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An advanced design method for propellers behind bodies of revolution

Calcul de l'hélice fonctionnant en arrière d'un corps à symétrie axiale

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Abstract

The flow around the unshrouded marine propellers operating in the wake of an axisymmetric body is rotational and tridimensional. An inverse method based on the model of inviscid and rotational fluid and coupling two complementary steps (axisymmetric computation + 3D panel method) is proposed for the design of the marine propellers. The meridional flow computation leads to the determination of axisymmetrical stream sheets as well as the approximate camber surface of the blades and gives a good estimation of the surface of the free vortex wake. The new aspects developed in this method are the involvement of the contraction and the stretching of the free vortex wake, the rotational character of the incoming flow in the axisymmetric computation with tridimensional effects due to 3D panel method. ***To cite this article: N. Settou, B. Viney, C. R. Mecanique 331 (2003).***

Résumé

L'écoulement autour d'une hélice marine non carénée fonctionnant derrière un corps axisymétrique est rotationnel et tridimensionnel. Une méthode de calcul inverse basée sur le modèle de fluide parfait, rotationnel couplant deux étapes de calcul complémentaires (méridienne + 3D singularités) est proposée en vue de concevoir des hélices marines. Les aspects nouveaux développés dans cette méthode sont la prise en compte de la contraction et de l'étirement des nappes du sillage tourbillonnaire, du caractère rotationnel de l'écoulement amont et de l'effet tridimensionnel par le couplage du calcul axisymétrique et de celui 3D singularités. ***Pour citer cet article : N. Settou, B. Viney, C. R. Mecanique 331 (2003).***

Keywords: Fluid mechanics; Inverse method; Panel method; Marine propeller

Mots-clés : Mécanique des fluides ; Calcul inverse ; Méthode des singularités ; Hélice marine

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L'étude d'une hélice fonctionnant en arrière d'un corps axisymétrique a déjà fait l'objet de nombreuses publications dans le cadre de la théorie de la surface portante [1–3]. Afin d'améliorer cette approche, on se propose de déterminer la géométrie de l'hélice en deux étapes. En première étape, on étale les tourbillons liés et libres engendrés par les pales dans le sens azimutal, où l'effet des tourbillons toriques provenant de l'état non uniforme de l'écoulement amont est pris en compte [5]. L'écoulement devient axisymétrique et le calcul inverse (S2) est effectué dans un plan méridien qui contient une zone constituée de pales mobiles appelée zone grille, et trois zones à écoulement libre (en amont, en aval et au dessus de l'hélice) appelées zones hors grille (Fig. 1). Dans cette étape, la résolution du champ est faite par la fonction de courant. En se basant sur la formulation tensorielle, et en prenant la circulation de la vitesse méridienne sur un circuit fermé élémentaire du maillage, on obtient l'équation régissant la variation du flux du rotationnel traversant ce circuit. Ce type de formulation permet d'avoir un contrôle rigoureux sur la dynamique du rotationnel dans le champ [5]. La méthode est développée dans le cadre de fluide non visqueux avec l'incorporation d'un schéma de dissipation lié au coefficient de frottement [6] pour simuler la perte définie par (4). Ce calcul permet de déterminer la géométrie approximative des pales exprimée par (8), la contraction et l'étirement des nappes tourbillonnaires du sillage (Fig. 2). Les paramètres géométriques de la contraction du sillage en fonction du couple moteur sont donnés dans le Tableau 1 vers la fin de l'article.

Dans la seconde étape, on traite l'écoulement tridimensionnel en admettant que le champ de vitesses est constitué d'une partie rotationnelle (écoulement de base regroupant l'écoulement amont rotationnel et les vitesses induites par le sillage éloigné de l'hélice) et d'une autre irrotationnelle induite par les tourbillons liés et libres des pales et du sillage proche de l'hélice. La partie rotationnelle déterminée par le calcul méridien direct est figée, elle reste axisymétrique. L'imposition de la charge sur l'aube (9) et la conservation de flux résiduel de pénétration (10) sont les conditions aux limites à imposer au champ de l'écoulement. La résolution par la méthode de singularités à répartition discrétisée conduit à la détermination géométrique des pales lorsque ce flux résiduel tend à s'annuler aboutissant ainsi à la condition de glissement [5].

1. Introduction

For the design of propeller operating in a prescribed axisymmetric effective wake, Luu and Dulieu [1], Kerwin and Leopold [2] and Brockett [3] used the vortex lattice method to solve the lifting surface problem with linearized boundary conditions satisfied on the blade mean camber surface. Kerwin et al. [4] presents a unified design method for a wide variety of propulsors by coupling viscous/potential flow. In the first step of our method, the bound and the free vortices are transposed into an axisymmetric distribution by spreading them in the azimuthal direction, and in which the rotational character of the incoming flow is taken into account [5]. The number of blades is supposed to be infinite, the flow field can be analyzed in a meridional plane. The thickness of the blade producing the flow channel striction is modelled by the modification of metric tensor in the continuity equation. If the meridional stream function is chosen to define the flow field, then the mass conservation is satisfied automatically. The governing equation is deduced from the kinematic relation between the azimuthal component of the vorticity and the meridional velocity in the one hand and from the radial equilibrium condition in the other hand. Our S2 inverse method consider as initial data: a radial distribution of circulation along the trailing edge with an appropriate loading function and a thickness law of the blade. This computation leads to the determination of the approximate blade camber surface, the contraction and the stretching of the free vortex sheet near the trailing edge. In order to take into account the effects of the far-field free vortex sheet, the swirl (kinetic moment) jump created by the propeller is simulated by an actuator disk located in the rear part of the hull at a distance of two or three chord length from the actual position of the trailing edge, and a direct meridian calculation is carried out, by replacing the propeller by the actuator disk while maintaining the relative totale pressure field obtained by former S2 inverse computation.

In the second step, for the case of the unshrouded propeller, the 3D field with finite number of the blades must be considered. The total velocity is divided into two parts. The first one is deduced from the direct meridian calculation mentioned above and the second from a potential flow due to the singularities such as sinks and doublets spread along on the propeller blades, and doublets on the very near free-vortex sheet and sinks on the whole hull. This computation leads to the final blade geometry and the correct pressure distribution on the blades.

2. Axisymmetric inverse approach

The fluid is considered inviscid and the flow incompressible and permanent. The hypothesis of axisymmetric flow allows us to write: $(\partial(\cdot)/\partial\theta = 0)$. In the meridian flow channel, a boundary fitted coordinate system (ξ^1, ξ^2, ξ^3) is created with $\xi^2 = \theta$. Let ζ^i denote the coordinates (z, θ, r). Mapping ζ^i to ξ^i, we get:

$$(g_{ij})_\xi = \frac{\partial \zeta^m}{\partial \xi^i}\frac{\partial \zeta^n}{\partial \xi^j}(g_{mn})_\zeta \quad \text{and} \quad \sqrt{g} = \frac{D(\zeta^1, \zeta^2, \zeta^3)}{D(\xi^1, \xi^2, \xi^3)} r^2$$

A meridian plan contains a zone constituted of blade surface, and three zones of free flow (Fig. 1). The meridian velocity is represented by: $\mathbf{U} = V^1\vec{e}_1 + V^3\vec{e}_3 = W^1\vec{e}_1 + W^3\vec{e}_3$, $\mathbf{V}$ absolute and $\mathbf{W}$ relative velocities. The continuity equation becomes:

$$\frac{1}{\sqrt{\tilde{g}}}\left[\frac{\partial\sqrt{\tilde{g}}\rho U^1}{\partial \xi^1} + \frac{\partial\sqrt{\tilde{g}}\rho U^3}{\partial \xi^3}\right] = 0 \tag{1}$$

where $\tilde{g}$ represents the determinant of the modified metric tensor due to the flow channel striction produced by the thickness of the blades. Using the stream function ψ to represent the flow field and setting:

$$U^1 = \frac{1}{\rho\sqrt{\tilde{g}}}\frac{\partial\psi}{\partial\xi^3} \quad \text{and} \quad U^3 = -\frac{1}{\rho\sqrt{\tilde{g}}}\frac{\partial\psi}{\partial\xi^1} \tag{2}$$

The continuity equation is satisfied automatically.

The momentum equation is expressed in terms of vorticity vector Ω (Crocco's form):

$$\begin{cases} \Omega \times \mathbf{W} = -\nabla I + \dfrac{\mathbf{F}_b}{\rho} + \dfrac{\mathbf{F}_d}{\rho} & \text{blade space} \\ \Omega \times \mathbf{V} = -\nabla H & \text{free space} \end{cases} \tag{3}$$

where $H = p/\rho + V^2/2$ is the absolute total pressure and $I = p/\rho + W^2/2 - (\omega r)^2/2$ the relative total pressure. When the number of blades is assumed to be infinite in the axisymmetric S2 flow, the volume force $\mathbf{F}_b/\rho$ due to the blades must be added in the momentum equation [4].

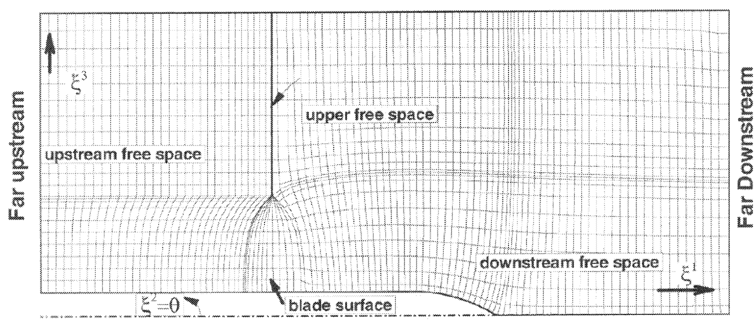

Fig. 1. Geometry of flow domain and computational mesh.

Fig. 1. Géométrie de l'écoulement et son maillage.

The loss scheme is intro duced in relation with the drag coefficient C_f or propeller efficiency coefficient η, based on experimental data base (available on specialized scientific websites). In the first case, Horlock [6] suggests that the dissipative force $\mathbf{F}_d/\rho$ can be written as:

$$\frac{\mathbf{F}_d}{\rho} = -C_f \frac{N_b}{2\pi r} \frac{|\mathbf{W}|^2}{\cos\vartheta} \frac{\mathbf{W}}{|\mathbf{W}|} \tag{4}$$

with N_b, number of blades and ϑ camber line angle with respect to the meridional plane. To get an idea of the influence of C_f on the propeller performances, it is also possible to make a sweep of a set of C_f values within an interval from 0.0 to 0.016 by step of 0.002.

In the second, $\mathbf{F}_d/\rho$ is subjected to the variation of $(V_\theta r)$ via η:

$$\frac{\mathbf{F}_d}{\rho} = (1-\eta)\left[\omega \frac{\mathbf{W}}{|\mathbf{W}|} \cdot \nabla(V_\theta r)\right] \frac{\mathbf{W}}{|\mathbf{W}|}, \quad \omega \text{ angular velocity} \tag{5}$$

$\mathbf{F}_b = 0$ as well as $\mathbf{F}_d = 0$ are imposed in the free space. The swirl distribution in a stream sheet is closely linked to the circulation of the bound vortices produced by the blades. Let Γ_ψ denote the circulation generated by the blade section cut by an axisymmetric stream surface $\psi = cte$, the kinetic moment generated by the bound vortices located between the leading edge l_e and the abscissa m is given by:

$$(V_\theta r)_{m,\psi} = (V_\theta r)_{l_e,\psi} + \frac{N_b}{2\pi} \Gamma_\psi f(m,\psi)$$

where the loading function $f(m,\psi)$, designer defined one, represents the fraction of circulation generated by the bound vortex located at the abscissa m of the stream line. The component along $\mathbf{e}_3$ of the momentum equation represents the radial equilibrium condition, which gives:

$$\begin{cases} \sqrt{g}\Omega^2 = \dfrac{1}{U^1}\left[\dfrac{\partial I}{\partial \xi^3} - \dfrac{(F_d)_3}{\rho}\right] + \dfrac{n_1}{n_2}\dfrac{\partial(V_\theta r)}{\partial \xi^3} - \dfrac{n_3}{n_2}\dfrac{\partial(V_\theta r)}{\partial \xi^1} & \text{blade space} \\ \sqrt{g}\Omega^2 = \dfrac{1}{V^1}\left[\dfrac{\partial H}{\partial \xi^3} - V^2 \dfrac{\partial(V_\theta r)}{\partial \xi^3}\right] & \text{free space} \end{cases} \tag{6}$$

The dot product of the momentum equation with $\mathbf{V}$ in the free space or with $\mathbf{W}$ in the blade zone leads to the following relations useful to update the nodal values of H or I during the iterative process:

$$\begin{cases} \dfrac{\partial I}{\partial m} = (1-\eta)\omega \dfrac{\partial(V_\theta r)}{\partial m} = -C_f \dfrac{N_b}{2\pi r}\dfrac{|\mathbf{W}|^2}{\cos\vartheta} & \text{blade space} \\ \dfrac{\partial H}{\partial m} = 0 & \text{free space} \end{cases}$$

The governing equation for ψ is obtained by writing $(\nabla \times \mathbf{U})^2 = \Omega^2$, where the first member is the kinematic relation for Ω^2, i.e., $\partial U_1/\partial\xi^3 - \partial U_3/\partial\xi^1 = \sqrt{g}\Omega^2$, where U_1 and U_3 are the covariant components of the velocity deduced from metric relations $U_m = g_{mn}U^n$ and (2), and the second member derived from the radial equilibrium condition (6):

$$\frac{\partial}{\partial\xi^3}\left(\frac{g_{11}}{\rho\sqrt{g}}\frac{\partial\psi}{\partial\xi^3}\right) + \frac{\partial}{\partial\xi^1}\left(\frac{g_{33}}{\rho\sqrt{g}}\frac{\partial\psi}{\partial\xi^1}\right) + \frac{\partial}{\partial\xi^3}\left(\frac{g_{13}}{\rho\sqrt{g}}\frac{\partial\psi}{\partial\xi^1}\right) + \frac{\partial}{\partial\xi^1}\left(\frac{g_{31}}{\rho\sqrt{g}}\frac{\partial\psi}{\partial\xi^3}\right) = \sqrt{g}\Omega^2 \tag{7}$$

For the inverse problem, the distribution of $(V_\theta r)$ or Γ_ψ is assigned along the trailing edge and the prescribed radial law of the circulation could be parabolic with gentle slopes (parabola inscribed in an equilateral triangle) at the hub and tip in order to minimize vortex shedding. Then using (6), Ω^2 is updated iteratively. Let the camber surface of the blade be defined by $\theta = \xi^2(\xi^1, \xi^3) + cte$, if the coordinate lines $\xi^3 = cte$ are updated to the streamlines when ψ equation (7) has converged, ξ^2 can be computed using the slip condition:

$$\xi_i^2(m, \psi) = \xi_{\text{ref}}^2(m, \psi) + \int_{\xi_{\text{ref}}^1}^{\xi_i^1} \frac{W^2}{W^1}\, \mathrm{d}\xi^1 \tag{8}$$

$\xi_{\text{ref}}^2(m, \psi)$ is a function of ξ^3 according to a prescribed radial skew distribution.

2.1. Boundary conditions

– At far upstream, the velocity distribution is assumed to be known. The flow rate and the total pressure are then calculated, which permits to impose Dirichlet condition for stream function;
– At far downstream, the flow becomes axial ($\partial\psi/\partial n = 0$, where $\mathbf{n}$ is the normal unit vector to outlet boundary);
– In order to obtain an adapted leading edge for the design condition, $f(m)$ must have a horizontal slope ($\mathrm{d}f/\mathrm{d}m = 0$),
– Kutta condition must be imposed at the trailing edge, loading must vanish ($\mathrm{d}f/\mathrm{d}m = 0$).

3. Coupling S2 and 3D-panel method calculation

The total absolute velocity is divided into two parts. The first one is the effective inflow velocity $\mathbf{V}_{\text{inc}}$ obtained by the intermediate direct meridian calculation with the actuator disk as mentioned in Section 1. This S2 computation is carried out while maintaining the relative totale pressure field obtained by the S2 inverse one, in order to determine the velocity induced on blades by both upstream rotational flow due to the boundary layer on the front part of the hull, and far field vortex sheet. This velocity is considered as the incident one for the 3D panel calculation, second step of our method. This step is characterized by a potential flow due to the singularities such as sinks and doublets spread along on the propeller blades, doublets on the very near free-vortex sheet and sinks on the whole hull. The resulting absolute velocity is given by $\mathbf{V} = \mathbf{V}_{\text{inc}} + \nabla\phi$.

3.1. Boundary conditions

– Bound vorticity assigned: the circulation of $\mathbf{V}$ along a blade contour from P^- and P^+, centers of the lower and upper associated blade elements must be a fraction $f(m)$ of circulation $\Gamma(r)$, this condition implies:

$$\int_{P^-}^{P^+} \mathbf{V}\cdot\mathbf{dl} = (\phi^+ - \phi^-) + \int_{P^-}^{P^+} \mathbf{V}_{\text{inc}}\mathbf{dl} = \Gamma(r) f(m) \tag{9}$$

– Penetrating flux conservation: the blade camber line is the unknown of the problem. On the presumed contour of the blade, the penetration of the fluid flow must be tolerated (transpiration model). The residual flux detected is then used to modify the camber line. In order to avoid any extra flux, i.e., to keep flow rate safe, the flux through each pair of associated elements must be conservative. This condition implies:

$$\left\{(\phi_n'\,\mathrm{d}\Sigma)^+ + (\phi_n'\,\mathrm{d}\Sigma)^-\right\} + \left\{(\mathbf{W}_{\text{inc}}\cdot\mathbf{n}\,\mathrm{d}\Sigma)^+ + (\mathbf{W}_{\text{inc}}\cdot\mathbf{n}\,\mathrm{d}\Sigma)^-\right\} = 0 \tag{10}$$

where the first part of the equation represents the flux produced by the bound and free vortices, and the second the flux produced by the effective incident flow.
– Slip condition on the hub: the slip condition on the hub is imposed ($\mathbf{W}\cdot\mathbf{n} = 0$ where $\mathbf{n}$ is the unit normal vector to the hub).

4. Rectification of the mean camber line

Once the problem of these boundary conditions has been solved by 3D panel method, it is necessary to rectify the camber line according to the flux detected on the associate elements. Let Θ denote the slope angle of each element of the camber line, the camber line correction $\delta\Theta$ is given by:

$$\delta\Theta = 0.5\left[\tan^{-1}\left(\frac{\sqrt{g}}{\tau}\frac{W_n}{\sqrt{W_{t_1}^2 + W_{t_2}^2}}\right)^{+} + \tan^{-1}\left(\frac{\sqrt{g}}{\tau}\frac{W_n}{\sqrt{W_{t_1}^2 + W_{t_2}^2}}\right)^{-}\right] \tag{11}$$

where W_{t_1} and W_{t_2} are the two tangential components of the velocity and τ represents the local thickness of the stream sheet. The camber mean line is then updated by integrating from a referential line to the actual local point.

5. Geometry of trailing vortex wake

The geometry of the trailing vortex has an important influence on the accuracy of the calculation of induced velocities on the blade [7]. For the inverse problem, the usual approach is to approximate the trailing wake sheet by a pure helical surface with a prescribed pitch angle obtained either from the undisturbed inflow or the hydrodynamic pitch angle calculated from lifting-line theory [1–3]. More elaborated wake models have been developed by Kerwin [8] and Loukakis [9] in which the roll-up of the vortex sheet and contraction of the slipstream are taken into consideration and where the transition wake is determined by a set of parameters, chosen in accordance with experimental data. In the present study, the propeller wake which is determined by the axisymmetric computation is divided into two parts (Fig. 2): a transition wake region where the contraction and the stretching of the slipstream occurs and a far stream wake region, where velocities induced by the latter will be replaced by the effect of an actuator disk in the intermediate axisymmetric computation.

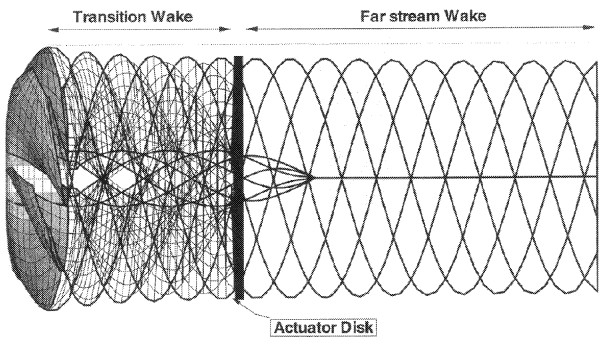

Fig. 2. Trailing wake geometry.

Fig. 2. Géométrie du sillage tourbillonnaire.

Table 1
Contraction parameters for different K_Q

Tableau 1
Les paramètres de contraction en fonction de K_Q

	K_Q	r_w	z_{tw}	β_c
r_w, the ultimate radius of the contracted slipstream	0.0503	9.67	2.56	0.905
z_{tw}, length of transition region wake	0.0526	10.42	3.07	0.897
β_c, contraction angle of tip vortex shed by the blade tip	0.0547	15.28	3.29	0.874

Table 1 shows values of contraction parameters of the discrete vortices representing the transition wake for different torque coefficients K_Q.

6. Conclusion

The new aspects developed in this method are the involvement of the contraction and the stretching of the free vortex wake, the rotational character of the incoming flow in the axisymmetric computation and the tridimensional effects due to the 3D panel method. A simplified design procedure suitable for engineering use and easily implementable on PC is proposed in this paper. This design approach considers the prescription of the thickness law of the blade and the loading distribution as the initial data. The representation of the blades by the vortex distribution enables the formulation of the well-posed inverse problem and leads to a preliminary design of propeller behind bodies of revolution.

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