Estimations of scale effects on blade cavitation

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Abstract. Estimations of scale effects on blade cavitation require consideration of multiple models for both water flows and cavities. In particular, distinction of laminar and turbulent boundary layers is very important. A qualitative impact of selection of models is manifested for blade sheet cavitation. Its quantitative impact is shown for vortex cavitation inception.

1. Introduction
Naval hydrodynamics considers three different kinds of flows. The first kind is created in laboratories; these flows are convenient for measurements and can be repeatable. The second kind exists in full-scale conditions, where measurements are difficult and expensive. The third kind consists of imaginary CFD flows. Up to now model (laboratory) tests are considered as the ultimate tool for prediction of ship hydrodynamic characteristics, but the difference of model test and full scale flows forces employ CFD tools at least for estimations and comprehension of scale effects. Confidence of such estimations critically depends on selection of the employed CFD models.

As already noted [1], single-model approaches (like ideal fluid cavitation or fully-turbulent multiphase flows) are convenient for computations and can satisfactorily describe some kinds of cavitating flows, but such models are insufficient for estimations of scale effects of cavitation that, as noted in [2]-[3], may be significant. This insufficiency takes place because, first, two kinds of boundary layer exist on blades (as on a blade model shown in [4] and in Fig.1 here) and, second, a sheet cavity is usually not a uniform mix of small bubbles, but it is more similar to a single gaseous volume (as...
presented in Fig.2). As shown below for several examples, multi-model (multi-zone) computations make it possible to understand and predict scale effects on various forms of blade cavitation.

2. Scale effect on pressure side cavitation

Blades rotation in the ship wake can lead to periodical appearances and disappearances of cavities. This periodical phenomenon occurs due to variations of the angles of attack $\alpha$ of the blade sections crossing the wake. The corresponding variations of the cavity volume can substantially contribute to pressure pulsations. As usual, pulsation predictions have been based on the model test results, but the marine propeller models have shown significant differences of pressure harmonics in comparison with the full scale propellers. The inflow velocities at the propeller disc experience a substantial scale effect just in its top sector, where cavitation is expected. The local inflow similarity can be achieved in this sector with increasing the blade advance ratio [6], but the cavities tend then to rise on the blade pressure side and the similarity of cavitation form becomes lost for another sector of the propeller disk.

The presented estimations were carried out for a 3D hydrofoil with distribution of the load, section thicknesses and cambers corresponding to typical blade characteristics (this is similar to the approach of [7]). The non-uniform incoming flow was fitted to a typical ship wake (like measured in [8]). Then viscous-inviscid interaction approach [5] considering boundary layer separation around the cavity and capillarity on its surfaces was used in these estimations (as in Fig.2). The outer inviscid flow has been analyzed here with including the unsteady vortex sheets behind the sections. The leading edge flows are laminar over both sides of the blade. Though in some ranges of the azimuth $\theta$ the pressure coefficients drops below $-\sigma$ there, the cavity appearance is mitigated by the capillarity impact and this impact is much greater in the model test conditions. On the contrary, the scale effect on the cavity location and length is small for the blade suction side due to great pressure gradients at its leading edge (as in Fig.3, where $C$ is the section chord) and even ideal fluid computations may be acceptable, as noted in [3]. The effect of the cavity detachment on the pressure side cavitation, as shown in Fig.4, is in a significant difference of cavity lengths.

![Figure 3](image3.png)

**Figure 3.** Cavity detachment on section suction side (SS) and pressure side (PS) of a blade. B-W relates to solution with Brillouin-Villat condition.

![Figure 4](image4.png)

**Figure 4.** Cavity lengths on the same section; B-W marks the location corresponding to Brillouin-Villat condition, IF – ideal fluid, FS – full scale

![Figure 5](image5.png)

**Figure 5.** Normalized cavity section areas for model test (a) and full-scale (b) conditions; number show ratios of the section radius to the blade radius.
As seen in Fig.5 due to this difference, a cavity exists on the full-scale blade pressure side during a big part of the period and the cavity volume dependencies on $\theta$ experience the qualitative scale effect. So, the high pressure harmonics should not be similar.

3. Scale effects on vortex cavitation inception

The dream of engineers to link model test and full-scale results by simple scaling laws in the form of smooth functions of Reynolds number is rarely attainable for cavitating flows. In particular, the attempts to elaborate the universal scaling low $\sigma_I \sim Re^\varepsilon$ with $Re$-independent power $\varepsilon$ for cavitation inception in vortices have lead to failures since the pioneer study [9]. As shown in Fig.6, the experimental data [9] on cavitation inception number for tip vortices do not collapse into a single trend, but there are two different trends for high-Re band and low-Re band there. Obtaining an acceptable approximation for the low-Re band with two mistakable assumptions (on the fully turbulent flow at any $Re$ and on the proportionality of the vortex core radius to the boundary layer thickness), McCormick even supposed [9] that the high-Re data were inaccurate.

Later trends $\sigma_I \sim Re^\varepsilon$ with close $\varepsilon$ for turbulent flows were found via a similarity analysis [10] ($\varepsilon=0.24$), RANS computations [11] ($\varepsilon=0.22-0.23$) and an approximation of the model test data at $Re>4.7\times10^6$ [12] ($\varepsilon=0.21$). Let us point out that cavitation inception of ships and their self-driven models has to be determined by a jump of hydrodynamic noise and it is important to register just this jump. It is incorrect to determine the cavitation inception speed as the highest speed of the low noise level (the speed of calm operations). In particular in [13], the speed of calm operations was 8.8 knots for the ship and 15 knots for its self-driven model. Its use gave $\varepsilon=0.3$, but this value indeed relates to cavitation-free flows. Using the experimental points [13] just with the jumps of noise level due to cavitation, one got $\varepsilon=0.21$. Nevertheless, this scaling problem cannot be considered as the solved problem yet because there is an issue to determine the point of trend change. As easy to find from Fig.6 with data of [9] (fig.14), an early transition from a low-Re trend to a high-Re trend will underestimate full-scale $\sigma_I$. On the other hand, one will overestimate it assuming that flow is laminar.

An inverse mistakable assumption affects prediction and scaling of cavitation inception in vortices located in wakes. It requires analyze pressure in vortex cores. The common assumption is the existence of a laminar vortex core (Rankine vortex) there. However, as derived by Amromin [14], indeed the vortex core velocity profile in turbulent flows is described by formula

$$u(\xi) = \Gamma \xi (1 - \ln \xi)/(2\pi R),$$

(1)

where $\xi = r/R$, $\Gamma$ is vortex intensity, and the core radius $R = \sqrt{-\Gamma \nu / (\pi u'v')}$. Eq.(1) is the exact solution of Reynolds momentum equation for axisymmetric flows. It can be applied to situations, where $R$ is much smaller than the scale of a substantial variation of the Reynolds stress $<u'v'>$. One
can see Fig.7 with data for quite high $Re$ that Eq.(1) gives the much better approximation of the measured velocity profiles. Besides, this equation gives the substantially lower pressure within the core (shown in Fig.8) and, at the vortex axis

$$\min(C_p)\big|_{\text{Turbulent}} = 1.5 \min(C_p)\big|_{\text{Rankine}} - 0.5$$

(2)

![Figure 8. Pressure drop within laminar (dashed curve) and turbulent (solid curve) cores [14]](image)

![Figure 9. Computed and measured $\sigma_I$ for vortices in the wake of a self-driven body [15]](image)

The use of Eq.(1),(2) made it possible a satisfactory correspondence of the dependencies computed with the viscous-inviscid interaction approach to experimental data, as shown in Fig.9. The corresponding axisymmetric flow was computed with consideration of the laminar boundary layer, transition, attached turbulent boundary layer and the zero-momentum wake [15], whereas the cavities were considered as spherical bubbles. However, the author supposes that one may improve some results of RANS computation for vortex cavitation simply including Eqs.(1) and (2).

**Conclusions**

The advantages of multi-model CFD analysis of scale effect on cavitation are manifested in this paper. The proven multi-model viscous-inviscid approach was employed in presented computations, but it would not be realistic to expect an extensive spread and amelioration of this approach in the near future. It would be more realistic to seek modifications of RANS or LES solvers or their merging with other solvers allowing for the multi-model analysis of blade cavitation and its scale effects.

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