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캐비테이션 터널에서의 반류분포 재현에 미치는 유동조절체의 영향

이진태*, 김영기**

Effect of Flow Liners on Ship's Wake Simulation in a Cavitation Tunnel

by

Jin-Tae Lee* and Young-Gi Kim**

요　약

캐비테이션 터널에서 모형선 혹은 부분모형선을 사용하여 3차원 반류분포를 재현시키고자 할 때, 유동조절체를 사용하여 터널 위벽효과(Tunnel wall effect)를 감소시키는 경우가 있다. 유동조절체가 선미후류 유동에 미치는 영향과 터널 위벽효과를 해석하기 위하여 직사각형 단면의 시험부에 설치되어 있는 모형선과 유동조절체 주위 유동을 표면양력판 이론을 사용하여 해석하였다.

Sydney Express 모형선 주위 유동에 대한 계산결과에 의하면 선체 표면 압력분포에 미치는 캐비테이션 터널의 위벽효과는 막음비(Blockage)가 5% 이내인 경우에는 무시할 정도이며, 막음비가 20% 이상인 경우에는 상당히 큼을 알 수 있다. 유동조절체를 선미 부근 터널벽에 설치함으로써 선미 유동중 축방향속도가 증가되었으며, 선체표면에서의 압력구배(pressure gradient)는 선미 경계층의 두께가 덜 증가되는 방향으로 변화되었음을 알 수 있었다. 유동조절체를 설치하여 재현된 반류분포는 등속도곡선의 폭이 좁아지기 때문에 추정된 실선반류 분포를 재현하기 위하여 유동조절체를 사용하는 경우가 있다. 표면양력판에 의해 계산된 반류분포는 이상유체 가정을 토대로 계산되었기 때문에 계측된 반류분포와의 차이를 보정하기 위해서는 경계층 계산이나 점성유동계산이 필요하다.

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* 정회원, 해사기술연구소
** 학생회원, 충남대학교 선박해양공학과

Abstract

Flow control devices, such as flow liners, are frequently introduced in a cavitation tunnel in order to reduce the tunnel blockage effect, when a three-dimensional wake distribution is simulated using a complete ship model or a dummy model. In order to estimate the tunnel wall effect and to evaluate the effect of flow liners on the simulated wake distribution, a surface panel method is adopted for the calculation of the flow around a ship model and flow liners installed in a rectangular test section of a cavitation tunnel.

Calculation results on the Sydney Express ship model show that the tunnel wall effect on the hull surface pressure distribution is negligible for less than 5% blockage and can be appreciable for more than 20% blockage. The flow liners accelerate the flow near the after body of the ship model, so that the pressure gradient there becomes more favorable and accordingly the boundary layer thickness would be reduced. Since the resulting wake distribution is assumed to resemble the full scale wake, flow liners can also be used to simulate an estimated full scale wake without modifying the ship model. Boundary layer calculation should be incorperated in order to correlate the calculated wake distribution with the measured one.

1. Introduction

Accurate simulation of a three-dimensional nonuniform wake distribution is crucial for the successful model test of a marine propeller in a cavitation tunnel. In practice the simulation of a three-dimensional wake distribution is not an easy task even though the same complete ship model, which was used in a towing tank, is installed in the cavitation tunnel for the simulation of the same wake distribution. Tunnel blockage effect deteriorates the flow around the ship model so that the resulting velocity field in the cavitation tunnel be different from that measured in the towing tank. The concept of employing flow liners to control the flow field near the aft-end of a ship model has been adopted by some cavitation tunnels[1].

Attempts to simulate the estimated full scale wake distributions by employing suitably designed flow liners were made in Ship Research Institute (SRI) of Japan. A pair of flow liners were installed in the lower corners of the tunnel wall near the aft-end of the ship. By simulating the full scale wake distributions using flow liners, better correlations between model and full scale test results were obtained not only on cavitation extents but also on pressure fluctuation values[2]. The design of flow liners, however, was carried out by a simple source method and modified by an empirical method or by a trial-and-error method[3]. A more rigorous method for the design of flow liners is needed urgently.

In this paper the effect of flow liners on the flow field around a ship model in a cavitation tunnel is studied using a surface panel method. Since the wake distribution behind a ship model is governed by the viscous effect of fluid, the assumption of ideal potential flow, on which the panel method is formulated, is not a proper one. Boundary layer correction to the calculated potential velocity distribution should be added in order to predict a reasonable wake distribution which can be correlated to the measured one. Only the relative difference between the flow around a ship model with and without flow liners is the main object of the present study.

In the previous paper by the present authors [4], the surface panel method was successfully applied to the calculation of the flow field around simple geometries, such as spheroidal bodies, in a cavitation tunnel. Calculations are extended in this paper for the Sydney Express ship model of which wake distributions were measured at the SRI cavitation tunnel with and without flow liners.

Calculation results show that the flow near the ship's aft-end is accelerated and the surface pressure gradient there becomes favorable to suppress flow separation when the flow liners are employed. It is evident from these calculations that the boundary layer thickness near the ship's aft-end would be smaller for the case of installing flow liners than that for the without-flow-liner case. Hence the width of the iso-axial velocity lines at the propeller plane when the flow liners are installed might be smaller than that for the without-flow-linear case.

2. Application of a surface panel method

An irrotational flow field with the assumption of inviscid and incompressible fluid inside a cavitation tunnel, where a ship model and flow liners are installed, is solved with a low-order potential-based surface panel method[5]. A schematic drawing of the problem with the coordinate system is shown in Fig. 1.

From Green's theorem, velocity potential on the ship, flow liner or wall surfaces can be written as.

$$-\frac{1}{2}\phi(p)=\iint_{S_S\cup S_F\cup S_W}\left[\phi(q)\frac{\partial G(p;q)}{\partial n_q}-\frac{\partial\phi(q)}{\partial n_q}G(p,q)\right]dS, \qquad (1)$$

where

$p(x,y,z)$=field point where induced potential is calculated,

$q(\xi,\eta,\zeta)$=source point where singularity is located,

$G(p;q)$=Green's function, $\frac{-1}{4\pi R(p;q)}$,

$R(p;q)$=distance between the source point and the field point,

S_S=ship surface,

S_F=flow liner surface,

S_W=wall surface.

Ship, flow linear and wall surfaces are replaced by a large number of plane quadrilateral panels, where singularity strength distribution is approximated by a piecewise constant distribution over the panels.

Since the flow around the ship and flow linear is symmetric with respect to the center plane of the ship, the number of unknowns can be reduced as the half of the number of discretized panels. Instead of discretizing the tunnel upper wall surface between the ship model and the tunnel side wall, a double body ship model and a reflected side and bottom wall model is adopted to satisfy the normal boundary condition on the tunnel upper wall surface. As shown in Fig. 1, N_S panels are distributed along the longitudinal direction and M_S panels are distributed along half the cross section of a ship. The flow liner surface is replaced by $N_F\times M_F$ panels and the tunnel wall surface by $N_W\times M_W$ panels in the longitudinal and transverse direction, respectively.

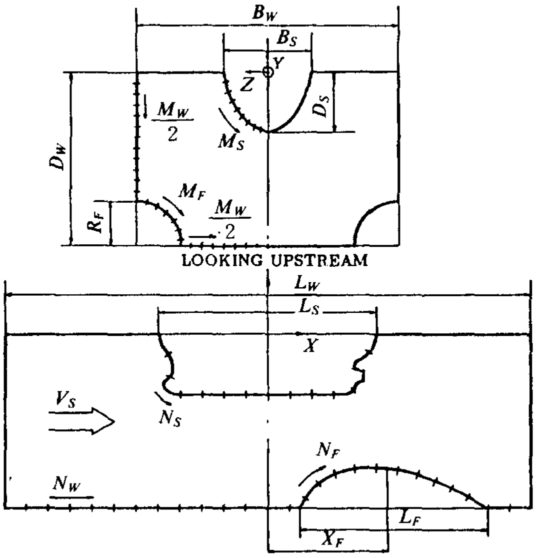

Fig. 1 Arrangement of a ship model and flow liners in a cavitation tunnel.

Discrete form of equation (1) is

$$\sum_{j=1}^{N_P} D_{ij}\phi_j = \sum_{j=1}^{N_P} S_{ij}\left(\frac{\partial \phi}{\partial n}\right)_j,$$

$$i=1,2,\cdots,N_p, \tag{2}$$

where

$$D_{ij}=\iint_{S_j} \frac{\partial G(p_i,q)}{\partial n_q} \, ds,$$

$$S_{ij}=\iint_{S_j} G(p_i,q) \, ds,$$

N_P=total number of unknowns.

$(N_P=M_S \times N_S + M_W \times N_W + M_F \times N_F)$

After equation 2 is solved for ϕ_j, then the velocity is calculated by differentiating the calculated velocity potential. The surface pressure is calculated using the Bernoullii's equation. The non-dimensional pressure coefficient is defined as

$$C_P=\frac{p-p_\infty}{\frac{1}{2}\rho V_S^2}=1-\left(\frac{V}{V_S}\right)^2. \tag{3}$$

3. Measured wake distribution of the Sydney Express ship model

The Sydney Express ship, a German container, has been used as a standard sample for comparative model tests of cavitation observation, hull pressure measurement and noise measurement since the 17th ITTC cavitation committee organized a comparative model test program. Detailed test conditions and test results of the full-scale experiments for the ship are given in Keller and Weitendorf[7].

Five Japanese organizations performed comparative model tests of the Sydeny Express ship model for the 19th ITTC cavitation committee[1]. SRI participated in the test program. The three dimensional wake distribution in the large cavitation tunnel of SRI was simulated using the complete ship model. In order to get a better correlation between the model and full-scale test results, an

Table 1. Principal dimensions of the working section of the SRI cavitation tunnel, the Sydney Express ship model and the flow liner.

Group	Description	Size
Tunnel working section	Length	8000mm
	Width	2000mm
	Depth	880mm
Sydney Express ship model	Lpp	6300mm
	B	915mm
	d(full load)	330mm
	d(tunnel)	420mm
Flow liner	Length	2200mm
	Max. radius	440mm

Fig. 2.a Surface panel representation of the Sydney Express ship model with the flow liners (side view, N_S=20, M_S=17, N_F=20, M_F=10, N_W=20, M_W=10).

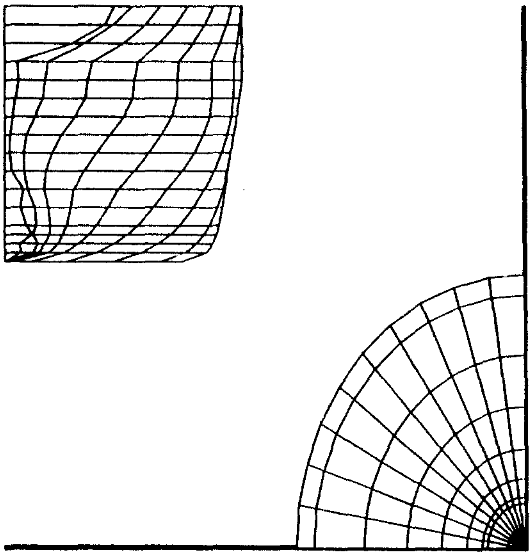

Fig. 2.b Surface panel representation of the Sydney Express ship model with the flow liners (sectional view, N_S=20, M_S=17, N_F=20, M_F=10, N_W=20, M_W=10).

Fig. 2.c Surface panel representation of the Sydney Express ship model with the flow liners (bottom view, $N_S=20$, $M_S=17$, $N_F=20$, $M_F=10$, $N_W=20$, $M_W=10$).

estimated full-scale wake distribution was selected as a target wake to be reproduced for the cavitation tests. The estimated full-scale wake was simulated using the complete ship model and also installing a pair of flow liners in the lower corners of the tunnel side wall.

Principal dimensions of the working section of the SRI cavitation tunnel, the Sydney Express ship model and the flow liner are summarized in Table 1. Geometry of the ship model and the flow liner is shown in Fig. 2.a through 2.c. Wake distribution data of the Sydney Express ship model were furnished by Dr. Ukon of SRI[6].

Fig. 3 and 4 show the iso-axial velocity contour and the cross flow velocity vectors obtained from the measured wake distribution data, respectively, at the propeller plane of the Sydney Express ship model without flow liner. Fig. 5 and 6 show the iso-axial velocity contour and the cross flow velocity vectors for the same ship model with the flow liners, respectively.

As seen from Fig. 3 and 5, width of the iso-axial velocity lines becomes narrower by employing the flow liners, which is believed to be more realistic for a full-scale ship's wake. By employing the flow liners, the flow around the ship's aft-end is accelerated and the pressure gradient there becomes more favorable to suppress the development of boundary layer. The upward cross flow velocity components are increased at the upper regions between $\theta=330$ deg and 30 deg, as shown in Fig. 4 and 6.

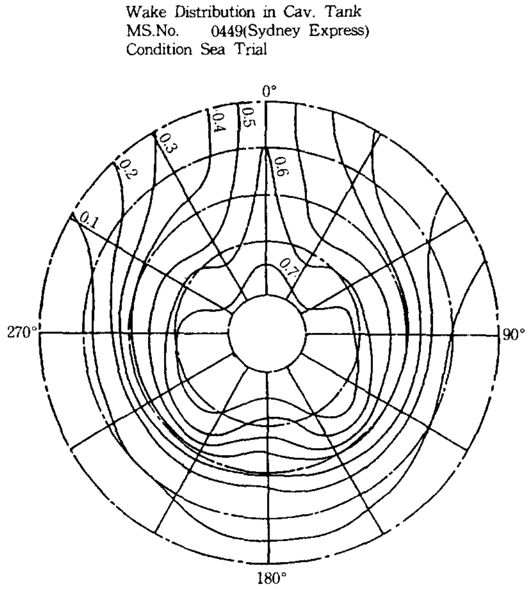

Fig. 3 Iso-axial velocity contour of the measured wake distribution at the propeller plane of the Sydney Express ship model without flow liner.

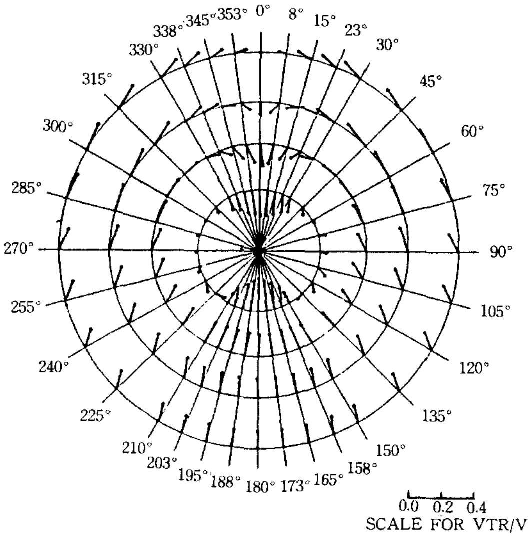

Fig. 4 Transverse velocity vector plot of the measured velocity distribution at the propeller plane of the Sydney Express ship model without flow liner at radial position of $\frac{r}{R_P}=$ 0.381, 0.667, 0.952, 1.238.

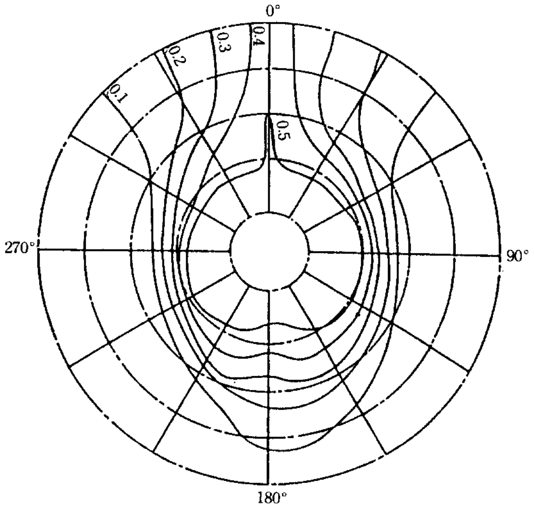

Fig. 5 Iso-axial velocity contour of the measured wake distribution at the propeller plane of the Sydney Express ship model with the flow liners.

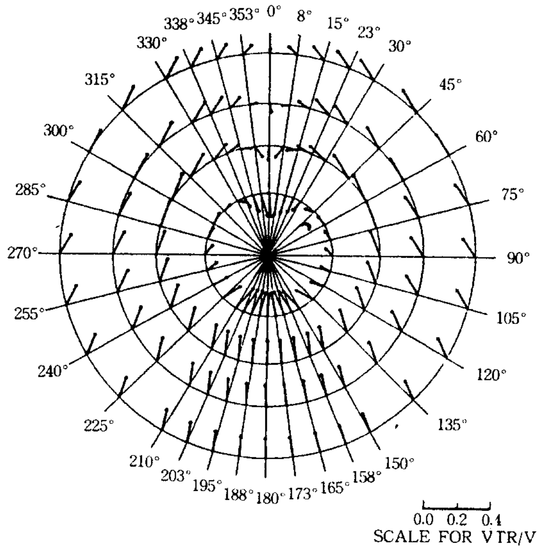

Fig. 6 Transverse velocity vector plot of the measured velocity distribution at the propeller plane of the Sydney Express ship model with the flow liners at radial position of $\frac{r}{R_P}=$ 0.381, 0.667, 0.952, 1.238.

4. Calculation of the velocity field around the Sydney Express ship model

4.1 Estimation of tunnel wall blockage effect

A low-order surface panel method is adopted for the calculation of the flow around the Sydney Express ship model with the flow liners, as described in Section 2. Surface panel representation of the ship and the flow liner is shown in Fig. 2.a through 2.c, where the sizes of the ship and the flow liner and the tunnel working section is selected according to the experimental setup at the SRI cavitation tunnel.

Number of panels on the half surfaces of ship model, flow liner and tunnel wall is selected as $N_S=20$, $M_S=17$, $N_F=20$, $M_F=10$, $N_W=20$, $M_W=10$, respectively, so that the total number of unknowns be 740. Longitudinal length of tunnel wall is selected as three times the ship length.

After solving the boundary value problem for the unknown singularity strength distributions, the field point velocities are calculated by summing up the individual contribution from each panel and the onset velocity.

In order to estimate the tunnel wall blockage effect, a series of calculations are performed for the same ship model in a rectangular test section with varying tunnel blockage. Tunnel wall blockage is reduced by increasing the sizes of tunnel wall, while keeping the same ratio of tunnel width over tunnel depth. Pressure distributions along the longitudinal ship surface above 130mm from the bottom are shown in Fig. 7 for varying blockage. The tunnel blockage is defined as the ratio of the maximum ship cross section area at the midship to the tunnel cross section area.

As the blockage is increased, the pressure values at the midship decrease and the pressure gradient near the ship's aft-end becomes steeper. As the adverse pressure gradient becomes steeper near the ship's aft-end, possibility of flow separation increases. For an excessive tunnel wall blockage, the flow separates from the main stream and becomes asymmetric.

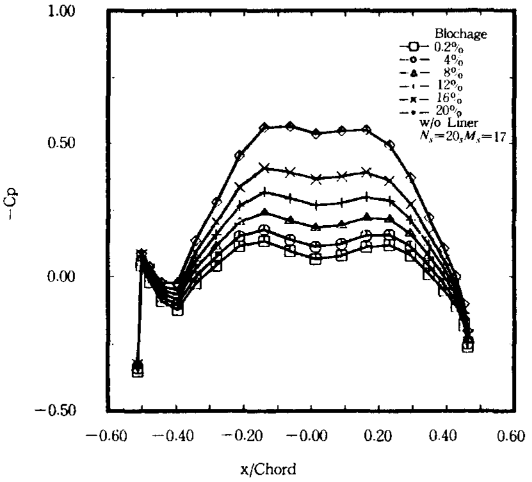

Fig. 7 Pressure distributions along the longitudinal ship surface with varying tunnel wall blockages(d / D=−0.69, without flow liner).

It can be stated from Fig. 7 that the tunnel wall blockage effect on the ship's surface pressure distribution is negligible for the blockage less than 5% and is appreciable for the blockage more than 20% for this Sydney Express ship case. For a full ship model having high block coefficient, the flow near the ship's aft-end can be easily separated from the main stream. For these cases use of flow liner is recommended even for the case of small wall blockage.

4.2 Flow around the Sydney Express ship model without flow liner

The pressure distributions along the three longitudinal strips of upper, middle, and bottom ship surface panels, calculated for the Sydney Express ship model without flow linear, are presented in Fig. 8. The bow and stern ends, where the flow is stagnant, have higher pressure values.

The iso-axial velocity contour, generated from the calculated field point velocity distribution at the tunnel cross section of the propeller plane, is presented in Fig. 9 for the without flow-liner case. Velocities far from the ship's surface are shown to be greater than the inflow velocity to satisfy the flow continuity.

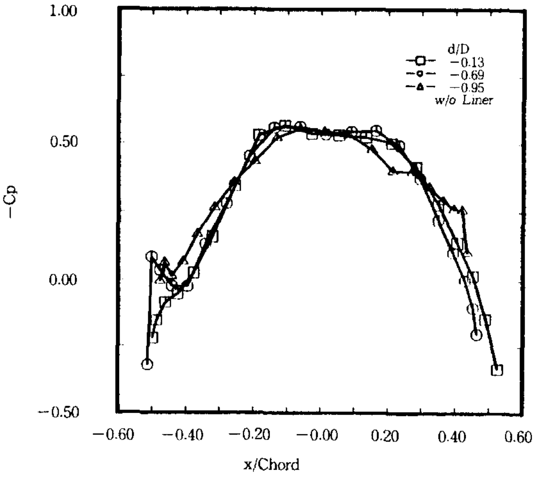

Fig. 8 Pressure distributions on the ship surface calculated for the without-flow-liner case.

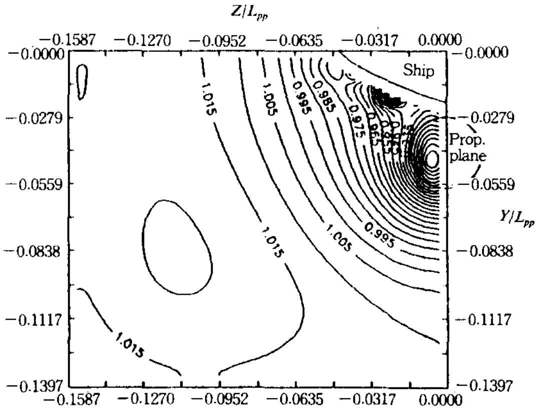

Fig. 9 Iso-axial velocity contour of the field-point velocity distribution at the tunnel cross section of the propeller plane calculated for the without-flow-liner case.

The calculated velocities on the propeller disk area are divided by the maximum value of the axial velocity on the locus of circumference of a circle having radius $\frac{r}{R_P}=1.238$, where the outer-most pitot tube is located, in order to compare the calculated velocity distribution with the measured one. Her R_P designates the propeller radius. The iso-axial velocity contour and the cross flow velocity vectors at the propeller plane, reproduced from the velocity field non-dimensionalized by the maximum axial velocity, are shown in Fig. 10 and 11, respectively, for the without-flow-liner case.

Since the propeller disk area is very small compared to the tunnel cross section area, the velocity differences in Fig. 10 are smaller than that in Fig 9. Moreover the calculated potential velocities do not include the viscous velocity defects. Boundary correction or viscous flow calculation is needed in order to correlate the calculated velocity distribution to the measured one. Correlation of the cross flow velocity component between the calculated and measured ones is better compared to that of the axial velocity. Exceptional regions are outer region of the angles between θ=330deg and 30deg and the inner-most region, where the influence of boundary layer of the ship surface is greater.

4.3 Flow around the Sydney Express ship model with flow liners

The pressure distributions along the three longitudinal strips of upper, middle, and bottom ship surface panels, calculated for the Sydney Express ship model with the flow liners, are presented in

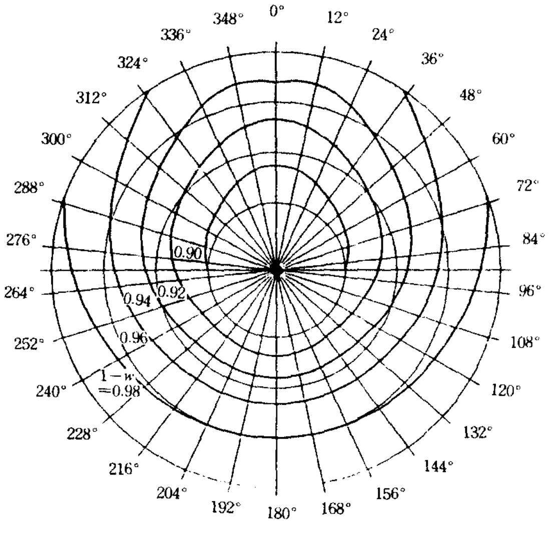

Fig 10 Iso-axial velocity contour of the velocity distribution at the propeller plane calculated for the without-flow-liner case.

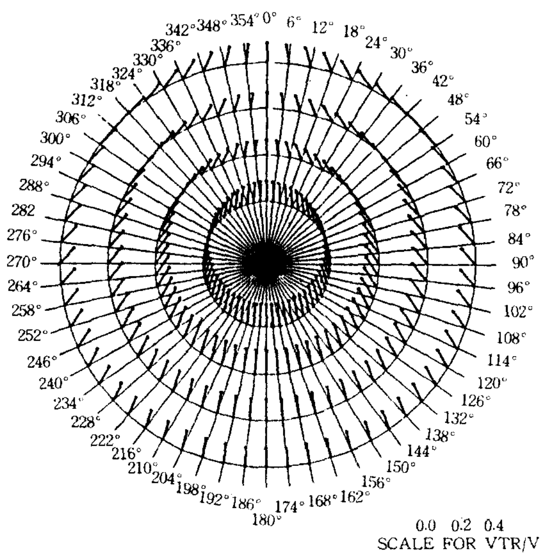

Fig. 11 The non-dimensioalized transverse velocity vectors at the propeller plane calculated for the without-flow-liner-case at radial position of $\frac{r}{R_P}$=0.381, 0.667, 0.952, 1.238

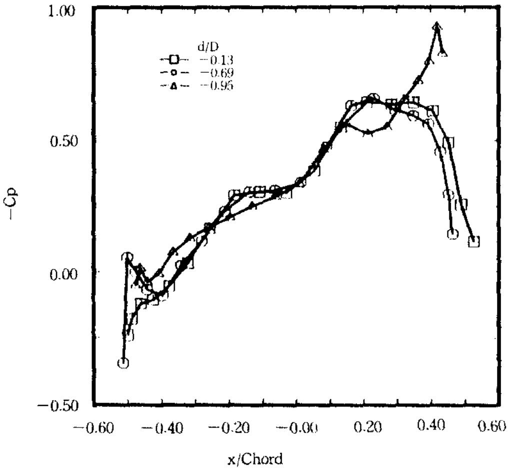

Fig. 12 Pressure distributions on the ship and flow liner surfaces calculated for the without-flow-liner-case.

Fig. 12. Since the flow is accelerated near the ship's aft-end due to the flow liners, pressure gradient becomes favorable up to the 85% of the ship length, while that for the without-flow-liner case is favorable only up to the 35% of the ship length from the ship's fore-end as shown in Fig. 8. It can be estimated from these pressure distributions that the boundary layer thickness near the ship's aft-end would be narrower by installing the flow liners. Also the maximum pressure values at the stern end is lower for the with-flow-liner case.

The iso-axial velocity contour, generated from the calculated field point velocity distribution at the tunnel cross section of the propeller plane, is presented in Fig. 13 for the with-flow-liner case. Overall flow field is seen to be accelerated appreciably due to the flow liners.

The volumetric mean axial velocity on the propeller disk surpace increases by 14% compared to that of the without-flow-liner case, for this Sydney Express case having 21% hull blockage and 17% flow liner blockage.

The iso-axial velocity contour and the cross flow velocity vectors at the propeller plane, reproduced from the velocity field non-dimensionalized by the maximum axial velocity along the locus of circu-

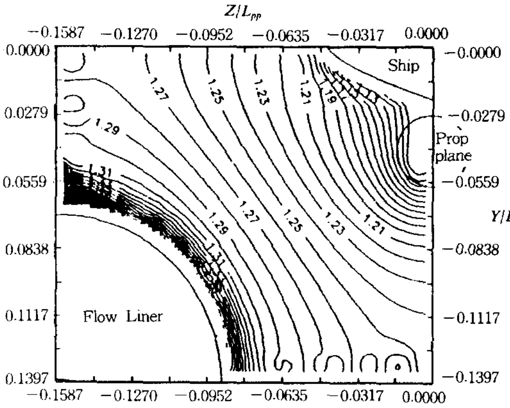

Fig. 13 Iso-axial velocity contour of the field-point velocity distribution at the tunnel cross section of the propeller plane calculated for the without-flow-liner-case.

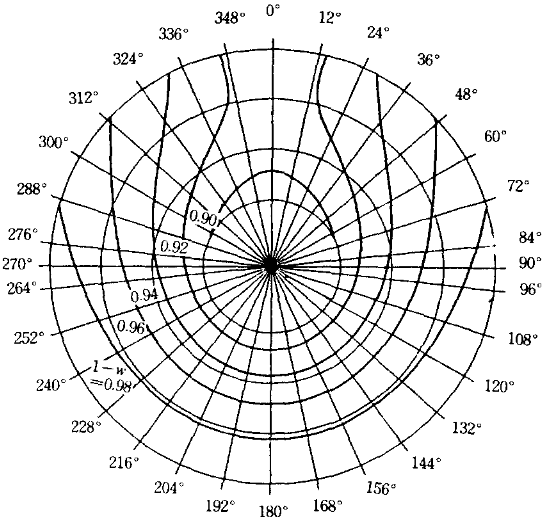

Fig. 14 Iso-axial velocity contour of the velocity distribution at the propeller plane calculated for the without-flow-liner-case

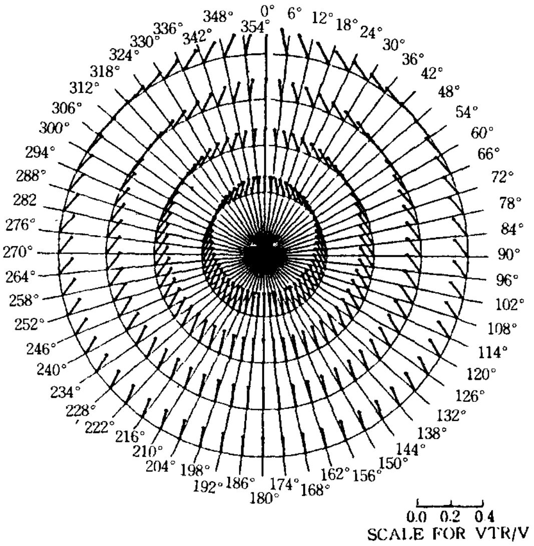

Fig. 15 The non-dimensioalized transverse velocity vectors at the propeller plane calculated for the without-flow-liner-case at radial position of $\frac{r}{R_P}$ =0.381, 0.667, 0.952, 1.238

mference of the circle having radius $\frac{r}{R_P}=1.238$, are shown in Fig. 14 and 15, respectively, for the with-flow-liner case. Even though overall velocities are increased appreciably by installing the flow liners, the non-dimensional iso-axial velocity contour does not change dramatically. No appreciable differences between Fig. 11 and Fig. 15 is found except that the upward cross flow velocity components in the outer region between $\theta=340$deg and 20deg are slightly increased.

5. Conclusions

In this paper a low-order surface panel method is adopted to calculate the flow around the Sydney Express ship model with flow liners in a cavitation tunnel. From the results in the previous sections following conclusions can be made:

- Velocity fields calculated at the propeller plane with and without flow liner show that flow liners can be used to control the wake distribution at the propeller plane. By designing a proper flow liner an estimated full scale target wake can be simulated in a cavitation tunnel without modifying the ship model.
- Tunnel wall blockage effect on the ship's surface pressure distribution is negligible in a close-type cavitation tunnel for the blockage less than 5% and is appreciable for the blockage more than 20% of the test section area.
- The flow liners accelerate the flow near the aft-end of the ship model so that the pressure values there be reduced. The effect of flow liners on the iso-axial velocity contour at the propeller plane, produced from the velocity field non-dimensionalized by the maximum axial velocity on the wake-surveyed surface, is not appreciable.
- Boundary layer correction should be added in order to correlate the calculated velocity distribution to the measured one. Since the pressure distribution near the ship's aft-end surface for the with-flow-liner case has a favorable pressure gradient to suppress flow separations, the width of the iso-axial velocity contour would become narrower compared to that for the without-flow-liner case, if the boundary layer correction is adopted.
- The CFD method solving the Navier-Stokes equations with a proper turbulent modelling is recommended for the calculation of the flow around a ship model in a cavitation tunnel with flow liners.

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