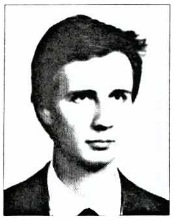

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Theoretical investigation of the wake duct effectiveness

SUMMARY

The effectiveness of cylindrical and elliptical wake ducts was investigated by using the theoretical methods. The method of surface vorticity distribution was applied to determine the velocity and pressure distributions on the surface of wake ducts in non-uniform stern flow.

This method accounts for actual geometry of duct and hull surface with no simplifications. Velocity distribution at meridional sections of a duct was used in calculation of boundary layer parameters in accordance with the Truckenbrodt method.

Relative effectiveness of different ducts was evaluated for a specific ship on the basis of the generated thrust and extent of flow separation.

INTRODUCTION

The wake ducts developed in the 1980s by Schneekluth are often applied on sea-going ships bringing the average fuel consumption gain of 8% [1].

The wake ducts are usually the halves of an axisymmetric annular airfoil with the foil section typical of the accelerating nozzles (Kort nozzles). They are attached to shell plates upstream of the propeller, close to propeller disk, above propeller axis (Fig.1). Originally wake ducts were devised to accelerate and straighten flow in the upper half of the propeller disk in order to equalize velocity distribution, increase propeller efficiency and reduce vibrations induced by the propeller on hull structure. However, total gains in the propulsion system efficiency are usually remarkably greater than those resulting from possible increment of propeller efficiency due to flow equalization. Close inspection of flow phenomena reveals that also duct thrust and reduction of flow separation on the hull surface considerably contribute to the gains. All above mentioned phenomena originate from the velocity circulation around foil section. An optimum wake duct shall then induce the maximum possible velocity circulation at no flow separation on its surface. In the author's opinion the analysis of duct flow by using the potential flow model can be successfully applied to estimate the intensity of circulation and hence the efficiency of wake ducts. Velocity and pressure distribution on the duct surface in potential flow can be further used in the analysis of boundary layer flow over the duct surface. In the case of the limited trailing edge separation also the hydrodynamic force acting on a duct can be reliably evaluated.

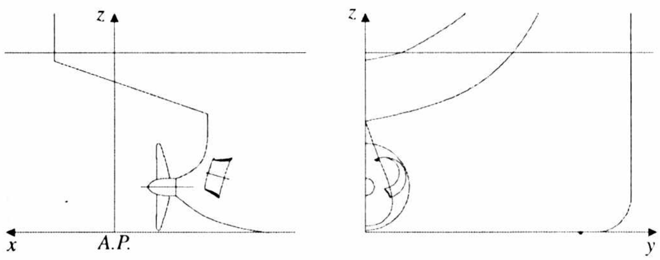

Fig.1. General arrangement of wake ducts

The next sections of the paper contain brief description of the theoretical methods applied to determine pressure distribution, hydrodynamic force and trailing edge separation on the wake duct surface. Results obtained for cylindrical and elliptical ducts are presented in the last section.

THEORETICAL BASIS

Originally the theoretical basis of the surface vorticity distribution method was given by Martensen [2] for two-dimensional potential flow around airfoil section. Lewis and Ryan [3] formulated the basic equation for the general 3-D flow. Details of the present application of this method were given in [4].

The considered rigid body immersed in flow is replaced by a region of motionless fluid which is separated from ambient flow by the vortex surface which coincides with the impermeable body surface. The boundary condition to be satisfied at each point on the vortex surface is either zero normal velocity or equivalent zero tangent velocity on the inner side of vortex surface. The latter condition appears to be more suitable for the surface vorticity distribution method.

It can be written in the curvilinear body-fitted coordinates ξ_1, ξ_2 for an arbitrary point F on the vortex surface, as follows :

$$\frac{1}{4\pi}\oint\!\!\oint_S \boldsymbol{i}_{3F}\cdot\left[\frac{(\boldsymbol{i}_1\gamma_1+\boldsymbol{i}_2\gamma_2)\cdot\boldsymbol{r}}{r^3}\cdot\boldsymbol{i}_{3F}\right]d\xi_1 d\xi_2 + \frac{1}{2}[\boldsymbol{i}_{2F}\gamma_{1F}-\boldsymbol{i}_{1F}\gamma_{2F}]+\boldsymbol{i}_{3F}\cdot(\boldsymbol{U}_d\cdot\boldsymbol{i}_{3F})=0 \qquad (1)$$

where the integration is performed over the entire body surface S. The disturbance velocity U_d includes the velocity of orginal U_S as well as all disturbances induced by other objects introduced into the flow.

Equation (1) resolved into two orthogonal directions ξ_1 and ξ_2 gives a set of scalar equations :

$$\frac{1}{4\pi}\oint\!\!\oint_S \frac{1}{r^3}(k_{11}\gamma_1+k_{12}\gamma_2)d\xi_1 d\xi_2-\frac{1}{2}\gamma_{2F}+U_{d1}=0 \qquad (2a)$$

$$\frac{1}{4\pi}\oint\!\!\oint_S \frac{1}{r^3}(k_{21}\gamma_1+k_{22}\gamma_2)d\xi_1 d\xi_2+\frac{1}{2}\gamma_{1F}+U_{d2}=0 \qquad (2b)$$

where:

$$k_{11}=(\boldsymbol{i}_1\cdot\boldsymbol{r})\boldsymbol{i}_{1F} \qquad k_{12}=(\boldsymbol{i}_2\cdot\boldsymbol{r})\boldsymbol{i}_{1F}$$

$$k_{21}=(\boldsymbol{i}_1\cdot\boldsymbol{r})\boldsymbol{i}_{2F} \qquad k_{22}=(\boldsymbol{i}_2\cdot\boldsymbol{r})\boldsymbol{i}_{2F}$$

$$U_{d1}=\boldsymbol{U}_d\boldsymbol{i}_{1F} \qquad U_{d2}=\boldsymbol{U}_d\boldsymbol{i}_{2F}$$

Equations (2a) and (2b) are sufficient to determine the unique distribution of vorticity on the vortex surface.

This approach was applied to determine the vorticity which replaces the hull surface in vicinity of the duct and compensates disturbances induced on the hull by the wake duct introduced into the original flow.

The equation (2b) can be neglected in some cases when the velocity disturbance component U_{d2} at each point on the vortex surface is small relative to the component U_{d1}. The vorticity γ_1 in equation (2a) is then a function of the other component γ_2 according to the Helmholtz theorem of vorticity conservation :

$$\frac{\partial\gamma_1}{\partial\xi_1}+\frac{\partial\gamma_2}{\partial\xi_2}=0$$

hence :

$$d\gamma_1=-\frac{\partial\gamma_2}{\partial\xi_2}d\xi_1$$

The local value of γ_1 can be obtained by integrating the above given differential along the path ξ_2 = const starting from the point where value of γ_{1S} is known (e.g. from the stagnation point where $\gamma_{1S} = 0$) :

$$\gamma_1=\gamma_{1S}-\int_{\xi_{1S}}^{\xi_1}\frac{\partial\gamma_2}{\partial\xi_2}d\xi_1 \qquad (3)$$

The only equation to be solved in those cases is eq. (2a) with γ_1 replaced by integral (3).

This approach was successfully applied in the analysis of flow around the axisymmetric nozzle in ducted propeller system [5]. In the present work it is applied to a duct which consists of the cylindrical part and two rectilinear foil segments between the ends of the cylindrical part and the hull.

As there exists a simple relationship between vorticity and tangent velocity on body surface, namely $u_2 = -\gamma_1$ and $u_1 = \gamma_2$, the pressure coefficient can easily be calculated by using the following formula derived from the Bernoulli equation :

$$c_p=\frac{p-p_0}{\frac{1}{2}\rho U_0^2}=1-\frac{u_1^2+u_2^2}{U_0^2}=1-\frac{\gamma_1^2+\gamma_2^2}{U_0^2}$$

NUMERICAL SOLUTION OF EQUATIONS

Numerical approach to solving the equations (2a) and (2b) requires all vortex surface to be divided into elements of finite dimensions, called panels. The panels on a duct are defined by the equidistant meridional sections and planes orthogonal to the duct axis (see Fig.2a) to maintain orthogonality of the body-fitted coordinates ξ_1, ξ_2 when the equations (2a) and (3) are used. Each tetragonal panel is associated with a control point located in the middle of the panel. The vorticity is assumed constant on each panel. When the velocity induced by a panel at an arbitrary point is calculated the vorticity γ_2 is concentrated in the vortex filament called bound vortex and located at the midspan of the panel (Fig.2b). Second component of vorticity, γ_1, is concentrated in the filaments (trailing vortices) coincident with the chordwise boundaries between panels. The vortical wake downstream of a duct is replaced by the filaments (free vortices) which start at the trailing edge and theoretically should extend to infinity along the streamlines in the resultant flow. The free vortices can be approximately shaped along streamlines in the original stern flow with no negative influence on results, as their actual geometry determination (including the disturbances induced by themselves as well as duct and hull vorticity) requires applying the labour-consuming iterative procedure.

a) ***b)***

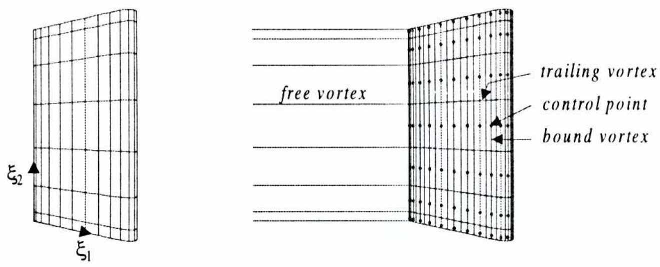

Fig.2. Distribution of vortical panels on duct surface (a) and equivalent grid of bound, trailing and free vortices (b)

Strength of trailing and free vortices can be expressed as a linear combination of the vorticity γ_2 on upstream panels. Equation (2a) is then written for each control point on a duct, giving a set of linear algebraic equations :

$$[A_{21}][\gamma_{2D}]=[-U_{1S}-U_{1HD}] \qquad (4)$$

The RHS vector contains a tangent component of disturbance velocity at the control points (sum of the local velocity in original flow, U_{1S} , and velocity induced by vortex surface on the hull, U_{1HD}).

The distribution of panels can be independent of the coordinates ξ_1 and ξ_2 because no differential relationship is imposed on the vorticity modelling hull surface (see eqs 2a and 2b). In general, the panels even do not have to be tetragonal. On the other hand the distribution of the panels on the hull should fit the distribution on the duct (Fig.3). The control points on the hull surface are allocated in the middle points of the panels. Equations (2a) and (2b) written in a discrete form for each control point constitute another set of linear algebraic equations :

$$\begin{bmatrix} B_{11}B_{21} \\ B_{12}B_{22} \end{bmatrix} \begin{bmatrix} \gamma_{1H} \\ \gamma_{2H} \end{bmatrix} = \begin{bmatrix} -U_{1DH} \\ -U_{2DH} \end{bmatrix} \quad (5)$$

Total number of the equations equals twice the number of panels. The RHS vector contains only tangent components of the velocity induced by the duct and its wake, because in the original viscous flow the velocity on hull surface is zero. It means that the vorticity on the hull is dependent only on the disturbance induced by the duct. The vorticity on the hull remains close to zero except for some region in vicinity of the duct as the magnitude of the velocity induced by the element of vortex surface or segment of vortex filament decreases with the square of the distance from that element or segment. The major part of the hull surface does not need to be replaced with vorticity. Vorticity at the distance greater than one duct length from the duct was found small and of a negligible effect on calculation results.

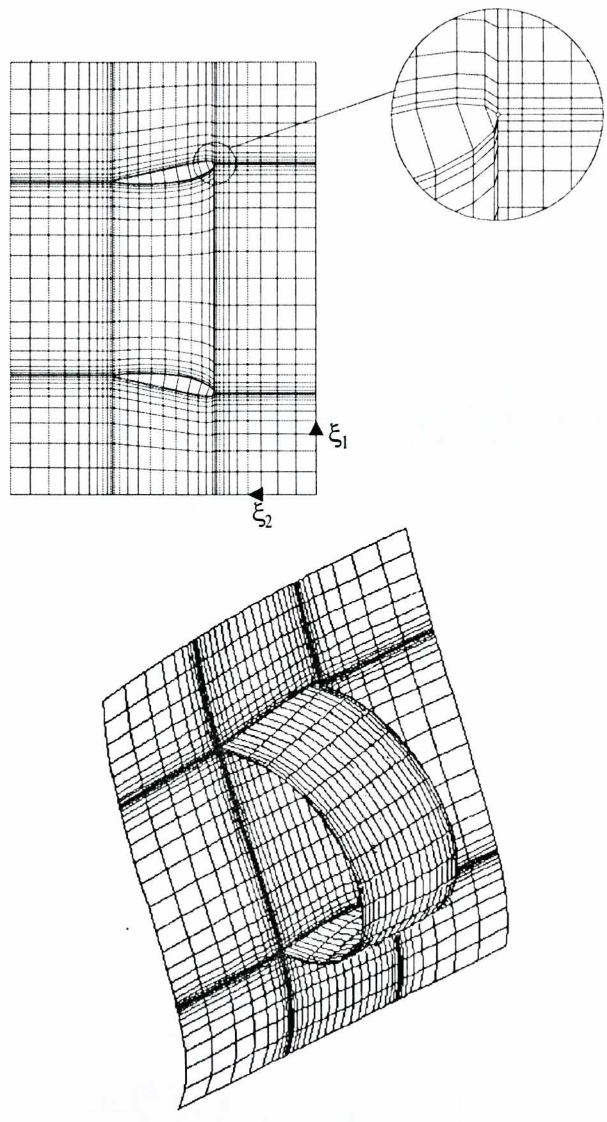

Fig.3. Distribution of panels on hull surface

The equations (4) and (5) are solved alternately for a given velocity distribution in stern flow. This iterative process starts from the initial guess $\gamma_{1H} = \gamma_{2H} = 0$ that implies $U_{1HD} = 0$ in (4). Once the equation (4) is solved the velocity components U_{1DH} and U_{2DH} are calculated by using the Biot-Savart law and the first approximation of hull vorticity is calculated from (5). The next step starts from the determination of the velocity induced by the hull vorticity at the control points on the duct, U_{1HD}. Convergence is obtained when the difference between the vorticity calculated in two consecutive steps is less than 1% of the ship speed used as the reference velocity.

The final step comprises the determination of the boundary layer parameters and estimation of the extent of separated flow on the duct surface. This is performed in accordance with the Truckenbrodt method and algorithm described by Scholz [6]. The assumption was made that the flow within the boundary layer is turbulent in the entire extent starting from the stagnation point on the duct leading edge, because the method is intended to be applied to wake ducts at full scale when conditions promote early transition from laminar to turbulent flow. The calculations are performed at the meridional sections defined by arrays of the control points from the potential flow solution. The velocity determined at those points by means of the surface vorticity distribution method is used directly in boundary layer calculations. Location of flow separation is estimated by using an appropriate separation criterion.

RESULTS OF EXAMPLE CALCULATIONS

A series of calculations was performed in order to prove that the present method is able to differentiate the effectiveness of various ducts. A huge tanker with pram stern was selected for that purpose. The velocity measured in the nominal wake of the model ship (see Fig.4) was used , because the distribution of velocity in full scale flow was not available. Such approximation was justified only in the example calculations and is not valid in design of wake ducts for a real ship when the distribution of total velocity is required including effects due to propeller action.

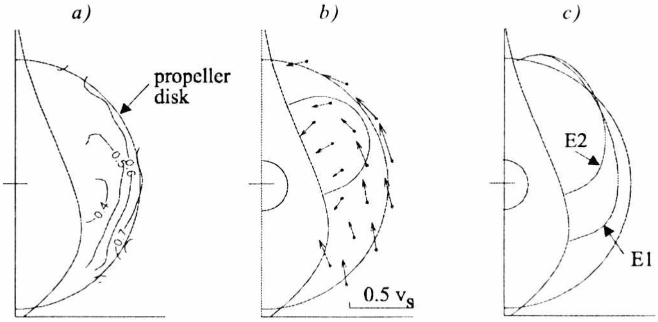

Fig.4. Velocity distribution measured in the transverse plane upstream of the propeller disk, at the anticipated longitudinal position of wake duct

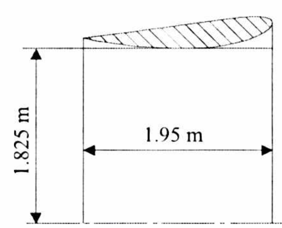

Fig.5. Horizontal section of the investigated wake ducts

NACA4414 airfoil section was assumed for the duct section. The assumed inclination of the section relative to the duct axis was 5 degrees (see Fig.5). The previous calculations [4] revealed that the extent of flow separation at this angle is acceptable. The outline of the previously investigated cylindrical duct is shown in Fig.4b. The calculated thrust is equal to 4.7 kN.

The first idea to increase the duct thrust, assumed a determinant of duct effectiveness, was to increase the foil length. At the same time the extent of duct interference into flow should be confined to the propeller disk area. One of the possible solutions was to apply an elliptical duct. Its outline, denoted E1, is shown in Fig.4c. The obtained thrust was 7.6 kN at 1.95 m duct length and 1.825 m horizontal inner radius (the same as of the cylindrical duct). The pressure distribution on the duct surface and unit thrust distribution along the duct perimeter are shown in Fig.6. It is apparent that all the thrust is generated on the upper half of the duct. Moreover the pattern of flow separation exhibits inclination to early separation on the outer surface of the lower half of the duct. On the basis of the present and previous results another elliptical duct was designed. Its lower end was fixed at the position of the cylindrical duct lower end and the upper end at the position of E1 duct upper end (see the duct E2 in Fig.4). Results obtained from calculations of the duct E2 appear promising. The pressure and thrust distributions shown in Fig.7 reveal that load distribution is symmetrical. The total thrust equals 18.2 kN which allows to expect this duct to be more effective than the E1. The positive velocity circulation around duct sections indicates that water is drawn into the duct and the flow downstream of the duct should be accelerated.

The pressure and thrust distributions shown in Figs.6 and 7 reveal the sensitivity of duct thrust to the local flow direction. One can expect that other more complex geometry, better adapted to local flow, would be even more efficient.

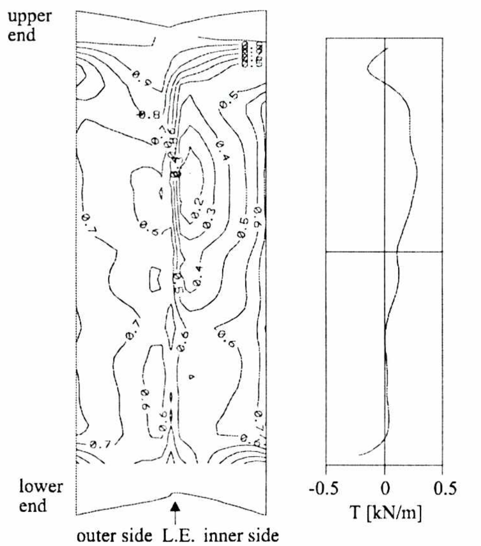

Fig.6. Pressure distribution on the duct surface (the pressure coefficient c_p calculated by using the ship speed as the reference velocity) and thrust distribution along the duct perimeter for the elliptical duct E1

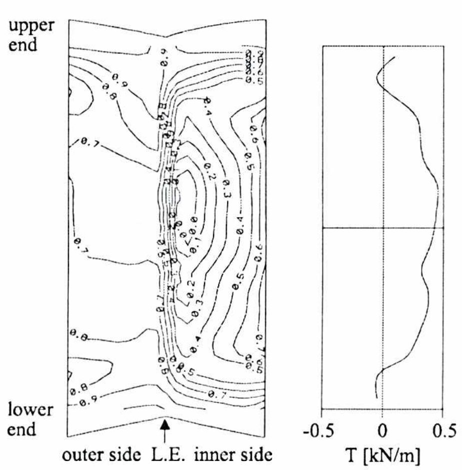

Fig.7. Pressure distribution on the duct surface and thrust distribution along the duct perimeter for the elliptical duct E2

CONCLUDING REMARKS

- The presented theoretical method for determining the hydrodynamic forces and flow separation on wake ducts appears to be a useful tool in evaluating the duct effectiveness. The method, although applied to the ducts of regular shapes, is also valid for more complex geometries of the so-called wake adapted ducts whose duct sections vary along duct perimeter. It can also be easily adapted to more general problems of flow around wing-fuselage junction.
- The only problem dealing with application of the method is its strong dependence on the velocity distribution in stern flow. Appropriate data can be obtained from measurements or calculations. The former source is expensive, but the latter offers a great potential nowadays.
- No general conclusion could be drawn from the presented results of the example calculations as the optimum duct geometry and arrangement depend strongly on the hull geometry and stern flow. The duct evaluation procedure should be repeated each time when a new hull form is considered, on the basis of a specific velocity distribution within stern flow.
- The method still needs experimental validation. Ducts designed or selected by using the presented approach still need to be tested on a model ship in towing tank.

NOMENCLATURE

c_p	-	pressure coefficient
i_1, i_2	-	versors in curvilinear co-ordinate system ξ_1, ξ_2
i_3	-	unit vector normal to body surface ($i_3 = i_1 \cdot i_2$)
k_{ij}	-	geometric coefficients (i,j = 1,2)
p	-	pressure
p_0	-	reference pressure
r	-	vector between the element of vortex surface and control point
u_1, u_2	-	components of tangent velocity on outer side of vortex surface
Aij, Bij	-	coupling coefficients (j-th component of tangent velocity induced at control point by an element of vortex surface with i-th vorticity component of unit strength ($\gamma_i = 1$); i,j=1,2
S	-	body surface
U_0	-	reference velocity
U_S	-	velocity in undisturbed (orginal) flow
U_{1S}, U_{2S}	-	components of orginal velocity at control point on body surface
U_{1DH}, U_{2DH}	-	components of velocity induced by duct vorticity at control points on hull surface
U_{1HD}, U_{2HD}	-	components of velocity induced by hull vorticity at control points on duct surface
U_d	-	disturbance velocity
U_{d1}, U_{d2}	-	components of disturbance velocity at control point on body surface
γ_1, γ_2	-	components of vorticity
γ_{1D}, γ_{2D}	-	components of vorticity on a duct
γ_{1H}, γ_{2H}	-	components of vorticity on a hull
γ_{1S}	-	trailing vorticity (component in ξ_1 direction) at the start-point of integration on duct surface
ξ_1, ξ_2	-	curvilinear body-fitted co-ordinates
ρ	-	fluid density

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