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PREDICTION OF LINE-SPECTRUM NOISE INDUCED BY UNDERWATER VEHICLE CONTRA-ROTATING PROPELLERS

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ABSTRACT

Line-Spectrum noise of contra-rotating propellers has constructed the main part of the radiated noise of underwater vehicles. The line-spectrum noise of the contra-rotating propellers is due to the interaction between the wake of the vehicle and the contra-rotating propellers, and the interaction between fore and aft propeller. Based on a combination of the lifting surface theory and acoustic techniques, the prediction method of line-spectrum noise is presented in this paper. Theoretical calculation method, characteristics and numerical prediction of the line-spectrum noise are detailed in this paper. The effect of different wake and different gap between fore and aft propeller on the propeller noise is also studied by numerical method. The agreement of predicted results compared with existing experimental data is quite satisfactory. Therefore, the methods are to have important values for performance prediction of the vehicles, identification of the noise sources and acoustic design of contra-rotating propellers ,etc.

1. INTRODUCTION

Up to now, contra-rotating propeller is a main kind of propulsion aspect for high speed vechile. There is no doubt that it is a main noise source. For non-cavitating contra-rotating propeller noise, it can be classified into line-spectrum noise and random broad-band noise according to the mechanism of noise. One part of the line-spectrum noise is due to the working of contra-rotating propellers in non-uniform wake, the interaction between the contra-rotating propellers and the wake resulted in the unsteady force, thus the discrete spectrum noise is yielded; the other part of the line-spectrum noise is induced by the unsteady force due to the potential interaction between the fore and aft propeller. Usually the contra-rotating propellers have more abundance line-spectrum than the single propeller, and it forms the main part of the contra-rotating propeller noise. Random broad band noise is due to the interaction between the propeller and the surrounding viscous flow, and it will not be discussed hereafter.

Theoretical research on this subject began in 1980's[1], and it mainly concerns the aeronautical propeller[2] which runs in the uniform flow. While for underwater situations, the propeller mostly works in the non-uniform flow, and the wake situation is the main factor of such a kind of noise, so the situation of marine propeller is really different from the aero-plane contra-rotating propellers.

2. PREDICTION OF CONTRA-ROTATING PROPELLER LINE-SPECTRUM NOISE

The research on the propeller noise can be classified into two categories: time domain method and frequency domain method[3]. Both of them have its advantages and shortcomings. Because the characteristics we studied are about spectrum in the far field, it is a convenient way for us to study the noise in the frequency domain.

First, the fixed coordinate system （ y_1, y_2, y_3) and a rotating coordinate system （ γ_0, r_0, ξ_0) are defined, γ_0, ξ_0 are coordinates on the surface of the cylinder whose radius is r_0， the direction of γ_0 is oppsite to the move direction of the source， it represent the helicoidal distance away from the propeller generator line， r_0 is radius， ξ_0 is perpendicular to the direction of γ_0 and r_0.

According to the acoustic analogy equation of Goldstein [4], while the Mach number of propeller in water is very small, the blade is thought to be rigid, the sound pressure produced by blade can be simplified into the following form:

$$p_i(\vec{x},t) = -\int_{-T}^{T}\int_{0}^{c}\int_{r_H}^{r_T} f_i \frac{\partial G}{\partial y_i} dr_0 d\gamma_0 d\tau \tag{2.1}$$

here i=1,2 stand for the fore and aft propeller respectively, $p_i(\vec{x},t)$ is the sound presuure radiated by fore or aft propeller at point $\vec{x}$, time t. the integral domain of time t [-T,T] should be long enough, c_i is the chord length, r_H, r_T are radius of hub and tip respectively, G is Green's function, f_i are the forces acting on the blade surface.

By Fourier transformation, and some necessary mathematical operation, we finally get the result:

$$\begin{aligned}
p_i(\vec{x},t) = &\frac{-i\rho_0 c_0^2 \sin\theta_i B_i}{8\pi(r_i/D_i)(1-M_{xi}\cos\theta_i)} * \{\sum_{n_1=-\infty}^{+\infty} \cdot \sum_{n_2=-\infty}^{+\infty} \exp\{i[(n_2B_2-n_1B_1)(\Phi-\Phi^{(i)}-\frac{\pi}{2})\\
&+\frac{(n_2B_2\Omega_2+n_1B_1\Omega_1)}{1-M_{x_i}\cos\theta_i}(\frac{r_i}{c_0}-t)]\} \cdot \int_{r_{H_i}}^{r_{T_i}} M_{r_i}{}^2 \cdot e^{i(\Phi_s^{(i)}+\Phi_o^{(i)})} k_y^{(i)} \cdot \frac{C_{L_i}}{2} \Psi_{Li}(k_x^{(i)})\\
&\cdot J_{n_2B_2-n_1B_1}[\frac{(n_2B_2\Omega_2+n_1B_1\Omega_1)}{1-M_{x_i}\cos\theta_i} Z_{0i} \cdot M_{ti} \cdot \sin\theta_i] dZ_{0i}\\
&+\sum_{n_i=-\infty}^{+\infty} \cdot \sum_{k_i=-\infty}^{+\infty} \exp\{i[(k_i w_i - n_i B_i)(\Phi-\Phi^{(i)}-\frac{\pi}{2})+\frac{n_iB_i\Omega_i}{1-M_{x_i}\cos\theta_i}(\frac{r_i}{c_0}-t)]\}\\
&\cdot\int_{r_{H_i}}^{r_{T_i}} M_{r_i}{}^2 \cdot e^{i(\Phi_w^{(i)}+\Phi_{ow}^{(i)})} J_{n_iB_i-k_iw_i}[\frac{(n_iB_iZ_{0i}M_{ti}\sin\theta_i)}{1-M_{x_i}\cos\theta_i}] k_{yw}^{(i)} \cdot \frac{C_{L_iw_i}}{2} \Psi_{Liw_i}(k_{xw}^{(i)}) dZ_{0i}\} *
\end{aligned} \tag{2.2}$$

here :

$$k_x^{(i)} = \frac{2}{M_{r_i}}[\frac{(n_1B_1M_{t_1}+n_2B_2M_{t_2})}{(1-M_{x_i}\cos\theta_i)} - n_iB_i(M_{t_1}+M_{t_2})]\frac{C_i}{D_i}$$

$$k_y^{(i)} = -\frac{2}{M_{r_i}}[\frac{(n_1B_1M_{t_1}+n_2B_2M_{t_2})}{(1-M_{x_i}\cos\theta_i)} \cdot M_{t_i} \cdot Z_{0i}\cos\theta_i + (n_1B_1-n_2B_2)\frac{M_{x_i}}{Z_{0i}}]\frac{C_i}{D_i}$$

$$\Phi_S^{(i)} = k_x^{(i)}\frac{MCA}{C_i}$$

$$\Phi_o^{(i)} = -k_y^{(i)}\frac{FA}{C_i}$$

$$k_{xw}^{(i)} = \frac{2}{M_{r_i}}[\frac{(n_i B_i M_{t_i})}{(1 - M_{x_i} \cos\theta_i)} - k_i w_i M_{t_i})]\frac{C_i}{D_i}$$

$$k_{yw}^{(i)} = -\frac{2}{M_{r_i}}[(n_i B_i - k_i w_i)\frac{M_{x_i}}{Z_{0i}} + \frac{(n_i B_i M_{t_i}{}^2 \cdot \cos\theta_i}{(1 - M_{x_i} \cos\theta_i)}]\frac{C_i}{D_i} \qquad (2.3)$$

$$\Phi_{Sw}^{(i)} = k_{xw}^{(i)} \frac{MCA}{C_i}$$

$$\Phi_{ow}^{(i)} = -k_y^{(i)} \frac{FA}{C_i}$$

here i=1 represents the fore propeller, i=2 the aft propeller, C_i is the chord length of the blade, D_i is the diameter of the propeller, n_1, n_2 are harmonic number, B_1,B_2 are the blade number of the fore and aft propeller respectively, MCA, FA are the geometric description of the skew and offset.Generally , the effect of FA can be neglected. Φ, $\Phi^{(1)}$, $\Phi^{(2)}$ are the initial phase angle. C_{L_i}, C_{LW_i} stand for the unsteady lift force coefficient induced by the interaction between fore and aft propeller and the interaction between propeller and the inflow respectively.

The overall line-spectrm noise of the contra-rotating propellers should be:

$$P(\vec{x},t) = P_1(\vec{x},t) + P_2(\vec{x},t)$$

3. PREDICTION OF CONTRA-ROTATING PROPELLER UNSTEADY FORCE

In order to study the line-spectrum noise of contra-rotating propellers, It is necessary to study the hydrodynamics performance, and get the unsteady force acting on the propeller, that is to say to get the noise source strength first, such as source terms in equation (2.2) .

Let the propeller work in inviscid and uncompressible flow, velocity potential function Φ stands for the disturbance of the propeller to the flow, and

$$\Phi = \Phi_1 + \Phi_2 + \Phi_B \qquad (3.1)$$

hereΦ_1、 Φ_2、 Φ_B represent the disturbance caused by fore, aft propeller and hub respectively.

The boundary value problem can be written as follows:

in the flow field

$$\nabla^2\Phi = 0 \qquad (3.2)$$

on the fore propeller blade surface

$$(\nabla\Phi + V_{I1}) \cdot \vec{n}_1 = 0 \qquad (3.3)$$

on the aft blade surface

$$(\nabla\Phi + V_{I2}) \cdot \vec{n}_2 = 0 \qquad (3.4)$$

on the hub of propeller

$$(\nabla\Phi + V_I) \cdot \vec{n}_B = 0 \qquad (3.5)$$

far field condition

$$|\nabla\Phi| \to 0 \qquad (3.6)$$

on the surface of trailing edge vortex sheet

$$\Delta P = P_+ - P_- = 0 \qquad (3.7)$$

on the trailing edge

$$|\nabla\Phi| < \infty \qquad (3.8)$$

here$\vec{n}_1$、$\vec{n}_2$、$\vec{n}_B$ are normal unit vector of the surface respectively, P_+、P_- are the pressure on the upper and lower surface of the trailing edge vortex sheet. V_{I1}、V_{I2} stand for the inflow velocity of the fore and aft propeller and V_1 is the advance speed.

According to the Green's theory, the disturbance potential Φ which satisfy (3.2) and (3.6) can be described as the contribution of distributed sources and vortex on the surface of the blade and wake

$$4\pi E\Phi_K(p,t) = \iint_{S_K}[\mu_K(Q,t)\frac{\partial}{\partial n_Q}(\frac{1}{R(P,Q)}) - \sigma_K(Q,t)\frac{1}{R(P,Q)}]dS_Q + \iint_{S_{WK}}\mu_{WK}(Q,t)\frac{\partial}{\partial n_Q}(\frac{1}{R(P,Q)})dS_Q \quad (K=1,2) \tag{3.9}$$

$$4\pi E\Phi_B(P,t) = -\iint_{S_B}\sigma_B(Q,t)\frac{1}{R(P,Q)}dS_Q \tag{3.10}$$

here P is the field point ,Q is the source point, R(P,Q) is the distance between the two point, $\frac{\partial}{\partial n_Q}$ is the normal derivative to the point Q, S_i、S_{Wi} represent the blade and wake surface, i=1 is the fore propeller, i=2 is the aft propeller, μ is the doublet density and σ is the distributed source density.

$$E = \begin{cases} 1 & P\ \text{is located in the fluid} \\ 1/2 & P\ \text{is located on the surface} \\ 0 & P\ \text{is inside the Blade} \end{cases}$$

substituting (3.9)、(3.10) into (3.3)、(3.4)、(3.5), we get the integration equation about the vortex strength and source density.

Supposing the blade is thin with finite span, the blade thickness is simulated by line source , and the blade loading is simulated by the vortex ring , thus the numerical analysis can be made[5 、 6].The hydrodynamic performance of the propeller in the uniform and non-uniform flow is obtained first (such as thrust coefficient 、 torque coefficient 、 and efficiency) , and the pressure difference between the upper and lower surface at point Q :

$$\Delta P_Q = (P_u)_Q - (P_\ell)_Q = -\rho\frac{\partial}{\partial t}(\Phi_u - \Phi_\ell)_Q - \frac{1}{2}\rho(V_u\cdot V_u - V_\ell\cdot V_\ell)_Q \tag{3.11}$$

here the subscript u 、 ℓ represent the upper and lower surface, V is the velocity.

When the unsteady force have been obtained, the propeller far field noise prediction can be made.

4. NUMERICAL PREDICTION OF THE NOISE

After the Fourier analysis of the vehicle wake and calculation of unsteady force on the blade, the prediction of contra-rotating propellers far field line-spectrum noise can be made by (2.2).Single propeller is a specialty of (2.2)[7].Table 1 is the main parameters of the two propellers which were calculated and tested in this paper.

According to the noise calculation formula , the line-spectrum frequency should be :

$$f_{n_1,n_2} = (n_1B_1\Omega_1 + n_2B_2\Omega_2)/2\pi \tag{4.1}$$

Let $\Omega_1 = \Omega_2$, $\Omega_1/2\pi = \Omega_2/2\pi = n$, (4.1) can be simplified as:

$$f_{n_1,n_2} = (n_1B_1 + n_2B_2)n \tag{4.2}$$

here n is the rotating speed of the shaft， B_1、B_2 are the blade number of the fore and aft propeller， n_1、n_2 are integer number which is greater than or equal to 0.

Table 1.

Model	CRP1		CRP2	
Parameter	fore propeller	aft propeller	fore propeller	aft propeller
Blade number （ B ）	6	7	7	5
Diameter (mm)	236	230	286	272
Area Ratio （ A_E/A_O ）	0.70	0.96	0.69	0.63
Advanced Coefficient （ J=V/nD)	2.8	2.9	1.8	1.9
Rotating speed(r.p.s)	33.3	33.3	11.0	11.0
Gap (mm)	83		71	

The sound radiation criterion is γ_{n_1,n_2}, only when $\gamma_{n_1,n_2} > 1$, the radiation efficient is high，

$$\gamma_{n_1,n_2} = \frac{(n_1B_1 + n_2B_2)}{(n_1B_1 - n_2B_2)} > 1$$

or

$$\gamma_{n_i,k_i} = \frac{n_iB_i}{(n_iB_i - k_iw_i)} > 1 \tag{4.3}$$

The noise and hydrodynamic performance of CRP1 and CRP2 were tested in cavitation tunnel. the hydrophone is mounted in the water cabinet which is attached on the tunnel wall outside.The experiment photo of the propeller is shown by figure 1.the frequency and hamonic number in non-uniform inflow is shown in figure 2 and figure 3.

It is known from figure 2 and figure 3， the predicted frequency of the line spectrum coincide with the measured results.The criterion of the sound radiation is correct. （ Note： the dashed line in figure 2 and figure 3 is the background noise ）.

The prediction of noise performance about the full scale CRP1 is also made.Figure 4 and 5 show the relative noise level of the fore, aft and overall at the location of 45^0、 90^0， it is known from the figure that the highest noise level of the fore propeller is near 1KHz， the number of line-spectrum is less than the aft propeller， on the contrary, there are more high order line-spectrum from the aft propeller, this may be the general situation for contra-rotating propellers[8].it is also known from the figure that the noise level of different frequency varies considerably with the direction （ 45^0、 90^0 ）， this also can be derived from equation(2.2).The above characteristics lead to the difficulty in the full scale vechile noise measurement.The predicted level agrees with the the mesurement result both in noise level and the frequency scope， so that the prediction method is feasible.

In order to study the effect of the inflow on the line-spectrum noise,we calculated noise performance of CRP1 in uniform and non-uniform inflow （ 90^0 direction ）.The result is given in figure 6 and figure 7， we could see that the high order noise of propeller (either fore or aft) in uniform flow reduced considerably than that in non-uniform situation. This proves that the non-uniformity of the inflow is the main reason of the propeller high order line-spectrum noise.The calculated result also shows that the overall noise level in non-uniform inflow is 3 decibels higher than that in uniform flow.

The gap between fore and aft propeller is another important factor which affect the propeller noise.In order to explain this phenomenon, the following situation of CRP1 is calculated.The gap is chosen to be 73mm、 83mm、 93mm (90 ° direction).The result is shown in figure 8. From the figure, we could know that the noise increased with the decreasement of the gap. When the gap is narrowed 10mm , the overall noise level of the fore propeller increased about 3 dB.This has been confirmed in corresponding experiment.This shows that the interaction between the fore and aft propeller is another important factor which affect the contra-rotating propeller noise.

The hydrodynamic performance of the propeller can also be predicted by the third part of the above method, including the thrust coefficient $K_T = T/\rho_0 n^2 D^4$, torque coefficient $K_Q = Q/\rho_0 n^2 D^5$, here T is the thrust of the propeller , Q is torque , n is the rotating speed and D the diameter , ρ_0 is the density of the water. The predicted result and experiment result are both shown in figure 9 and figure 10.we can know from the figure that the two results fair agree with each other , and it indicates that the prediction method is successful.

5. CONCLUSIONS

Concluding the above study on the line-spectrum noise, the following meaningful result can be obtained:

[1] No matter fore or aft propeller , Its line-spectrum noise is resulted from the interaction between the fore and aft propeller, and the interaction between the propeller and the non-uniform inflow.The method presented in this paper is adaptable to any contra-rotating propellers.

[2] Because of the interaction between the fore and aft propeller, the line-spectrum is more abounded than the single propeller, and it is of the main part of the underwater vehicle radiation noise.

[3] The high order line-spectrum noise comes from the non-uniform inflow, so if we can improve the uniformity of the inflow, the line spectrum noise can be reduced.

[4] The frequency of the line-spectrum can be represented by algebra equation , and only when $n_1 \geq 0, n_2 \geq 0$ the line spectrum will be important to the noise.

[5] The noise level depend on some of the propeller parameters, such as: the noise distribution varies with blade number ; the noise will be increased greatly when the fore and aft propeller have the equal blade number.

[6] The line-spectrum noise level of contra-rotating propellers at different location will be different greatly, that is to say that the direction of such noise is complex, and this result in the difficulty in the full scale vehicle noise measurement.

[7] The gap between the fore and aft propeller is an important factor which affect the line-spectrum noise, increase of the gap properly will be benifit to the noise reduction.

[8] From the comparison between the predicted result and the experiment result , the numerical results agree with the experiment both in magnitude and the frequency scope , This indicates that the method using combined lifting surface and acoustic technology in this paper can be used to predict the performance (hydrodynamics and noise) of the vehicle not only, it can be used in the identification of the vehicle noise source and contra-rotating propellers acoustic design but also.

6. REFERENCES:

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Figure 1. photo of the tested CRP1 in water tunnel

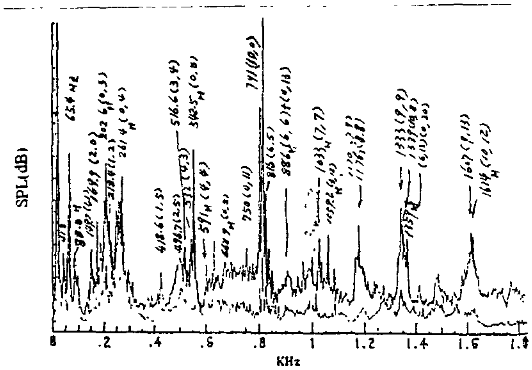

Figure 2. line spectrum of CRP1

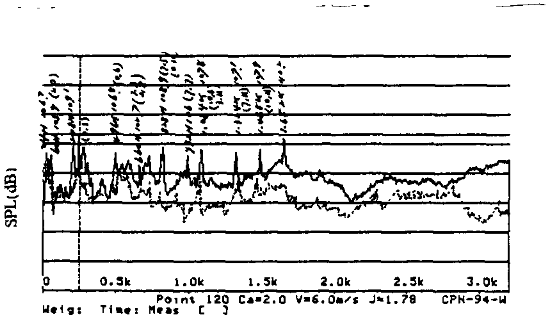

Figure 3. line spectrum of CRP2

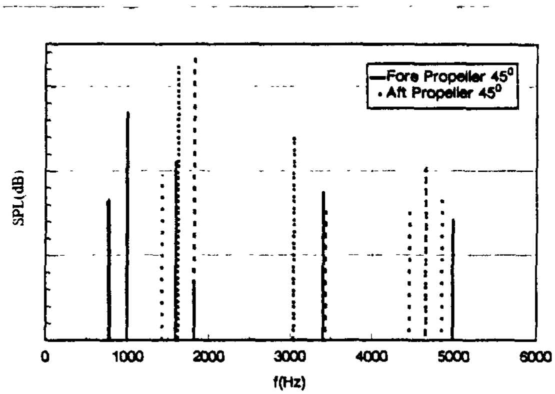

Figure 4. line spctrum noise of CRP1 at 45^0 direction

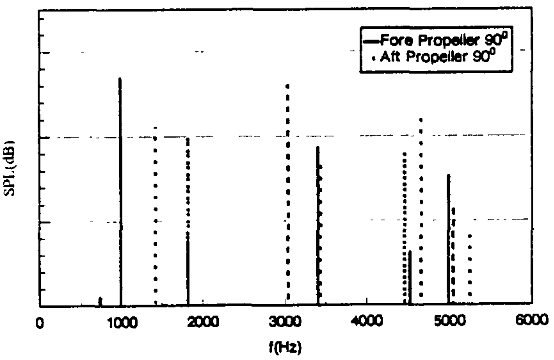

Figure 5. line spectrum noise of CRP1 at 90^0 direction

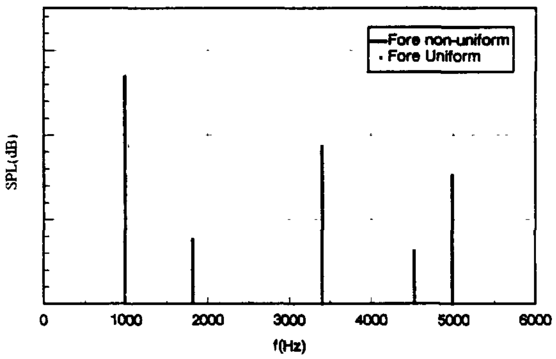

Figure 6. line spectrum of CRP1 fore propeller in uniform and non-uniform flow

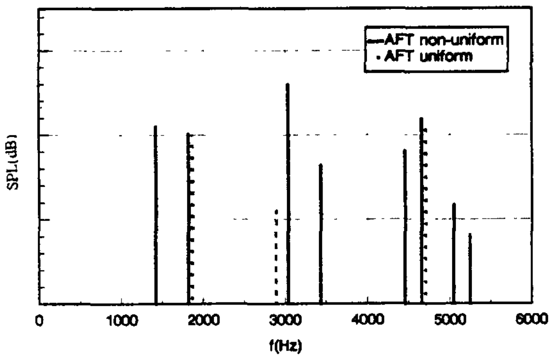

Figure 7. line spectrum noise of CRP1 aft propeller in uniform and non-uniform flow

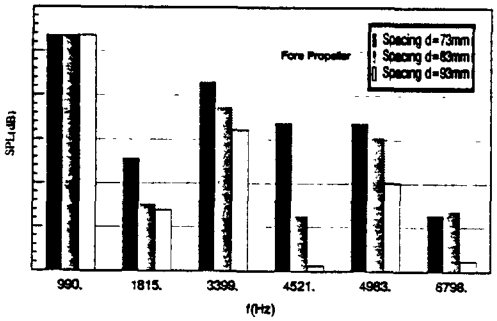

Figure 8. effect of gap variation on noise

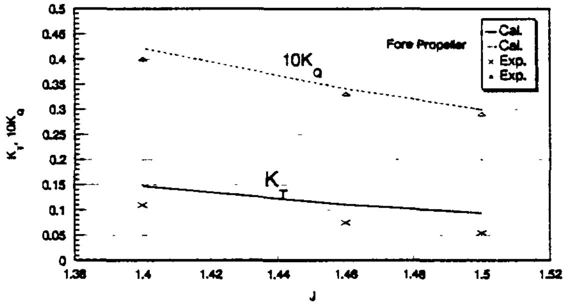

Figure 9. hydrodynamic performance of CRP2 fore propeller

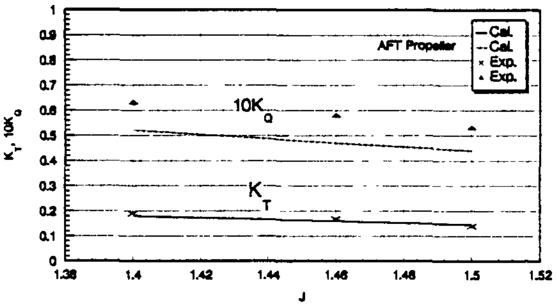

Figure 10. hydrodynamic performance of CRP2 aft propeller