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Assessment of Flow Fluctuation Pressure Models for Simulating the Cavitating Flow

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A numerical study is performed to simulate the cavitating flow, evaluating the applicability of different flow fluctuation pressure (FFP) models such as the Singhai FFT model, the modified Singhal FFT model, the shear strain model, and the present shear strain-vorticity model. The axisymmetric blunt-body with the availability of experimental data is selected for the simulation purpose. According to the results, the first three FFP models produce nearly similar pressure coefficient C_p distribution on the blunt-body. On the other hand, the numerical results indicate the influence of both turbulent shear strain rate and the vorticity in the flow. A slightly better prediction of the cavitation mechanisms such as the flow parameter C_p and cavity length is thus produced with the present shear strain-vorticity model.

Keywords: Cavitation, turbulent fluctuation, shear strain, voticity, homogeneous model.

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Cavitation is an important phenomenon that highly influences the performance of hydraulic machines. Cavitation occurs, resulting in noise, vibration, and the decrease of the machine's efficiency. Importantly, the cavitation causes erosion that dramatically criticizes the working safety condition. Hence, understanding the cavitation mechanism is important for the design of hydraulic machines with high performance and safety.

Recently, the homogeneous model is a valuable method for clarifying cavitation mechanisms in the industry compared to the other models [1–6]. In this model, the multiphase flow can be simplified as a pseudo-single phase flow with an additional phase's transport equation and a source term for modeling the mass transfer processes. The key problem is the choice of a cavitation model that can reasonably produce the onset and development of the cavitation bubble. Most cavitation models are derived from the simplified Rayleigh−Plesset equation [7–9]. For which the criteria phase change pressure is the key indicator to determine whether the evaporation or condensation occurs.

Typically, cavitation occurs in high Reynolds flow, showing the high interaction between flow fluctuation and the phase change mechanism [6,7,10], and has to be considered in the numerical simulation. Therefore, this study aims to evaluate different flow fluctuation pressure (FFP) models for modeling the phase change in cavitation. Four FFP models are performed such as the Singhai FFP model (SM), the modified SM model (MSM), the shear strain model (SSM), and the present shear strain-vorticity model (SVM). The first three models account for the turbulent Reynolds stress effect while the latter model considers the increase of Reynolds stress owing to the vorticity in the flow.

The cavitating flow is simulated using a homogeneous compressible liquid−vapor two-phase flow model [2–6]. The SST $k-\omega$ model [11] coupled with the Allmaras wall function [6] is used. The Saito cavitation model [12] is selected to model the mass transfer rate in cavitation. The criteria indicator, the threshold phase change pressure p_v^*, is calculated as follow,

$$p_v^* = p_v + p_{ff}. \quad (1)$$

With, p_v is the saturated vapor pressure. p_{ff} indicates the flow fluctuation pressure that is the key indicator in this study and is calculated as follows.

Singhal flow fluctuation pressure model (SM): the p_{ff} caused by the turbulence is calculated from the local turbulent kinetic energy k as follows [7],

$$p_{ff} = 0.195\rho k. \quad (2)$$

Modified Singhal flow fluctuation pressure model (MSM): Chebli et al. [10] found that within the cavity region, the viscous shear stress changes non-linearly with the mixture density. Therefore, for the MSM model, the p_{ff} is modified by,

$$p_{ff} = \frac{(1-\alpha)^{10}(\rho_l - \rho_v) + \rho_v}{(1-\alpha)(\rho_l - \rho_v) + \rho_v}\rho k. \quad (3)$$

Shear strain model (SSM): In this model, the right-hand side term of Eqs. (2) and (3) is replated by the shear strain rate S as follow [13],

$$p_{ff} = \mu|S|. \quad (4)$$

Present shear strain-vorticity model (SVM): This is known that the vortices in the flow would affect the cavitation behavior because it increases either wall's Reynolds stress or the criteria phase change pressure [6]. Therefore, in this model, p_{ff} is calculated as follow,

$$p_{ff} = \mu|S|, \quad |\Omega| < |S|,$$

$$p_{ff} = \mu(|S| + |\Omega|), \quad |\Omega| > |S|. \tag{5}$$

For which where the vorticity magnitude Ω are dominant, p_{ff} is the summation of the pressure by shear strain rate and the additional pressure by the vorticity. Otherwise, p_{ff} is calculated by the shear strain rate S as in the SSM model.

The cavitating flow around the blunt body is selected for evaluation of the models above [14]. Notably, this object has a simple geometry, the symmetry two-dimensional (2D) simulation with a structured grid of 279×85 points is thus performed. For the inflow boundary, the velocity inlet $U_{in} = 5.45$ m/s based on $\mathrm{Re} = 1.36 \times 10^5$ and vapor void fraction $a_0 = 0.001$ are specified. The constant pressure p_0 is used at the outflow boundary based on the flow cavitation number $(\sigma = p_0 - p_v)/0.5\rho U_{in}^2)$ of 0.6, 0.4, and 0.3. No-slip and symmetry boundary conditions are applied to the body and the axis, respectively, as shown in Fig. 1. The simulations are performed using the in-house code with Finite Difference Method and explicit Total Variation Diminishing Harten–Yee 2nd upwind scheme. This numerical scheme was reasonably benchmarked for various flow fields [4–6].

Regarding the pressure distribution, almost identical pressure coefficient $(C_p = (p - p_0)/0.5\rho U_{in}^2)$ distribution on the blunt surface and inside the cavity region is produced by all FFP models for the tested cavitation numbers σ, as presented in Fig. 1. The low C_p region increases as the σ decreases, indicating the increase of cavity length on the body. The discrepancy becomes visible in the cavity's rear region. For which the predicted C_p is better slightly in the present SVM model, which is closer to the measured data than the first three Reynolds stress models at $\sigma = 0.4$ and 0.3.

Figure 2 presents the comparison of the cavity void fraction and streamline (*) and the p_{ff} (**) between the SSM (left) and SVM (right) modes at the flow cavitation number $\sigma = 0.4$. The results allow a better understanding of the mechanism behind the improvement in the flow prediction with the present SVM model. The reentrance flow occurs at the rear of the cavity, detaching the vapor from the body's surface. In addition, the circulation flow results inside the cavity region in both models. Regarding the SSM model, p_{ff} is visualized from the sharp edge of the blunt surface and increases along the cavity area. The flow separation in this region causes a large change in the shear strain rate S, resulting in the maximum p_{ff} of about 650 Pa at the rear of the cavitation region, as depicted in Fig. 2-left. Inside the cavity, p_{ff} is obviously higher in the SVM model. Owing to flow circulation and vortex, more fluctuation pressure p_{vor} is added to p_{ff}

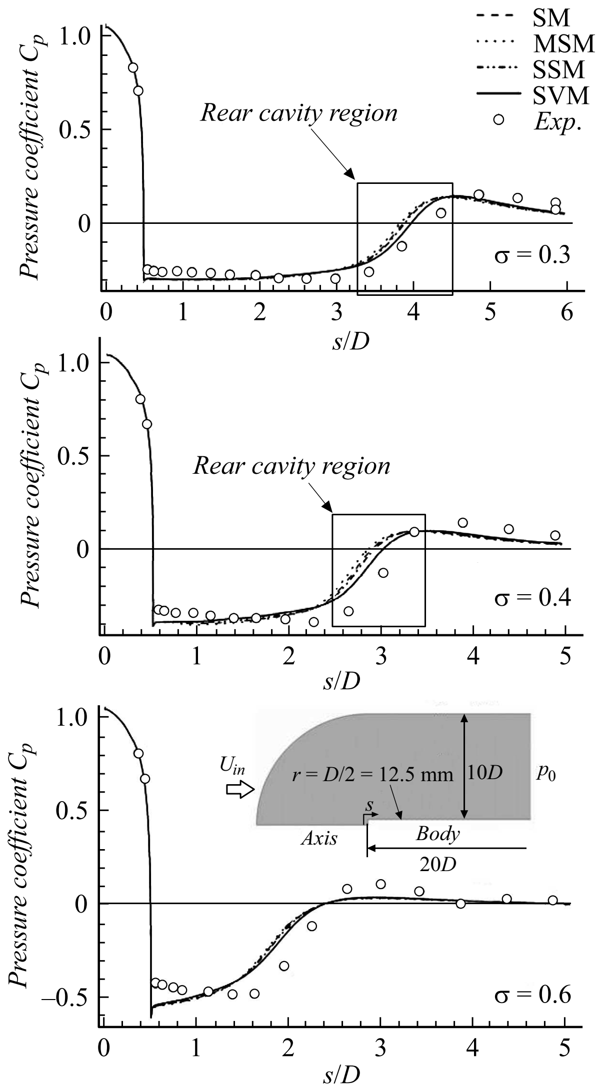

Figure 1. Comparison of C_p on the blunt-body between four p_{ff} models and experiment [14].

that reaches the maximum value of 1200 Pa, as shown in Fig. 2-top right. Thus, stronger evaporation and a better agreement with measured data are produced in the present SVM model. Behind the cavity, p_{ff} caused by the shear strain rate is produced in the SVM model as in the SSM models. This implies that the vortex that existed in the flow would affect the phase change process and has to be taken into consideration in simulation. The present SVM model, accounting for both shear strain rate and vorticity effect on the criteria phase change condition, is applicable for modeling the cavitation process.

In conclusion, the result of this study showed that the simulation of cavitating flow is influenced by flow fluctuation behavior. Various FFP models based on the shear train rate produces a similar result that underestimated the cavity region and the pressure distribution on the body. The present shear strain-vorticity model produces a slightly better agreement with measured data than the

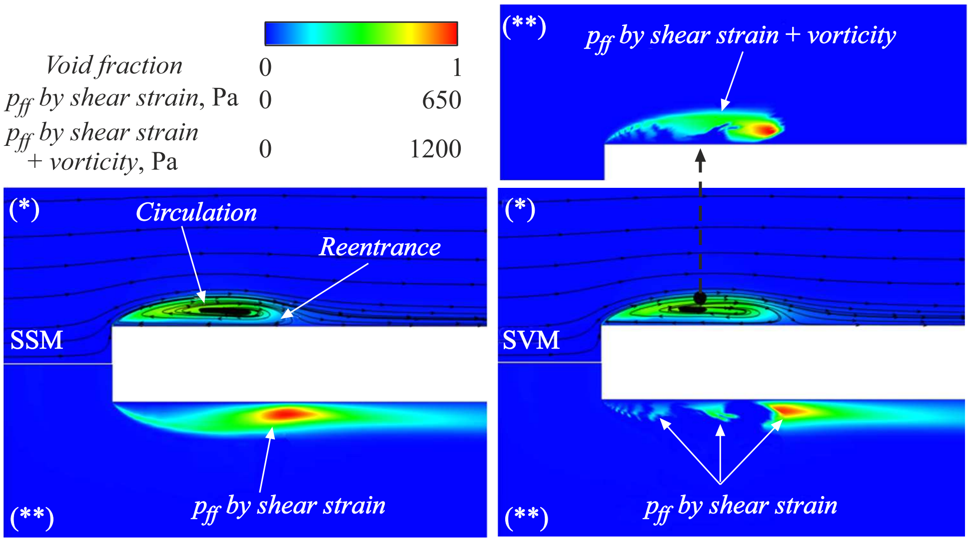

Figure 2. Contour of void fraction and streamline, p_{ff} by shear strain rate, and p_{ff} by shear strain + vorticity in SSM and SVM models.

other Reynolds stress models. The results demonstrate an important effect of the vortices and recirculation in the flow that should be considered in the mass transfer process. Since the steady cavity was produced, the effect vortices may not be significant. However, this is believed that the proposed model would provide a much better result for the case of unsteady cavitation and its applicability with other cavitation models will be reported in the next study.

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Conflict of Interest

The authors declare that they have no conflicts of interest.

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