this step, the interpolated CAD sections are used to interpolate new pressure side streak lines. Those new streak lines have first points with radius similar to the interpolated CAD sections. The step of CAD section interpolation is used to optimise the locations of the pressure side streak lines. Thus, pairs of original suction side streak lines and interpolated pressure side streak lines are obtained. Those pairs are still discontinuous at the leading edge but, they are predisposed to the connection on the leading edge because their first points have a same radius (Fig. 9.3).

Before connecting the streak lines, a step related to the final roughness is introduced. This step consists in making the number of streak lines denser to obtain a mesh that, after machining, will generate a 0.22 mm final roughness (Fig. 9.4).

After first machining tests, it has been observed that the roughness of the machined leading edge was not smooth and showed unexpected grooves. Those drawbacks are due to the fact that the trajectories used for tool path planning are only C^0 continuous and not C^1. Thus, at the leading edge, the inclination angles suddenly vary and mark the piece.

To overcome this disadvantage, previous solution has been optimised. To build the final streak line, the original suction side streak line is used and the previous interpolated pressure side streak line is conserved. Opposite to the prior solution, the continuity between both parts of streak lines is obtained with a Bezier curve. To build this Bezier curve, the two extremity points at the leading edge of the suction side streak line are used as the first poles and the two extremity points at leading edge of the pressure side streak lines as the last poles. So, the continuity of tangency between the interpolated curve and the streak line is ensured. The fifth point required to define the Bezier curve is chosen on the leading edge to be sure that the geometry is respected (Fig. 9.5). Moreover, thanks to a geometrical criterion, the point chosen on the leading edge extends as well as possible the suction side streak line.



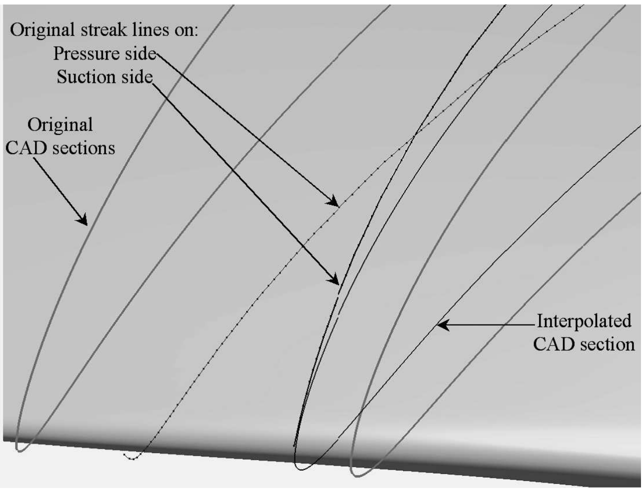
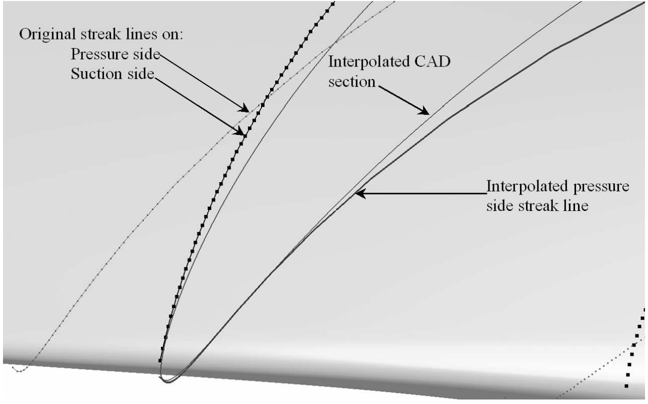


Fig. 9.1. Streak line discontinuities on blade edges.

Fig. 9.2. CAD section interpolation on leading edge.



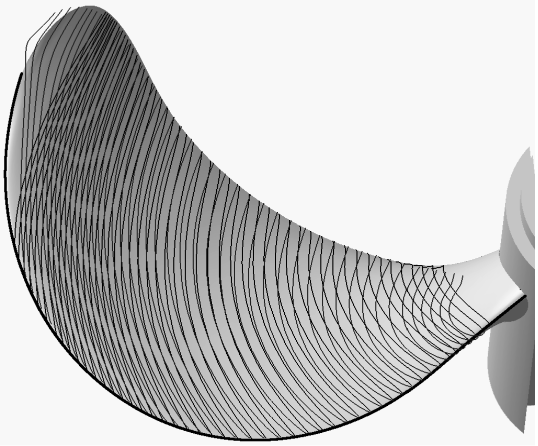
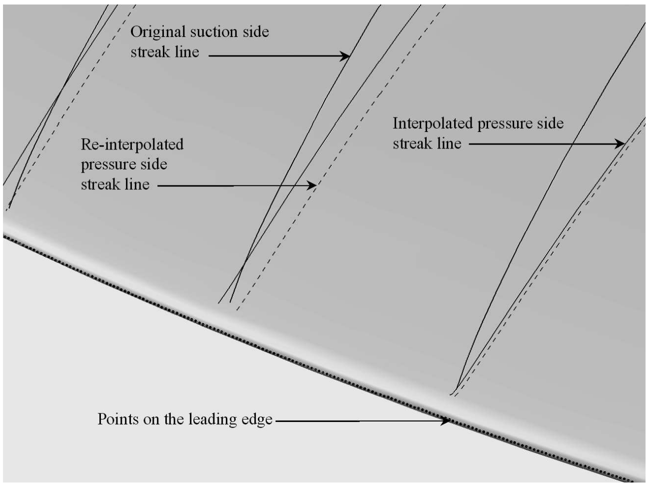


Fig. 9.3. Pressure side streak line interpolation on leading edge.

Fig. 9.4. Increasing of the streak line number.



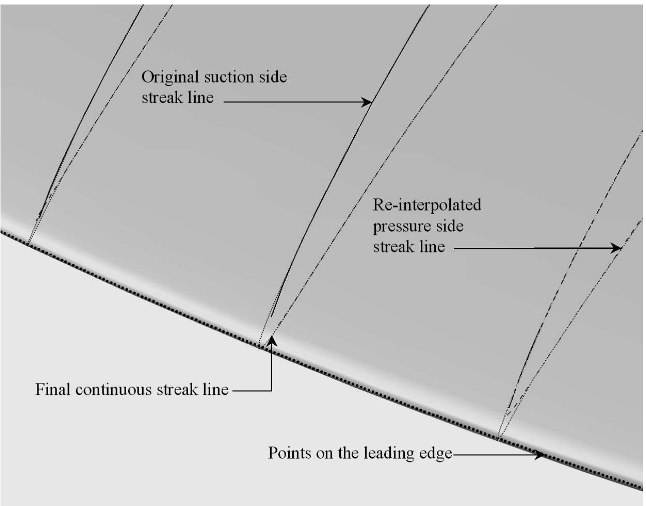


Fig. 9.5. Re-interpolation of the pressure side streak lines.

Fig. 9.6. Obtening of the continuous streak lines.

Fig. 9. Streak lines interpolation on the leading edge

Using this criterion for the pressure side streak lines, the found point is generally different from the found point for the suction side streak lines. To ensure the best continuity of the suction side streak lines but also of the pressure side streak lines, the suction side streak lines are re-interpolated to obtain an identical point selected on the leading edge with the geometrical criterion (see Fig. 9.6.).

Finally, continuous streak lines are obtained by linking an original suction side streak line and a re-interpolated pressure side streak line link with a Bezier curve.

4. MACHINING AND CONTROL.

4.1. DIMENSIONAL ASPECT

This work aims at studing the impact of the blade roughness on its hydrodynamic performances. The developed strategy will be used to machine real propellers but must be tested beforehand on propeller models. The dimensions of the tested propellers are linked with a previous similarity study [4]. Their diameter depends on the testing device: the cavitation tunnel. For those reasons the tested propeller has a 246.93 mm diameter, 6.925 times smaller than the real propeller.

To obtain results coherent with reality, the machining surface roughness has to respect the previous similarity study. In a similarity study with a real propeller whose diameter is 1710 mm, [4], Damay et al. have shown that a 0.22 mm maximum cusp height should not be penalizing. For this reason and because the machined propeller is a 6.925 scale model of a 1710 mm diameter real propeller, the maximum cusp height is set to 0.22 mm.

4.2. CHOICE OF MILLING KINEMATICS AND SETUP WORK-PIECE.

As it can be observed on Fig. 10, the machining propeller is not a cylindrical surface and has no symmetry axis. Moreover, the surface curvature varies along the wall surface and if the tool orientation is fixed, collisions between the tool and the piece may appear. For this reason a five axis milling machine is required to machine the blades. The Turbomill 1200 from Liechti is used.

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 almost perpendicular to the machine tool rotational axis A (see Fig 5). 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 vibrations during milling. Unlike a two-phase machining, the developments and the new approach allow a one phase milling. The trajectories are designed for manufacturing without discontinuity at the leading edge from hydrodynamic data. In this orientation, due to the blade geometry, the most requested displacement axis is the one perpendicular to A, namely the Z axis. In fact, considering the kinematics of the machine, Z is the fastest axis according to acceleration performances.

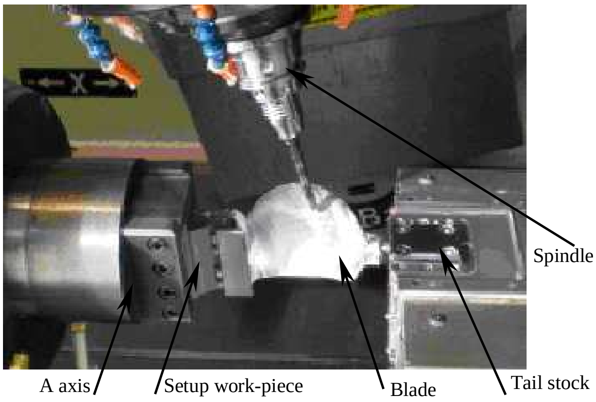


Fig. 10. Milling on an aluminium blade (IRENav)

4.3. MACHINING INFLUENCE TO THE TOOL PATH PLANNING METHODOLOGY

On Fig. 9.4. it can be observed that the developed methodology is not relevant on the head and the foot of the blade. This disadvantage is due to the methodology but also to the hydrodynamic data. Nevertheless, the methodology is relevant in the most important part of the blade (96%). Moreover, the parts where the methodology is not relevant are the parts where the thrust is the smaller (5%). In those parts the propeller is machined according to the isoparametric curves of the blade surface. This methodology takes only into account the propeller geometry for this zone.

5. CONCLUSION AND OUTLOOK

In the general context of propeller machining, a methodology that optimizes the tool path planning by integrating hydrodynamic constraints is suggested. The hydrodynamic constraints are specified in the functional domain and are generally transfered in the virtual domain thanks to the C.A.D. model. But, with this method, the whole hydrodynamic constraints can not be transfered to the real domain. A lack of information appears. With the developed methodology, links are created between the three domains of the propeller production cycle to avoid this lack of information (see Fig. 7) and to obtain a “functional machining” and a “functional roughness”. Through the streak lines, the irregularities are oriented according to the fluid behavior. The surface roughness is continuous at the leading edge too; this continuity aims at avoiding the cavitation appearance. Finally, the methodology covers more than 96% of the propeller surface. This zone corresponds to more than 95% of the thrust on the blade.

Then, after milling the four blades with the five axis machine, geometrical and functional measurements can be planed to compare the performances obtained with this methology to the performances of a mirror polished propeller.

Finally, a complementary study could be carried out on the choice of the roughness parameters taking into account the boundary layer around the blade.

REFERENCES

[1] BERNARDOS P.G., VOSNIAKOS G.C., *Prediting surface roughness in machining: a review.*, International Journal of Machine Tools & Manufacture, 2003, Vol. 43, 833-844.

[2] BRIENT A., HASCOET J.Y., MARTINEAU J.P., *Influence of Machining Paths on Hydro Propeller Performance.*, Intenational Journal of Engineering Manufacture, Vol. 217, Number 12, 2003, 1757-1762.

[3] CARLTON J. S., Butterworth Heinemann Ltd, 1994, 432 pp., ISBN 075061143X.

[4] DAMAY T., JAOUEN R., HASCOËT J.Y., MARTINEAU J.P., BRIENT A., ASTOLFI J.A., HAUVILLE F., *Design for Manufacturing applied to Hydrofoils dedicated to Marine Propellers*, Proceedings of sixth International Conference (2007) on High Speed Machining, San Sebastian, Espagne, 21-22 Mars, 2007, 432--437.

[5] HOLL J.W., BILLET M.L., TADA M., STINEBRING D.R., *The Influence of Pressure Gradient on Desinent Cavitation from Isolated Surface Protusions.*,Transactions of the ASME, 1986, Vol. 108, 254-260.

[6] NITTEL M.F., *Numerically controlled machining of propeller blades,* Marine Technology, 1989, Vol. 26, 202-209.

[7] SVENSEN E., MEDHURST J.S., *Asimplified Method for the Assessment of Propeller Roughness Penalties.,* Marine Technology, 1984, Vol. 21, Number 1, 41-48.

[8] TOURNIER C., *Contribution to the complex surfaces design: The machining surface in iso-scallop5 axis milling.,* PhD Thesis: Ecole Normale Supérieur de Cachan, 2001.