Effective measures of eliminating propeller-hull vortex cavitation

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ABSTRACT
Propeller-hull vortex cavitation (PHVC) is always accompanied with severe local vibration, and therefore, the PHVC should be avoided in propeller and hull design. Lately, the PHVC was appeared on a low speed container vessel at both ballast and design draft conditions. Some special measures for eliminating the PHVC were used, such as adding some accessories in front of propeller. They include accessory vortex generator and pre-swirl duct. This paper presents the test results and CFD analysis, the results show that the measures of adding accessory can improve the inflow field onto the propeller and eliminate the PHVC effetely.

Keywords
PHVC, separation, vortex generator, pre-swirl duct.

1 INTRODUCTION
When a marine propeller operating at a high loaded condition and with small tip clearance, unsteady vortex cavitation may occur between blades and near hull surface. It was firstly found by E.Huse (1972), and the paper was published on the I.S.P. in 1972. It has been widely known as propeller-hull vortex cavitation (PHVC), which may cause severe stern local vibration and noise. So, PHVC should be prevented during the primary design. It has been found that PHVC may occur not only in conventional propeller case but also in ducted propeller case although less occasions. However, there are only fewer papers published related to the measures for preventing PHVC. A systematic experiment investigation of PHVC performance was carried out by shigeki (1986), who analyzed the occurrence conditions of PHVC, gave a flow diagram of forming PHVC, showed in Fig.1, and a criteria curve of PHVC inception in Fig.2. His test used a flat plate instead of stern hull. He also investigated the PHVC and PHV, and the flow field by using high speed camera. The test results indicated that the PHVC started from the propeller side and developed toward the plate side, and it disappeared from the wall side toward the propeller side. The PHV is attributed to the interaction between the propeller and plate (hull), and it is strengthen if vortex of hull wake exists near the propeller.

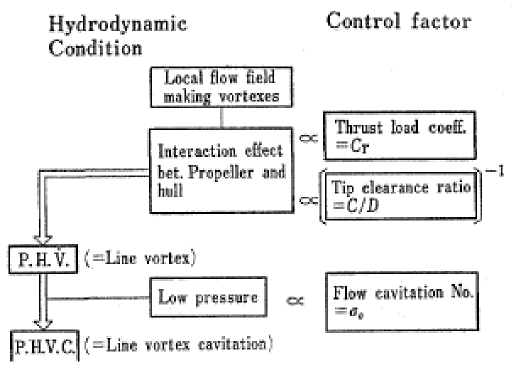


Figure 1 flow diagram for forming PHVC

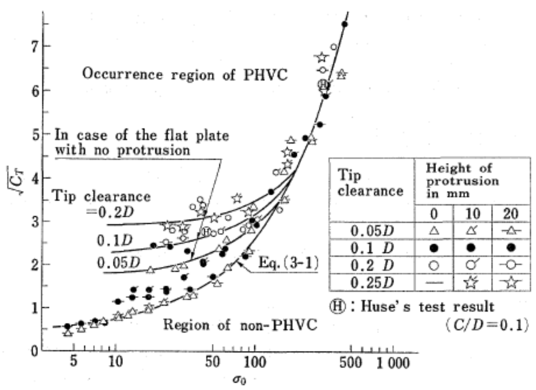


Figure 2 limiting lines of inception PHVC

Sato et al (1986) also investigated PHVC with six model propellers, a flat plate representing the hull surface located above the propeller, the tip clearance varied by moving the propeller, and air bubbles were injected into the flow field for visualization on the plate. Based on the observations, the flow patterns on plate were classified into six specific types, such as : 1) NO-reverse flow stage ;2) No-vortex reverse flow stage,3) Aft vortex flow stage ; 4) Double vortex flow;5) Fore vortex flow stage ;6) Splatter flow stage. This method was proved very useful to demonstrate the occurrence and intensity of PHVC.

PHVC is a special type of cavitation, because of its complication and seldom occurrence, only a few theory calculation was reported, Jussi Martio (2011) modeled the propeller-hull vortex (PHV) using the time – accurate solver. Both steady-state and time-accurate approaches are utilized in the investigations. The computations indicate that the parameters affecting the strength of PHV are blade loading and tip clearance, and the limiting streamlines on the flat plate were found to be the most appropriate method of tracing the vortices, but this technique did not give the way to evaluate the strength of the vortex. The fundamental mechanisms causing the PHV could be modeled with some accuracy based on the RANS method, the next step, the cavitation modeling would be added in to improve the simulations at full scale.

Several months ago, for a container vessel A under construction, the cavitation test of propeller was carried out in China Large Cavitation Channel (CLCC), and the PHVC was appeared and shocked the ship stern at both ballast and design draft, showed in Fig.3. In order to eliminate the PHVC and reduce the local vibration, some measures of eliminating the PHVC were conducted. This paper presents some methods how to eliminate the PHVC.

Figure 3 PHVC of container vessel A at ballast condition

2 THE OCCURRENCE OF PHVC ON A CONTAINER VESSEL A

The cavitation observation and pressure fluctuation measurement for a container vessel A have been conducted. During the cavitation test, the model propeller rotated with 28r/s at all times. The PHVC was found both at ballast draft and design draft. Table 1 shows the test condition, and Fig.4 shows the cavitation pattern on blade 1 at different angles. The PHVC could occur at the rim of fluctuating sheet cavitation of outer radio or appear at the location of bursting tip vortex cavitation. The PHVC seemed to occur randomly and persisted less than 0.5seconds, but in fact, each blade entered to the high wake, the PHVC appeared like a lightning and shifted with the propeller rotating.

During the model cavitation test, the fluctuation pressure induced by cavitation was also measured, shown in Fig.5. Normally, the signals of fluctuating pressure appear as oscillating form in time frame, but for the PHVC, the pressure signal appears as a sudden shock with much higher strength and in random. For this container vessel, the normal fluctuation pressure is about 3.0kPa when PHVC has not appeared. In case of occurrence for PHVC the pulse pressure will increase rapidly, the value of fluctuation pressure will be over 15.0kPa, which induces serious stern vibration. As well, the PHVC also increases the amplitude of fluctuation pressure at low frequency, like as in Fig.6. So, some measures must be taken to eliminate the PHVC for reducing the local vibration.

Table1 cavitation test condition of container vessel A

NO.	Ballast draft (CSR)	Design draft (CSR)
P_D (kW)	2503.7	2503.7
Draught (T_F/T_A) (m)	2.45/4.55	5.6/5.6
D_S (m)	4.1	4.1
Tip clearance ratio (T/D)	0.209	0.209
C_B	0.82	0.86
Vs (kn)	12.89	12.55
Ns (rpm)	138	138.5
Cavitation number $\sigma_{n(0.8R)}$	0.3471	0.4079
K_T	0.2166	0.2152
C_T	1.116	1.178
$K_T = \frac{T}{\rho n^2 D^4}$	$\sigma_{n(0.8R)} = \frac{P-Pv}{0.5\rho(0.8\pi nD)^2}$	$C_T = \frac{8\times K_T}{\pi \times J^2}$

The Cavitation number $\sigma_{n(0.8R)}$ was based on the propeller rotating speed and the pressure at 0.8R while the blade position at zero angle (12 O'clock).

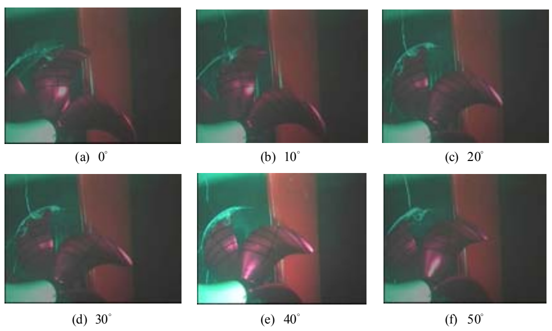


Figure 4 the cavitation pattern of propeller blade 1 at different angles (ballast draft)

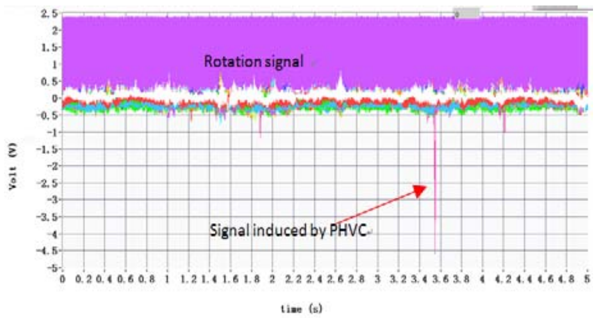


Figure 5 signal of fluctuation pressure induced by cavitation in time-domain field

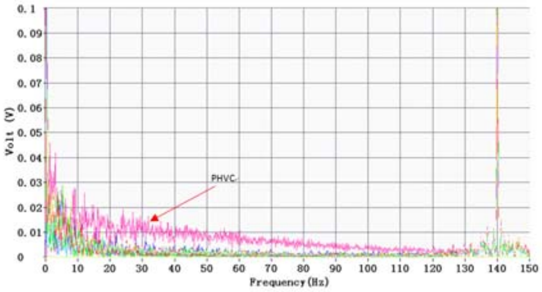


Figure 6 the distribution of fluctuation pressure in frequency field

3 THE ANALYSIS ON PHVC FOR A CONTAINER VESSEL

3.1 The condition of occurrence for PHVC

As above-mentioned, high loaded and small tip clearances are the main reasons causing occurrence of PHVC physically. Here C_T is used to present the propeller load, and T/D is used to present the dimensionless tip clearance.

$$I_H = \frac{C_T}{(T/D)} = \frac{8 \times K_T}{\pi \times J_S^2 \times (T/D)}$$

Where: C_T = thrust load coefficient;

(T/D) =the ratio of blade tip clearance to propeller Diameter at 12 O'clock;

K_T =thrust coefficient;

Js =advance coefficient of propeller for full scale ship;

The index I_H is suggested to judge the possibility of occurrence for PHVC when propeller is at design stage. Here I_H is called hydrodynamic interaction intensity for estimate the cavitation performance. May be I_H could be as a criterion regarding the PHVC. The higher I_H means more dangerous regarding to appearance of PHVC.

Based on our data base of model experiments accepted value of I_H could be suggested by means of statistics. The suggested value for I_H is 3.2 at ballast draft condition (at design draft, I_H will be a little different) for most merchant ships, shows in Fig.7. When the I_H is beyond the criterion, local vibration on ship stern or PHVC may appear, but for some ships with good wake, the criterion value can properly increase.

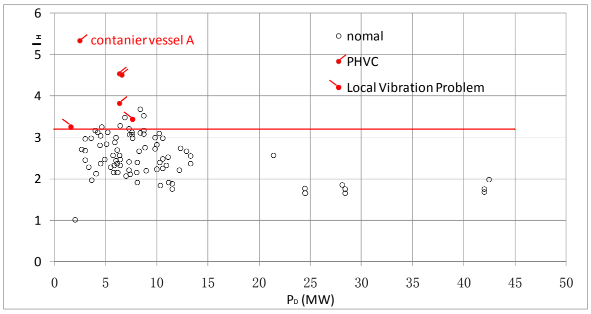


Figure 7 the distribution of I_H for different delivered power of propeller at ballast draft condition

3.2 The validation of suggested I_H

For this container vessel A, after the occurrence of PHVC, the ship-owner asked to change the propeller. Then three new propellers were designed with different diameter under limitation of ship speed, list at table 2.

Table2 comparison of three new propellers and original propeller

NO	B	C	D	original
D_S(m)	4.0	3.9	3.8	4.1
T/D	0.227	0.2451	0.2647	0.209
I_H	5.27	5.11	5.03	5.34

(a) Ds=4.1m Z=5 T/D=0.209 I_H=5.34

(b) Ds=4.0m Z=5 T/D=0.227 I_H=5.27

(c) Ds=3.9m Z=5 T/D=0.2451 I_H=5.11

(d) Ds=3.8m Z=6 T/D=0.2647 I_H=5.03

Figure 8 the cavitation pattern propellers with different diameter

Three new propellers operating at the power of 2503.7kW, and the cavitation tests were carried out in the CLCC. Fig.8 shows the cavitation pattern for different propellers. The test results indicate that comparing the cases of diameter 4.1m and 3.9m, the smaller diameter gets weaker and thinner PHVC, but further reducing the diameter to 3.8m, the PHVC becomes stronger again. The reason of it could be explained as that reducing the diameter causes the K_T increased, and therefore it leads the tip vortex cavitation and sheet cavitation of outer radius stronger and the effect of increasing tip clearance is not enough to overcome the negative effect from the tip vortex. Considering of the propulsion efficiency and ship speed, the diameter of propeller could not reduced further, and the change of I_H is not so much with different diameter. Therefore, the hydrodynamic interaction intensity I_H seems reasonable to judge the possibility of PHVC or local vibration problem for ship stern.

4 THE MEASURES FOR ELIMINATING PHVC

Improving the lines of hull is not possible because the ship had been already under construction in a shipyard during model test. As above-mentioned, the PHVC is also exist with re-designed propellers, then some other way had to take to eliminate the PHVC, such as adding some accessory to improve the inflow and reduce the local reversed flow onto propeller plane.

4.1 Analysis on flow field of container vessel A

Based on the measured wake from towing tank, the axial wake fraction contour and the vector diagram of transversal velocity are shown in Fig.9. Moreover, the streamlines along stern surface calculated by CFD is shown in Fig.10. It can be seen that there are high wake and flow separation. Therefore, it can be expected that the occurrence of PHVC of container vessel A caused by the flow separation and high hydrodynamic interaction intensity.

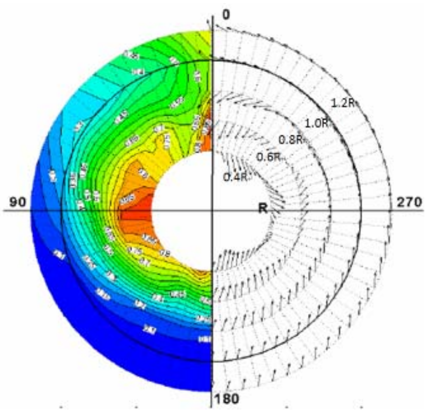


Figure 9 contours of axial wake fraction and diagram of transversal velocity vector

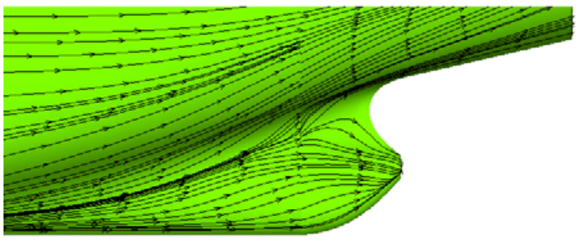
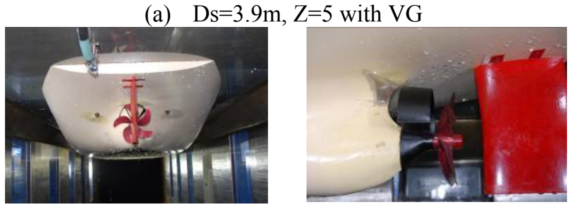


Figure 10 streamlines on ship stern surface

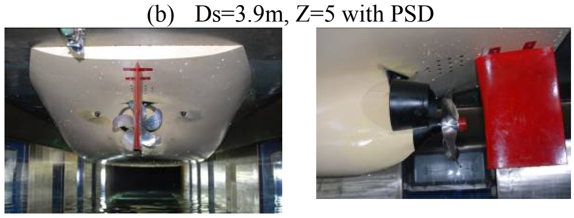
4.2 Installing accessories in front of propeller for improving the flow quality

Therefore to improve the inflow quality, several accessory devices were tried, such as pre-swirl duct (PSD), wake equalizing duct (WED) and vortex generator (VG).When there is flow separation, the VG has been proved very useful for PHVC elimination (Lu,2009). The VG should be installed in front of the location of flow separation and inside the boundary layer, which can improve the flow quality starting from the upstream. The PSD and WED can also improve the flow distribution (Huang, 2014) ahead of propeller. Fig.11 shows the test setup of different accessories, the VG (fig11.a) was installed below the shaft line and in front of propeller with an angle. The PSD (fig11.b) was just ahead of propeller, and the outlet height of PSD was approximate to the tip of blades. The WED (fig11.c) was installed just ahead of propeller, and the outlet height of WED was about 0.8R of blade height, this WED and propeller matched based on the method of energy saving, in Fig11.d the WED matched with a small diameter of propeller, which the outlet height of WED was approximate to the tip of blades. Fig11.b and Fig11.d were mainly improving the flow field of outer radius of blades which expected to eliminate the PHVC.

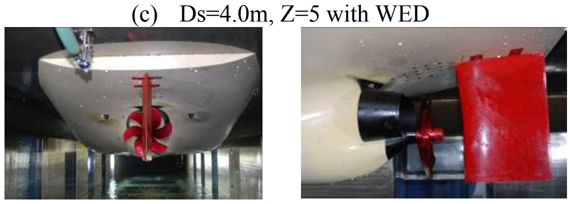
(a) Ds=3.9m, Z=5 with VG



(b) Ds=3.9m, Z=5 with PSD



(c) Ds=4.0m, Z=5 with WED



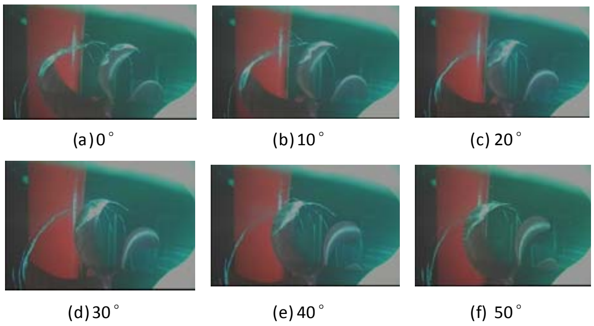
(d) Ds=3.8m, Z=6 with WED

Figure 11 test setup of different accessories

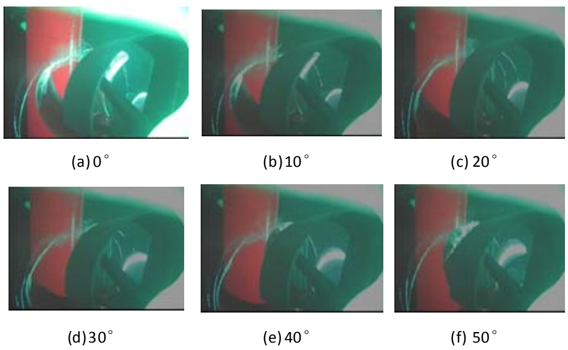
Fig.12 is the cavitation pattern at ballast draft condition. It was found that the PHVC was eliminated completely for VG or PSD case (Fig.12a&Fig.12b); what's more the sheet cavitation on blades was much more stable compared with no Accessory. VG is proved very useful for avoiding the PHVC as it used for 30000 ton bulk carrier (Lu, 2009). For the PSD and WED, it is found that the location of duct is very important, and it has obvious effectiveness if the top of duct outlet is as much as possible at same altitude level with the tip of propeller. The PHVC still occurred for WED with propeller diameter 4.0m, but almost disappeared for WED in case of propeller diameter 3.8m (about once occurred occasionally for 2-3min), this was the same reason like PSD, the outlet height of WED was almost the same as the propeller tip height with diameter 3.8m.

In order to find the way for improving the flow quality, the wake field and streamlines were calculated with

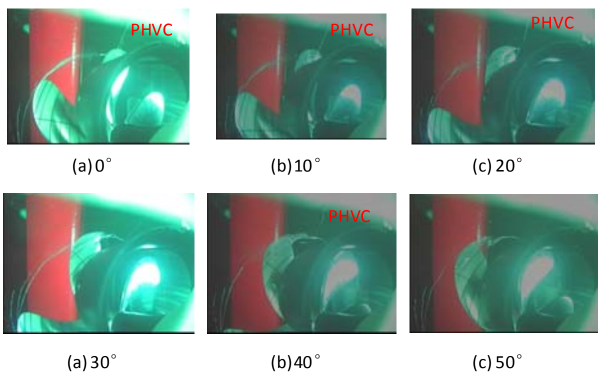
VG installation, shown in Fig.13. It shows that the flow is smoothed along the ship stern surface, and the separation disappears, and the VG shifts the high wake peak aside the center area that may reduce the negative influence from high wake. As the PSD and WED are much closed to the propeller, the interaction between accessories and propeller make the flow very complicated, this paper only the flow distribution of PSD & propeller was calculated, shown in Fig.15, the PSD increases the flow speed of the area between the tip blade and fore-upward stern surface, which reduce the risk of the occurrence of reverse flow and vortices in front of the propeller. The WED improved the PHVC might be the same reason, but lacked of stator blades, the capability of flow improvement is limited.



(a) Ds=3.9m, Z=5, with VG

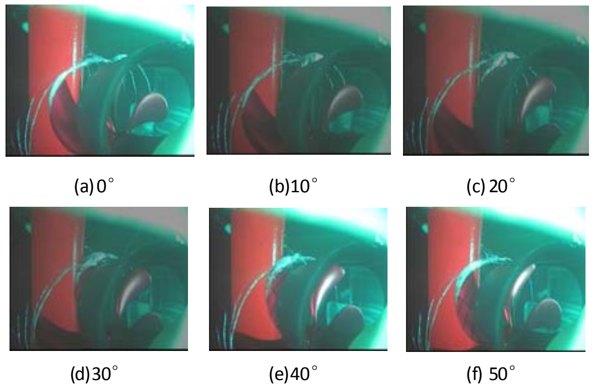


(b) Ds=3.9m, Z=6, with PSD



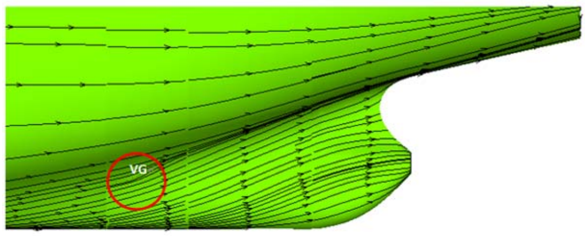
(c) Ds=4.0m, Z=5, with WED

Figure 12 the cavitation pattern on blade with different accessories

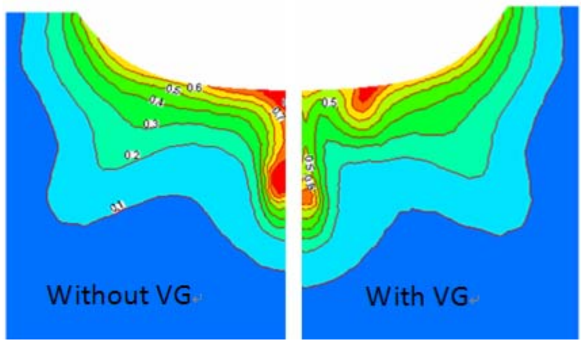


(d) Ds=3.8m, Z=6, with WED

Figure 12 the cavitation pattern on blade with different accessories (continued)



(a) Streamlines on ship surface



(b) Nominal wake distribution at propeller plane

Figure 13 the streamlines and flow field at propeller plane for VG installation

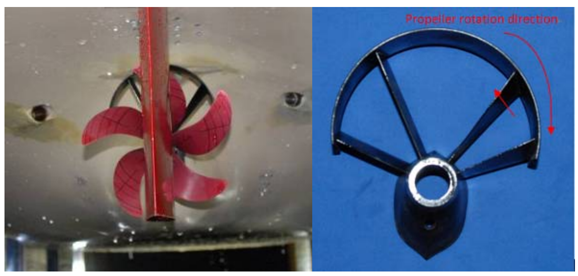


Figure 14 the detail of PSD installation

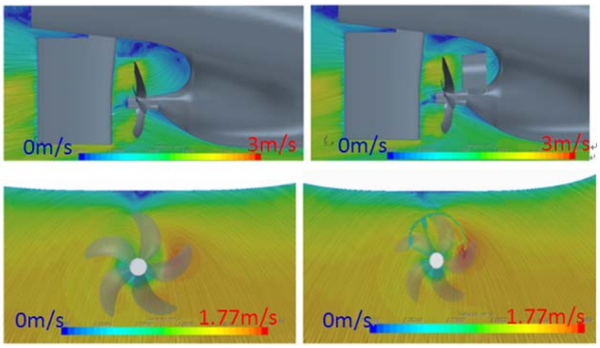


Figure 15 the comparison of flow with/without PSD

5 Further investigations

In order to understand deeply the mechanism and accurately judge the possibility of occurrence for PHVC, further investigations will be recommended as following:

1) Collecting more cases to enhance our data base;
2) Study the effect of flow wake on PHVC;
3) Unitizing the CFD method to modeling the PHVC.

6 CONCLUSIONS

PHVC is occurred easily for high intensity of hull and propeller interaction, especially there is a separation on ship stern surface. When the PHVC exists, it always leads to local vibration problem, so some measures must be taken to avoid hull serious vibration for all kinds of ships. Based on the model test and calculation results. Some conclusions can be drawn:

1) For most of ships, the hull and propeller hydrodynamic interaction intensity I_H should be below 3.2, once it is near 5.0, the risk of local vibration will rapidly increase;
2) Once PHVC appears, it is always the case with the high hull and propeller hydrodynamic interaction intensity. Specially, when here are some added vortexes (example bilge vortex as an inflow to propeller), the PHVC appearance will early. The effective way to eliminate PHVC is to improve the inflow speed and reduce the local reverse flow and vortices to the propeller plane, VG and PSD are the best choices;
3) WED is useful for solving PHVC problem if the propeller and WED can match well.

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